The Efficacy of Fitting Cochlear Implants Based on Pitch Perception

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Declaration

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

Abstract

Cochlear implants (CI) provide useful hearing for many hearing-impaired individuals. The CI’s external sound processor has to be programmed to optimise performance. However, performance varies greatly amongst CI recipients.

This thesis evaluated a pure-tone electrode-differentiation (PTED) pitch-ranking task for optimising programming. The PTED was evaluated for reliability, validity and clinical-suitability. PTED scores were a significant ($p<0.05$) predictor of speech-perception.

The angular-depth-of-insertion for the CI array was estimated for 16 recipients, there was a significant correlation with speech-perception. Cone beam computed tomography (CBCT) increased accuracy for estimating scalar-placement of electrodes and no association was found with speech-perception.

25 unilaterally-implanted recipients received programs with indiscriminable electrodes deactivated based on PTED. Two programs were provided, one with the same rate-of-pulses-per-channel (RPC) as the clinical program and one with increased RPC. Programs were evaluated in a cross-over study. Speech-perception was evaluated using BKB (Bamford-Kowal-Bench) sentences in quiet and noise and the Coordinate Response Measure (CRM). Statistically significant improvements were found with at least one research program on all measures.

A pure-tone intermediate frequency (PTIF) task was conducted to compare pitch perception in regions of good ED with regions of poor ED. Participants gaining benefit from electrode deactivation had fewer intermediate frequencies (IF) in poor ED regions compared to good ED regions and more IF in electrode deactivation regions following deactivation. This pattern was not observed in participants not gaining benefit from electrode deactivation.

Six bilaterally-implanted participants underwent pitch matching between ears and new programs were created using only discriminable electrodes. Two matching approaches were used; direct stimulation *via* clinical equipment and pure-tone stimulation. Significant improvements were found in localisation and BKB in noise with at least one research program.

The results of these experiments suggest potential for improving performance for CI users by programming based on PTED; a clinically viable task.

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Publications and conference presentations

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Saleh, S.M., Saeed, S.R., Meerton, L. and Vickers, D. 2011, “Clinical Mapping of Cochlear Implants Based on Electrode Differentiation.” Oral presentation at the Med-El UK 7th Clinical Symposium, Windermere, UK.

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Saleh, S.M., Saeed, S.R., Meerton, L. Moore, D. and Vickers, D. (in press) “Clinical use of electrode differentiation to enhance programming of cochlear implants.” Cochlear Implants International. (Extended abstract).

Saleh, S.M., Vickers, D., Meerton, L. and Saeed, S.R. 2010, “Fitting Cochlear Implants Guided by Electrode Discrimination.” Oral presentation at the BAA Annual Conference, Challenging Audiology, Edinburgh, UK.

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Glossary

*n*I- *n*AFC	*n* interval *n* alternative-forced-choice task
AAI	Age at implantation
AB	Advanced bionics
ACE	Advanced combination encoder
AEPC	Across ears pitch comparison (test)
ADRO	Adaptive dynamic range optimization
AGC	Automatic gain control
AI	Articulation index
ANOVA	Analysis of variance
ART	Auditory nerve response telemetry
APHAB	Abbreviated Profile of Hearing Aid Benefit
AUX	Auxiliary (input only)
BKB	Bamford-Kowal-Bench
BKB-SIN	BKB-Speech In Noise test
BPF	Band pass filters
C	Comfortable level (loud but comfortable)
CA	Compressed Analog
CBCT	Cone beam computed tomography
CI	Cochlear implant

c.i.	Confidence interval
CID	Central Institute of Deafness (everyday sentence test)
CIS	Continuous interleaved sampling
CNC	Consonant-Nucleus-Consonant
CPI	Clinical programming interface
CRM	Coordinate response measure
CSSS	Channel specific sampling sequence
CST	Connected speech test
CU	Clinical units
CUNY	City University of New York (sentence test)
dB	Decibel
dBA	A-weighted dB (decibel) Sound Pressure Level
DE	Deactivated electrodes
DED	Direct-stimulation ED (electrode differentiation)
DEHF	Deactivated electrodes at high frequencies (> 2600 Hz)
DELF	Deactivated electrodes at low frequencies (< 2600 Hz)
df	Degree of freedom
DIF	Discriminable intermediate frequency/ies
DL	Difference limen
DS	Direct stimulation

E	Electrode
EABR	Electric auditory brainstem response
EAS	Electro-acoustic stimulation
ECAP	Evoked compound action potential
ED	Electrode differentiation
ENV	Common environmental sounds
EP	Electrode pair
F0	Fundamental frequency
F2	Second formant
F1	First formant
FDA	U.S. Food and Drug Administration
FDL	Frequency difference limen
FM	Frequency modulation
FSP	Fine structure processing
H	Higher (pitch)
HDCIS	high definition CIS (continuous interleaved sampling)
HINT-N	Hearing in Noise Test in noise
HINT-Q	Hearing in Noise Test in quiet
HiRes	High resolution
HiRes P	High resolution paired

HSM	Hochmair- Schulz-Moser (sentence test)
Hz	Hertz
IDR	Input dynamic range
IF	Intermediate frequency/frequencies
IIR	Infinite impulse response
ILD	Interaural level difference
IPI	Inter-pulse interval
ISI	Inter-stimulus interval
ITD	Interaural time difference
IQ	Intelligence quotient
IQ (range)	Inter-quartile (range)
L	Lower (pitch)
LM	Loudness matching
LPF	Low pass filter
M	Most comfortable level
kHz	Kilohertz
MCL	Most comfortable level
MDS	Multidimensional scaling
MDT	Modulation detection threshold
MNEP	Maximum number of electrode pairs

MRI	Magnetic resonance imaging
ms	Millisecond
MSCT	Multi slice computed tomography
N	Number of test participants or data sets
NCIUA	National Cochlear Implant Users Association
NH	Normal hearing
NICE	National Institute for Health and Clinical Excellence
NRI	Neural response imaging
NRT	Neural response telemetry
NU-6	Northwestern University Auditory Test No. 6
OSLA	Oldenburger sentences
PAT	Pat Associate Test
PPS	Paired Pulsatile Sampler
PPS	Pulses per second
PR	Pitch ranking
PT	Pure tone
PTA	Pure tone average
PTED	Pure tone electrode differentiation
PTIF	Pure tone intermediate frequency test
RAU	Rationalized arcsine-transform units

RNTNEH	Royal national throat nose and ear hospital
RPC	Rate per channel
RPM	Raven Progressive Matrices
S	Same (pitch)
SAS	Simultaneous analog stimulation
SD	Standard deviation
SII	Speech intelligibility index
SLT	Sequence Learning Task
SNR	Signal-to-noise ratio
SOE	Spread of excitation
SPEAK	Spectral peak
SR	Spatial resolvability
SRM	Spatial release from masking
SRT	Speech-reception threshold
ST	Scala tympani
SV	Scala vestibuli
T	Threshold
THR	Threshold
Q_1	First quartile (lower 25th quartile)
Q_3	Third quartile (upper 75th quartile)

VCV	Vowel Consonant Vowel
VMT	Visual Monitoring Task
WAIS-R	Wechsler Adult Intelligence Scale-Revised

Chapter 1

Cochlear implants

"The aspects of things that are most important to us are hidden because of their simplicity and familiarity." Ludwig Wittgenstein (quote). Simple things such as enjoying our favourite music, talking on the telephone, having a conversation in a busy restaurant or exchanging small talk with a neighbour are common place to normal hearing listeners yet they seem so difficult and sometimes impossible for the hearing impaired. Perhaps this is why the cochlear implant (CI) is one of the greatest innovations of the 20th century in the field of Otorhinolaryngology, helping to restore a sense of hearing to over 188,000 hearing impaired recipients across the world (National Institute of Deafness and other Communication Disorders, 2012).

CIs have been recognized as a safe and effective procedure for the management of patients with a severe to profound hearing loss who derive minimal benefit from hearing aids (FDA, 1984 and Summerfield and Marshall, 1995). CIs can provide useful hearing for adults to a level that allows normal conversation and even telephone use for some good performers (Brown et al., 1985). Various studies have been conducted that provide evidence of post-CI benefits on many aspects of auditory detection and speech perception. (UK Cochlear Implant Study Group, 2004) reported speech perception changes following implantation for 84 post-lingually deafened adults implanted between 1997 and 2000 in 13 hospitals in the UK; They found that the mean percentage correct scores achieved when listening in quiet to the Bamford-Kowal-Bench (BKB) sentences significantly increased from 13% pre-implantation to 57% at 9 months post-implantation.

This chapter provides a general overview of CIs how they work and the main parameters involved in programming them. It will start with a description of CIs and the basic functionality and components, followed by major design issues that may affect processing and, ultimately, performance. Finally it will provide a general description of the main aspects of fitting CIs and programming the device, including signal/speech processing strategies and the basic procedures involved.

1.1 The CI device

A CI is an electronic device that helps transduce sound to electrical signals that directly stimulate auditory nerve fibres by bypassing the damaged cochlea hair cells in the peripheral auditory system. .

1.1.1 Components of the CI device

The CI consists of internal and external parts:

Internal parts are the surgically implantable components and consist of an implant receiver (radio antenna, magnet, and a micro-computer to process the signal), stimulator and an array of electrodes that is inserted into the cochlea and stimulates the spiral ganglion. The receiver/stimulator package receives the electrical signal from the transmitter coil (in external parts) and processes the information to allow the stimulator to transmit the information as electrical pulses *via* the electrode array (see Figure 1.1).

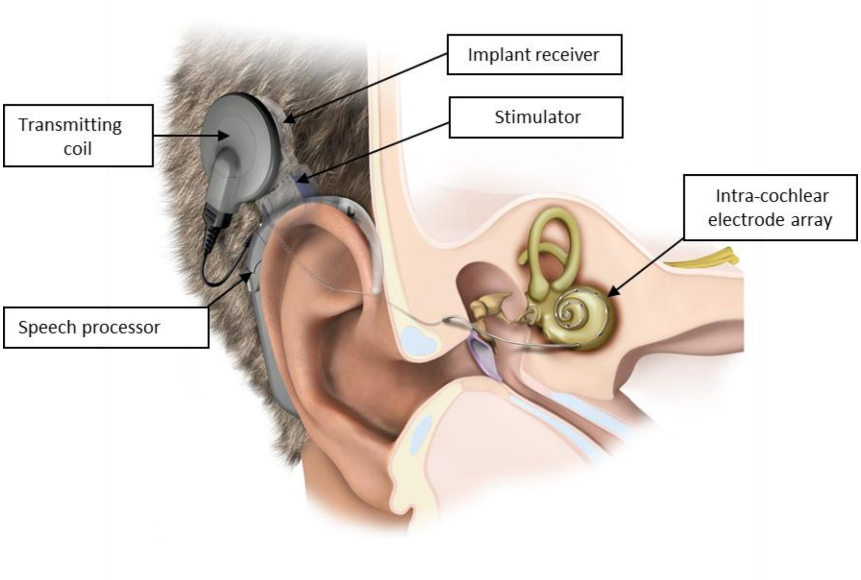


Figure 1.1 A schematic diagram of a CI; courtesy of MED-EL^{TM}

External parts comprise of the speech processor which could be either body-worn or behind-the-ear (see Figure 1.2 for examples from different manufacturers). The speech processor uses a micro-computer to convert sound waves into electrical signals and transmit them to the implant receiver through the head piece which contains a transmitting coil (coil) which is a radio-signal transmitter with a magnet of opposite polarity to that of the implant's receiver, thus allowing energy efficient signal transmission. See Figure (1.3) showing the internal and external components of the cochlear Freedom speech processor.

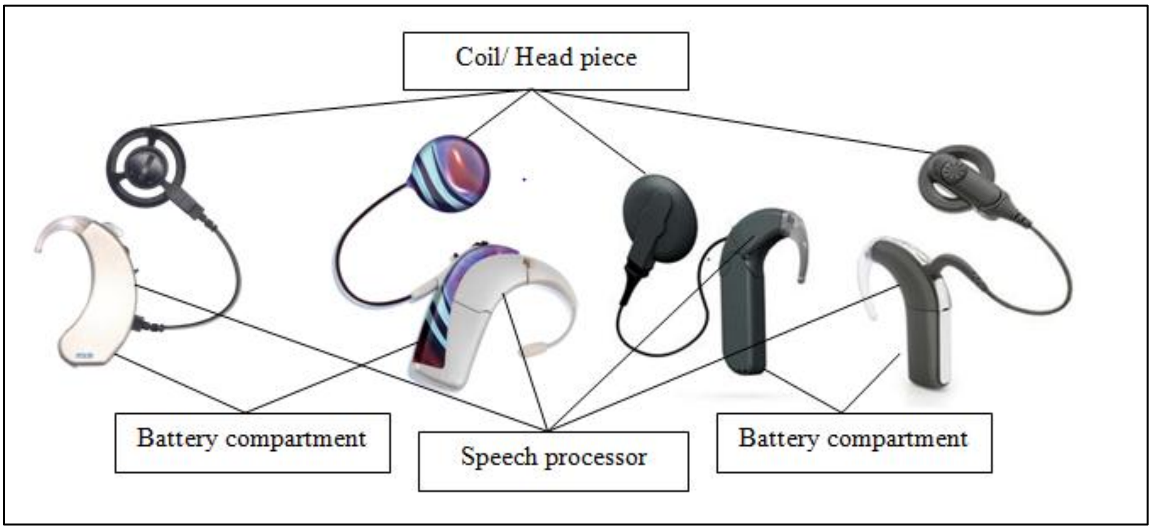


Figure 1.2 Behind-the-ear speech processors; courtesy of Neurelec, Advanced Bionics (AB), MED-EL™ and Cochlear®.

Figure 1.3 Picture of the CI device; (A) external behind the ear speech processor; (B) the transmitting coil and (C) the internal implant with the receiver, stimulator and electrode array; courtesy of Cochlear®

1.1.2 How the CI functions

The main stages of the working mechanism of the CI sound processing and delivery are as follows:

1. The speech processor has a microphone that picks up the sound.
2. The speech processor converts the input sound into electrical signals that will be delivered within the electrical dynamic range of the listener based on the individualized program parameters stored in the speech processor. The sound processing strategy used by that particular implant system will be used to determine the pattern of delivery of the sound.
3. The electrical signal is transmitted to the internal receiver *via* the transmitting coil (in the head piece) to the receiver coil as FM radio signals by transcutaneous communication.
4. The implant stimulator sends the signal to the electrode array.
5. Different electrodes are triggered differently according to the sound properties (frequency and level) and the speech processor's settings.
6. Auditory nerve endings pick up the electrical signals which travel along the auditory pathway to the brain where the information is decoded in the auditory cortex.

Although all current day CIs have the same general structure and working mechanism different manufacturers use slightly different approaches for design and stimulus delivery.

1.2 The CI design and specifications

CI design has evolved since the original stimulation of the auditory nerve with an implanted electrode and induction coil conducted by Djourno and Eyries's (1957). Numerous scientists and clinicians have contributed to the development of the present day CI devices. The early devices were single channel implants including those of Simmons (1966) and House and Urban (1973) and the single-channel electrode-pair implant by Robin Michelson (Michelson, 1971 and Schindler and Merzenich, 1974). The latter was the starting point for the Advanced Bionics CIs. All current day devices are multi-channel systems, among the early multi-channel designs was Graeme Clark’s 20 platinum electrode system; the starting point for today’s Cochlear® device (Clark et al., 1975 and Clark, 2008). Early four/ six and eight-electrode Vienna CIs by Hochmair, Burian and Hochmair-Desoyer developed into ME-DEL^{TM} 12-electrode CIs (Hochmair et al., 1983) and Chouard’s work in France in the 1970’s was the starting point for the first 15 – channel digisonic CI for Neurelec (Pialoux, Chouard and McLeod, 1976). The introduction of multi-channel CIs had a great impact on the quality of the sound perceived by CI users and was the greatest catalyst for improvements in speech perception. However many factors can have an effect on the performance and outcome with a CI and some of the most important and relevant design issues were characterised by Grayden and Clark (2006) and Zeng et al. (2008) and fall into the following categories:

1. Performance.
2. Reliability.
3. Safety.

1.2.1 Performance

1.2.1.1 CI specifications and performance

The CI devices have developed over the years into having closer specifications across the different manufacturers (Zeng et al., 2008). Several changes have been applied to the CI specifications in an attempt to enhance performance. These include increasing the input dynamic range (the ratio between the loudest and softest sounds that the speech processor will present at any given time), widening the frequency range stimulated by CI, increasing the rate of stimulation, back telemetry and practical modifications of the speech processor.

There was an increase in the input dynamic range (IDR) (and the delivered frequency range for all systems. The IDR has increased from an initial 30 dB in the Nucleus 22 device (from Cochlear) to 75-80 dB with a default setting of 45-

60 dB to better reflect the amplitude variations in real life listening situations (Zeng et al., 2002; James et al., 2003; Dawson et al., 2007 and Spahr et al., 2007).

The frequency range was widened and now incorporates frequencies lower than 300 Hz in some systems, Zeng et al. (2008) argues that these changes were applied in an attempt to enhance temporal pitch cues and tonal languages perception that require cues in the fundamental frequency (F0) range (e.g. Fu, Zeng, Shannon and Soli, 1998).

Rate of stimulation has increased mainly for AB (e.g. Frijns et al., 2003) and MED-EL devices (e.g. Zeng et al., 2008) in an attempt to improve performance (e.g. Frijns et al., 2003) although there isn’t clear evidence supporting that assumption (e.g. Friesen et al., 2005). Cochlear devices on the other hand haven’t increased rate of stimulation mainly because in contrast to AB and MED-EL devices that have multiple current sources (up to 16 in AB and up to 24 in MED-EL) Cochlear devices have only one current source (Zeng et al., 2008).

Back telemetry is an important feature that CI devices have added. It provides information about the integrity of the internal device, the “electrode-tissue interface” (Zeng et al., 2008) which include impedance telemetry (see Section 1.3.1 for detailed description) and neural response (more recent) such as Neural Response Telemetry/Imaging (NRT in Cochlear and NRI in AB) and Auditory Nerve Response Telemetry (ART in MED-EL). Neural response tests (NRT/ NRI/ ART) can provide objective measures of the auditory-neural response to the CI electrodes’ stimulation and can help in programming of the speech processor especially of young children. They can also be used for research purposes.

Other practical advancements included incorporating directional microphones (e.g. Cochlear’s Freedom speech processor) or water resistance features (e.g.

Cochlear’s Nucleus 5 speech processor’s water resistance and AB’s Neptune completely swimmable Neptune speech processor).

1.2.1.2 Array design and performance

Beyond the shift from single to multiple-electrode arrays, changes have been implemented to the CI array design in an attempt to (1) enhance performance by matching electrical stimulation to the tonotopic organisation of the cochlea (e.g. long and thin electrode arrays for deep insertion) or by enhancing coupling between electrodes and spiral ganglion (e.g. preformed arrays that hug the modiolus) or (2) reduce insertion trauma (e.g. flexible electrode arrays such as the FLEX*soft* array from MED-EL). The physical attributes of the array changed as surgical procedures evolved along with better understanding of cochlear anatomical structures and electro-physiological factors that may affect CI performance (Zeng et al., 2008). Since electrode array design affects surgical insertion it will be discussed in detail in Section (2.2.4) along with surgical insertion aspects.

1.2.1.3 Localization of current

This is considered by some manufacturers to be of importance in order to ensure that stimulation is localized to specific regions of the auditory nerve fibres. Stimulation mode can be referred to as electrode coupling, which can be defined as “how electrodes are electrically connected to form an electrical circuit; all consist of active and reference electrodes” (Wolfe and Schafer, 2010). The main types of stimulation or electrode coupling that are used are common ground, monopolar and bipolar (see Figure 1.4). Some companies such as AB have introduced what they refer to as advanced electrode coupling which potentially includes tripolar and quadro/partial tripolar polar coupling (e.g. Zhu et al., 2012 and Bierer et al., 2011) (see Figure 1.4). For a comparison between the different electrode coupling types see Table (1.1).

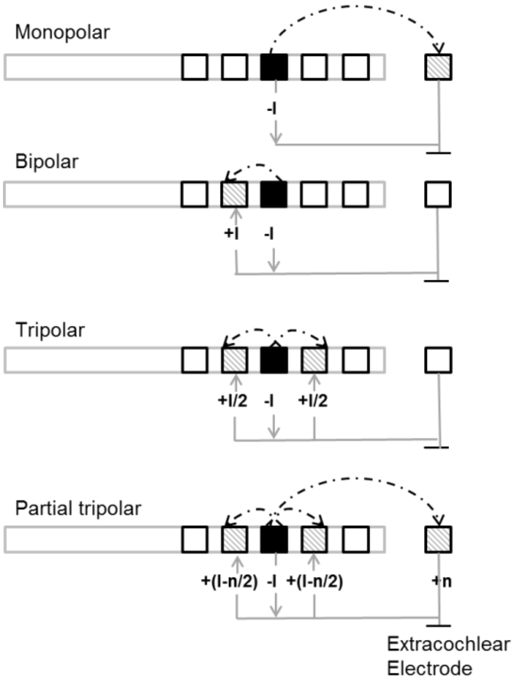


Figure 1.4 Current flow in monopolar, bipolar, tripolar and partial tripolar coupling, all have the same active electrode [black bar represents active electrode (El)], but different return electrodes (patterned bars; EL -1 or EL+1 or extra-cochlear electrode). The solid lines indicates the electric circuit; the dashed arrow represents the current path from active to return electrode, with (-I) indicating the cathodic phase. n represents the fraction of current returning from extracochlear electrode and the rest (I-n) is divided by two and returned through the two adjacent electrodes. Adapted from Zhu et al. (2012).

Table 1.1 Summary of the different types of stimulation, current flow and advantages.

Type of stimulation/ electrode coupling	Current flow	Advantages and/or current localization
Common ground	Occurs between one electrode and all the other electrodes in the array.	Better current localization than monopolar
Bipolar stimulation	Occurs between a pair of electrodes in the array.	Better localization than monopolar.
Monopolar	Occurs between one electrode in the array and at least one extra-cochlear electrode.	Less localization than bipolar and common ground but allows for less energy consumption
Tripolar	Occurs between one electrode as active and the two adjacent electrodes in the array acting as ground.	Claimed to have better localization than bipolar and common ground but greater energy consumption making it too impractical for implementation.
Quadropolar/Partial tripolar	Occurs between one electrode as active, the two adjacent electrodes in the array and an external electrode acting as ground. A combination of Tripolar and Monopolar.	Claimed to have localization as good as tripolar but less energy consumption than the tripolar approach.

1.2.1.4 Power and data transmission

For transcutaneous transmission such as that used in current CI systems, signal carriers are required; great care has to be taken to ensure that it does not cause tissue damage; thus carriers must have as a low frequencies as possible (e.g. 5 MHz for Cochlear Freedom devices, 12 MHz Med-El Sonata and 49 MHz for AB HiRes90k). Another issue which needs to be considered is that of power efficiency in order to prolong battery life, this can be achieved by improving the transmitting and receiving coils' designs (Zeng et al., 2008).

1.2.2 Reliability

Reliability is one of the major design concerns, considering that device failure is the most frequent long-term complication (Parisier et al., 2001 and Cote et al., 2007). All the CI components must endure prolonged use and frequent minute movements of the different internal parts for a long time without breakage especially at vulnerable points such as the juncture between the electrode array and the receiver/stimulator package. This requires robust electronic components and some flexibility of the moving parts to avoid wire breakage. To overcome wire breakage problems, wires are made longer than required to accommodate for movement and growth in children. Surgical techniques have also been developed to help protect the receiver; a bony well is usually drilled in the mastoid to house the receiver rather than leaving it protruding and exposed to impact trauma to the head. This surgical technique made it necessary for companies to make the stimulator smaller and thinner to ensure use in young children with thinner skulls, this demand affected the implant design for all systems. A decrease in device failure and increase in reliability is expected with improved technology; however design problems may still occur such as leakage of excessive moisture that could cause device failure (Cote et al., 2007).

Failures are classified into: (1) hard failures involving malfunction of the internal components, (2) impact failure due to direct hits, which is more common in children than adults and (3) soft failures where there is a decrement in auditory performance, but the malfunction cannot be proven with available in-vivo tests (Balkany et al., 2005 and Cote et al., 2007). Figure (1.5) below shows the classification and definition of CI failures as categorized in the European consensus statement on CI failure and explantation (2005). Impact failures were reported to occur more frequently with ceramic implant housing as compared to silicone and titanium housing (Gosepath et al., 2009). Device failures require explantation and re-implantation of a new device which can have a negative impact because of the disruption caused by the device failure and waiting time to receive a new functioning implant. Especially in light of the finding that device failure was the most common reason for CI non-use among implanted adults

(Bhatt et al., 2005). Researchers also reported cases where full explantation of the electrode array was not possible due to pathology such as fibrosis, in these cases the contralateral ear had to be implanted (Brown et al., 2009 and Kang et al., 2009).

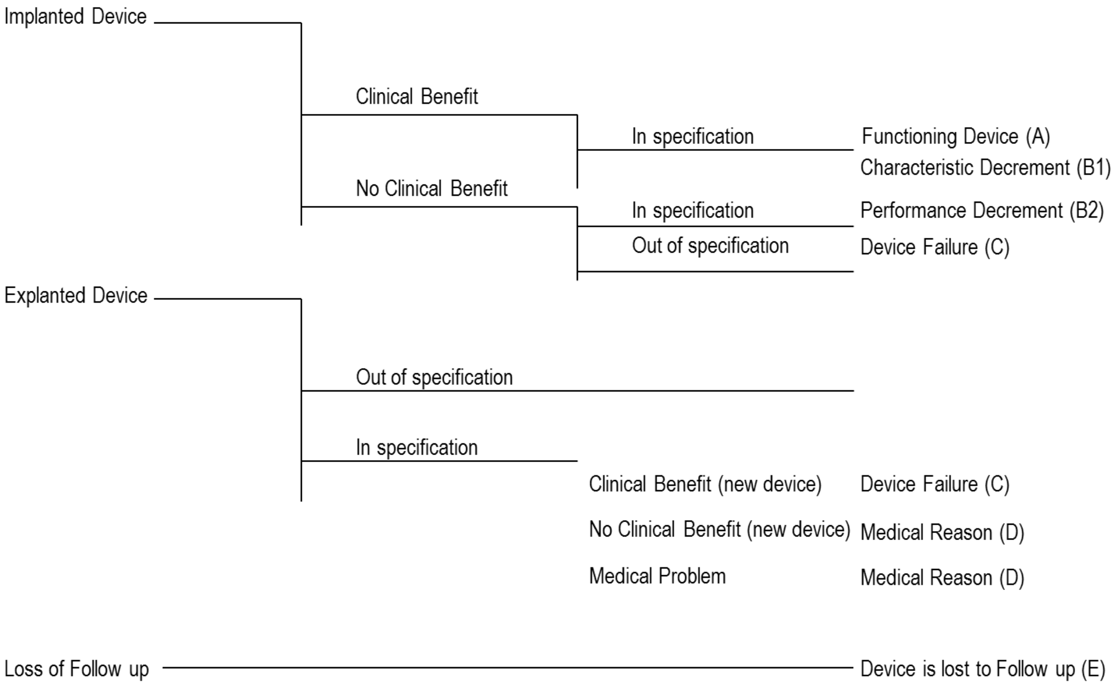


Figure 1.5 European consensus statement on CI failures and explantations (2005).

“The failure categories are based on manufacturer specification and clinical benefit showing the different possible assignments are explained in the lower part of the figure. A, normal functioning device; B1, characteristics decrement (A device with measured characteristics outside the manufacturers specification, but still of benefit to the patient): replacement of device not necessary as long as clinical benefit is preserved; B2, performance decrement (Unexplained but documented decrement in performance or a device that causes non-auditory sensations): explantation and reimplantation recommended; C, device failure (device with characteristics outside the manufacturers specification resulting in a loss of clinical benefit): explantation and reimplantation recommended. Report to competent authority and manufacturer is mandatory. Goes into cumulative survival rate calculation; D, medical reason: explantation due to medical problems (i.e., infections, electrode misplacement, etc.) shall be reported into a future European data bank; E, population of implantees who no longer show up for after care shall be reported into a future European data bank.”

1.2.3 Safety

When considering safety with CIs we have to consider:

1. Biocompatibility: This includes three major issues: (a) the design of the electrode array must allow insertion without causing excess damage to

the cochlea (Richter et al., 2001 and Rebscher et al., 2008). This therefore has an interactive relationship with the surgical procedures used which will be discussed later in detail (Section 2.2), (b) the implant components must be bio-compatible without causing any adverse tissue reaction (toxic, immunological or injurious) (Harnack et al., 2004 and Zeng et al., 2008) and (c) the material used must have certain mechanical, electrical properties and must ensure hermetic isolation so that the electrical parts are sealed and protected from bodily fluids and salt (Zeng et al., 2008).

2. Sterilization: This would include the sterilization process, the material used, which has to be designed and manufactured in a manner that ensures tolerance for the sterilization process, and the implant design, which has to avoid any pockets or spaces that could potentially collect bacteria rendering the sterilization useless.
3. Mechanical safety: to avoid tissue injury; the design must be easy to place and stabilize and the surface of the device must be soft, with round corners in order to reduce internal tissue trauma and avoid long term possible problems such as necrosis. This requires cooperation between designers and surgeons (Zeng et al., 2008).
4. Energy exposure: Energy must be constrained to safe levels.
   The electrical charge is a product of time and current, the limit of safe electrical charge density (per cm^2) is less than 15 to 65 μC/cm2/phase (Leake et al., 1990 and Zeng et al., 2008). Safe heat limits have been specified as no more than 39° centigrade for the internal implanted parts (ISO 14708-1 part 17, 2000) and up to 41° centigrade for the external parts contacting the skin (Zeng et al., 2008).

1.3 The fitting (programming) of the CI device

The CI speech processor analyses the signal and converts the acoustic input into an electrical signal, which is customized for the individual CI recipient to ensure optimised delivery of the information to the CI recipient. This is accomplished by programming the CI speech processor through a designated fitting station for each manufacturer (e.g. Skinner et al., 1995; Holden et al., 2002; James et al., 2003; Dawson et al., 1997; Skinner et al., 1999 and Zeng et al., 2008). In this section basic procedures involved in fitting will be briefly described, for further details of a typical programming protocol see appendix A.

1.3.1 Impedance telemetry

Impedance telemetry has to be measured before the fitting (programming of the speech processor) takes place. When measuring telemetry, resistance of each of the electrodes in the CI array is measured; this electrical resistance can affect the ability of each of the electrodes to deliver electrical stimulation to the surrounding tissue. Changes in surrounding tissue can affect telemetry (e.g. Hughes et al., 2001). Telemetry provides us with information about the function of the CI electrodes, including which electrodes have a short circuit (impedances too low), or an open circuit (impedances too high). These problematic electrodes are usually switched off (deactivated) during routine clinical fittings (e.g. Zeng et al., 2008).

1.3.2 Creating a CI program

When creating a CI program, certain parameters have to be set: (a) a speech processing strategy has to be chosen (strategies will be described at length in Section 1.4), (b) rate of stimulation per second can be chosen for some strategies for some devices, but typically the default is used. The per channel stimulation rate “refers to the number of biphasic pulses that are delivered to an individual electrode contact within one second and is specified in pulses per second (pps)” (Wolfe and Schafer, 2010, pp30), (c) the frequency table has to be selected which determines the frequency range covered by the implant and the frequency to electrode mapping of the stimulation (d) active electrodes, as mentioned earlier electrodes with an open or short circuit are deactivated and (e) the value of maxima or “n” in “n of m” strategies (not for all manufacturers) (see Section 1.4.4) the maxima value refers to the number of electrodes being stimulated per stimulation cycle. After choosing these parameters and a CI program has been created, individualized stimulation levels have to be determined.

1.3.3 Setting stimulation levels

Stimulation level is one of the most important parameters in the programming of CIs. There are two stimulation levels that should be optimized for each CI electrode (channel); the lower threshold (T or THR) levels and the upper stimulation levels, also known as comfort or most comfortable (C or M or MCL) levels (e.g. Dawson et al., 1997; Skinner et al., 1999 and Zeng et al., 2008). Each manufacturer provides specific guidelines for setting these levels (see appendix A for manufacturer specific guidelines), most of which are related to the speech processing strategy employed by that specific manufacturer (Wolfe and Schafer, 2010). Changing the stimulation level involves either changing the current level or the pulse width of the electrical pulses used in stimulation.

1.4. Signal/speech processing strategies

The speech processing strategies and mapping options affect how the speech processor transforms the sound input into electrical signals. CIs and speech processors' have design limitations that restrict the extent to which "normal hearing" can be achieved. Different CI companies aim to overcome the limitations with different approaches utilising different processing strategies in an attempt to optimise electrical signal delivery to provide the greatest information and thus the highest level of performance for the CI user.

All speech processing strategies have one thing in common: they represent the spectral properties of sound by place of stimulation in the cochlea i.e. each electrode represents the information in different frequency bands. They provide the rules by which sounds are converted into electrical signals that stimulate the auditory nerve. However, they are significantly diverse; they differ in terms of number of stimulated electrodes in total and simultaneously, electrode to frequency assignment, stimulus waveform, type of compression used, what particular aspects of the sound are represented and temporal representation across the channels.

Anatomical considerations and implant design issues limit performance with CIs and have a restricting effect on the plausibility of certain processing strategies; hence the newly developed strategies are not compatible with some of the older models in the different makes. This section provides a brief description of the major and available speech processing strategies, see Figure (1.6) for classification of processing strategies.

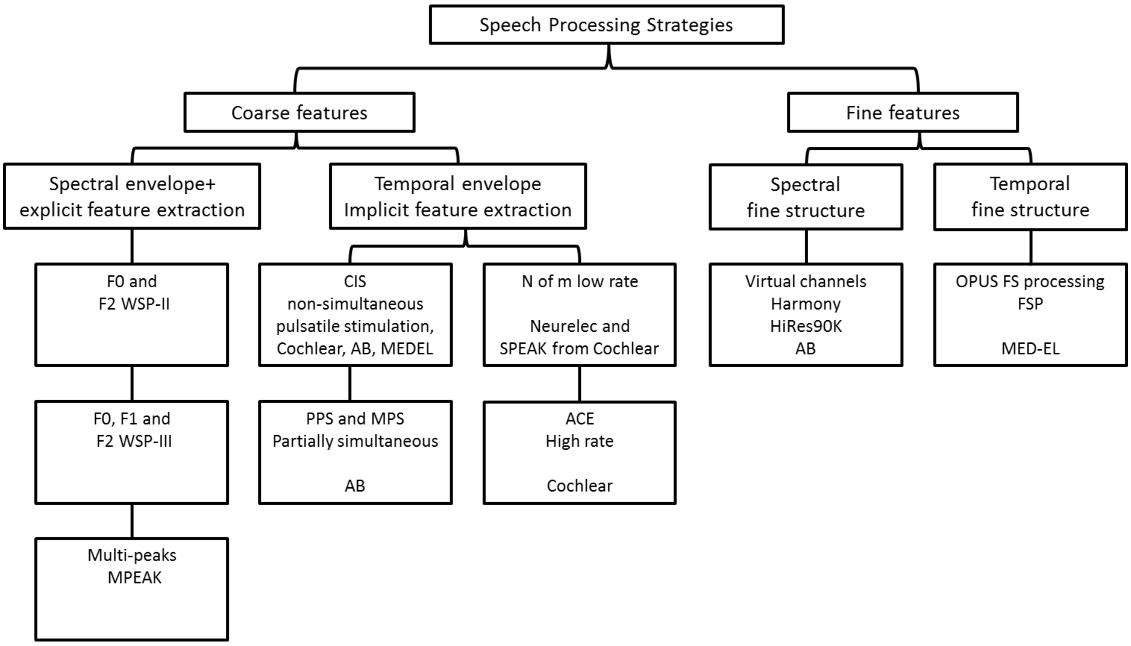


Figure 1.6 A classification scheme for the speech processing strategies in CIs; adapted from Zeng et al. (2008).

1.4.1. Explicit feature extraction strategies

This type of strategy was used in the wearable speech processor (WSPII) (Clark et al., 1984 and Zeng, 2004). In an F0/F2 strategy the fundamental frequency (F0) and its second formant (F2) are extracted based on the assumption that these formant frequencies/ spectral peaks represent the resonance characteristics of the vocal tract during speech production. (F0) which reflects voice pitch is used to determine the stimulation rate while (F2) determines the stimulated electrode with the underlying assumption of a tonotopic relationship between the location of the electrode and the stimulated frequency. The first formant frequency (F1) was a later addition to Cochlear's (WSPIII). Later on, Cochlear's MPEAK strategy included up to 6 spectral peaks (with the highest intensity in the original signal); in addition to the (F0) (F1) and (F2) the amplitude of three high frequency bands (2kHz-2.8 kHz, 2.8kHz-4kHz and 4kHz-6kHz) were extracted (Skinner et al., 1991; Skinner et al., 1996 and Loizou, 1998). See appendix B for a table summarising the strategies involving explicit feature extraction.

1.4.2 Simultaneous analog speech processing strategies

This would include the Compressed Analog (CA) monopolar strategy (see Figure 1.8) used by the Ineraid device (an early CI that is not available today, Zeng et al. 2008) and Clarion's (Advanced Bionics') Simultaneous Analog Stimulation (SAS) bipolar strategy (Battmer et al., 1999 and Zeng, 2004). In these strategies the sound is divided into frequency bands by using band-pass filters, following which the narrow band signal is compressed *via* gain control to the narrow dynamic range of electrical hearing (approximately 20 dB) and is then transmitted as current to intra-cochlear electrodes (Zeng, 2004). The most apical electrode represents the lowest frequency band while the most basal electrode represents the highest frequency band, and the distribution of stimulation depends on the frequencies present in the sound/speech segment. In general, these simultaneous analog strategies provide more accurate natural representation of temporal cues compared to non-simultaneous pulsatile strategies, whereas the non-simultaneous pulsatile strategies provide better representation of the spectral cues (Battmer et al., 1999).

1.4.3 Pulsatile speech processing strategies

Many of the recent speech processing strategies employed by the three CI manufacturers Advanced Bionics, Cochlear and Med-El are pulsatile processing strategies. These would include the basic Continuous interleaved sampling (CIS) strategy, the high resolution (HiRes) strategies from Advanced Bionics, including those that utilise current steering technology, the high definition CIS (HDCIS) and the fine structure processing (FSP) strategies from Med-El.

1.4.3.1 Continuous interleaved sampling (CIS)

Continuous interleaved sampling (CIS) is a non-simultaneous pulsatile strategy that stimulates all active electrodes for each cycle (Wilson, 1993). It is available on the majority of CI systems. It aims to extract and deliver temporal envelope cues (Wilson et al., 1991and Zeng, 2004). The sound is first pre-emphasized “to attenuate strong components in speech below 1.2 kHz” (Wilson and Blake, 2008) then is passed through a number of band-pass filters (BPF) (Wilson et al., 1991). The temporal envelope for each of those waveforms is then extracted by either half-wave or full-wave-rectification, followed by low-pass filtering (LPF); or, more recently, by the Hilbert transform (Zeng, 2004 and Wilson and Dorman, 2008). These extracted envelopes undergo linear logarithmic compression to map the signal into the narrow electric dynamic range (Loizou, 1998 and Zeng et al., 2002).

The compressed envelope outputs are then used to modulate biphasic pulses with amplitudes proportional to those of the envelopes and are delivered at a rate that can vary from hundreds to thousands per second (Loizou, 1998 and Zeng et al., 2008) see Figure (1.7). A key point in CIS is that each pulsatile carrier interleaves with the other bands’ pulsatile carriers; only one electrode is stimulated at any given time; thus, avoiding electrode interaction that could cause smearing of the band specific envelope cues (Zeng, 2004 and Zeng et al., 2008) and avoiding the problematic electrical-field interference caused by simultaneous stimulation which was a concern with the early analog Ineraid implant. Later, in Clarion’s Paired Pulsatile Sampler (PPS) and Multiple Pulsatile Stimulation strategies, two or more distant electrodes could be stimulated simultaneously by pulsatile carriers (Loizou et al., 2003). To see the difference between pulses used in CIS and PPS, see Figures (1.8 and 1.9).

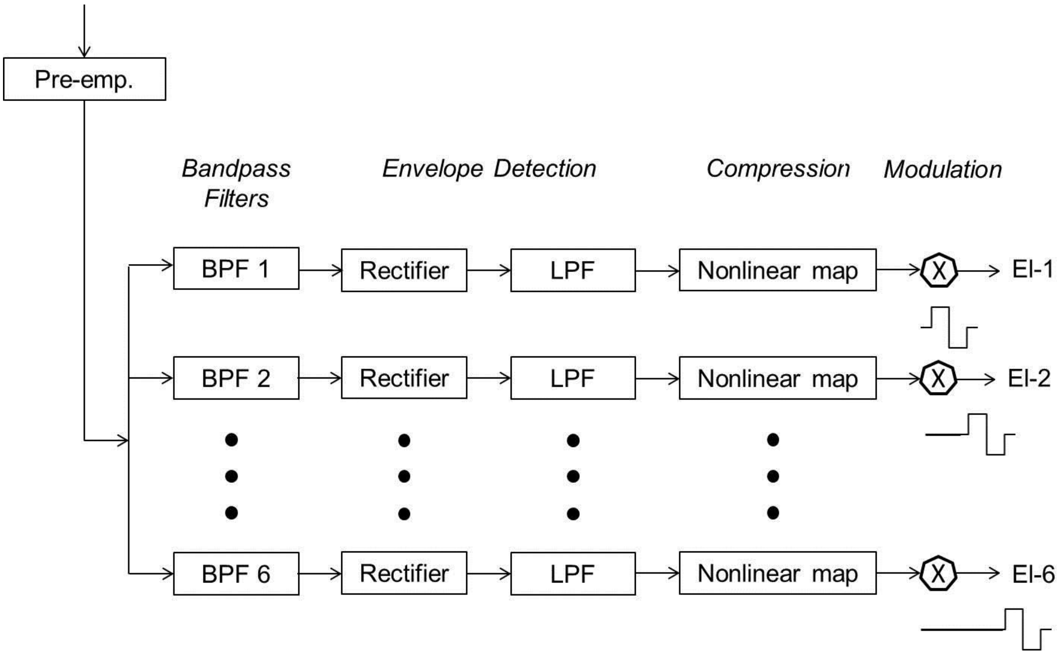


Figure 1.7 Block diagram of CIS strategy adapted from Loizou (1998).

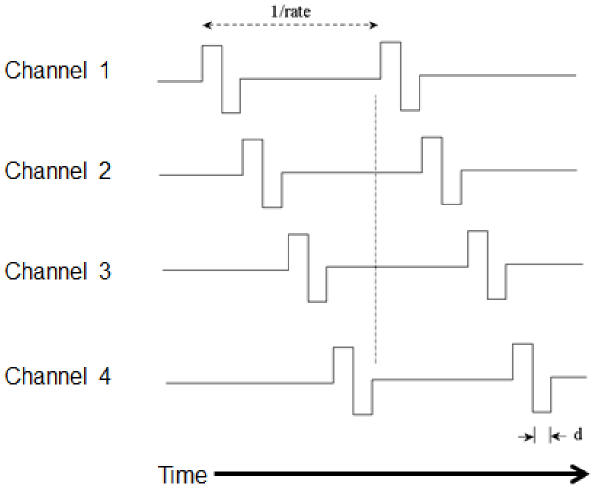


Figure 1.8 Block diagram of the interleaved pulses used in a CIS strategy adapted from Loizou (1998), the 1/rate indicates the period between pulses on each channel while (d) stands for pulse duration/phase.

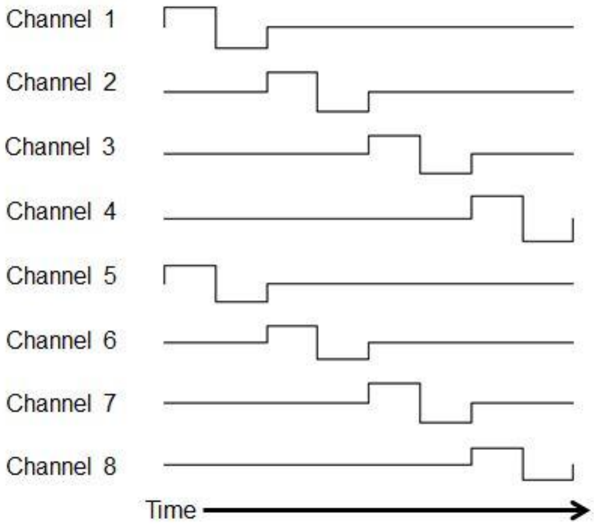


Figure 1.9 Block diagram of the pulses used in the PPS strategy adapted from Mishra (2000).

1.4.3.2 The High Resolution Strategy (HiRes)

This strategy is available with AB devices known as the Harmony implants (CII and HiRes90k) and the Auria and Harmony sound processors. In this strategy in the pre-processing stage, the audio input is sampled at 17400 Hz and emphasized by the microphone (Nogueira et al., 2009). A dual loop Automatic Gain Control (AGC) is then used to perform a digital AGC (Firszt, 2003). An infinite impulse response (IIR) sixth order Butterworth filters is used to divide the signal into frequency bands that range from 250 Hz to 8KHz (Firszt, 2003), the centre frequencies for these bands are logarithmically spaced and each frequency band is associated with a single electrode. Each of the filter outputs are then half-wave rectified by setting the negative amplitudes to 0, then they're averaged for a Ts duration of a stimulation cycle (Nogueira et al., 2009). The acoustic values obtained are then transferred into amplitudes of current that are used to modulate biphasic pulses (Firszt, 2003, Buechner et al., 2006).

Since the system has 16 independent current sources, it allows for two or more electrodes to be simultaneously stimulated (Firszt, 2003). In HiRes S (High Resolution sequential) strategy all 16 electrodes are sequentially stimulated in each stimulation cycle; thus avoiding channel interaction. The per channel stimulation rate is uniform for all channels with a maximum value of around 2899 pulse per second (pps) (Firszt, 2003; Dunn et al., 2006 and Nogueira et al.,2009); see Figure (1.10). In HiRes P (High Resolution paired) two non-adjacent pairs of electrodes are simultaneously stimulated increasing the maximum per channel stimulation rate to 5,156 pps (Firszt, 2003 and Dunn et al., 2006).

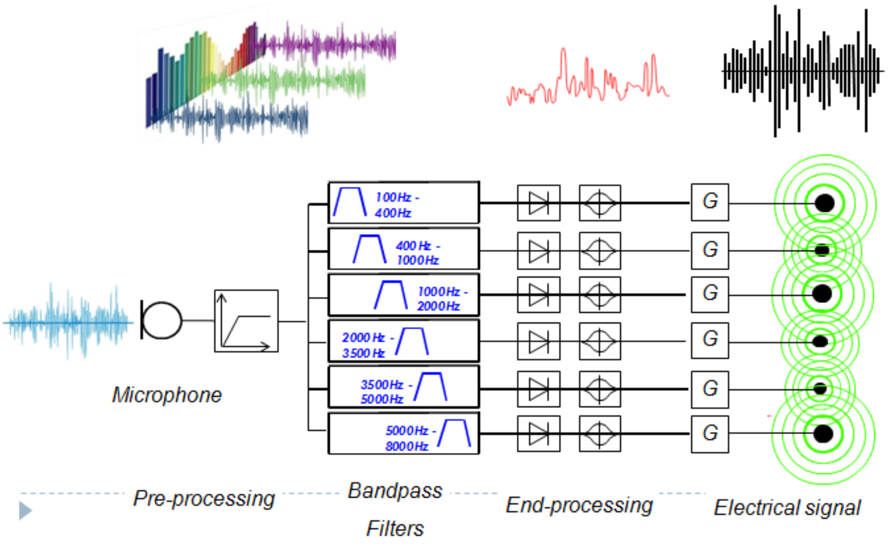


Figure 1.10 Block diagram of Hi-Res strategy courtesy of AB.

1.4.3.3 Signal processing strategies using current steering

The Fidelity HiRes120 strategy can be used with a Harmony speech processor and Harmony AB implants. In this strategy it is hypothesised that frequency resolution is increased by using current steering. Current steering is based on the observation that subjects were able to distinguish several distinct pitches between two electrodes when these electrodes were simultaneously stimulated (Donaldson et al., 2005). In current steering the proportion of current is varied for each of the adjacent electrode pairs to create the percept of different pitches. 15 electrode pairs are used in stimulation when all 16 electrodes are switched on, 8 distinct stimulation places (bands) are created between each electrode pair with a maximum of 120 possible stimulation sites. See Figure (1.11) below demonstrating current steering.

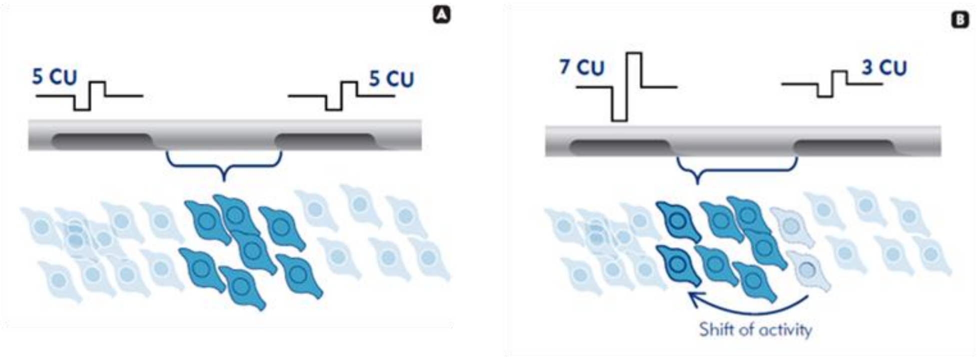


Figure 1.11 A diagram of active current steering. Whereby in the first example (A), half the current (CU clinical units) is “steered” to each of two neighbouring electrodes so that the locus of stimulation is approximately halfway between the two contacts. In the second example (B), as a greater proportion of current is steered toward one of the electrodes, the locus of stimulation is shifted closer to that electrode. Courtesy of Advanced Bionics (2006).

This strategy provides a higher spectral resolution than that by the HiRes strategy (Firszt et al., 2009). See Figure (1.12) demonstrating the 120 stimulation sites provided by the Fidelity HiRes 120 strategy.

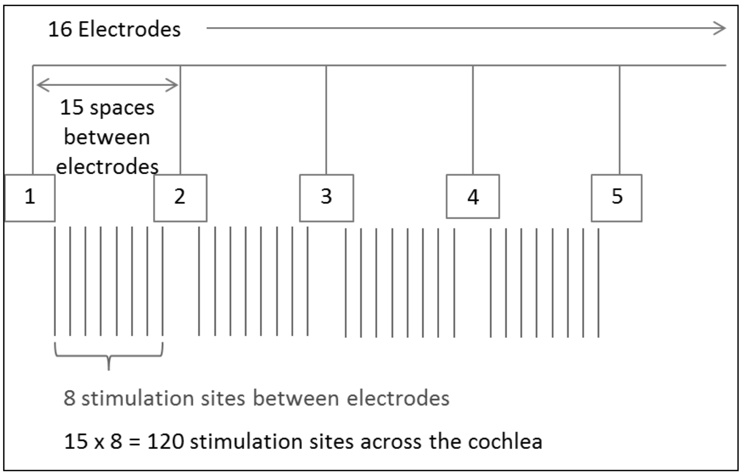


Figure 1.12 The 120 stimulation sites provided by the Hi-Res 120 strategy.

1.4.3.4 Med-El’s CIS+ and High Definition CIS (HDCIS)

These strategies were designed to provide better fine spectral information than the old CIS strategy. This was done by employing 12 overlapping filters with bell shaped stimulation response which are allocated algorithmically to cover the frequency range (250-8500 Hz). It is assumed that this design allows the creation of virtual channels, hence providing a finer spectral resolution (Arnoldner et al., 2007 and Magnusson, 2011). A Hilbert transform is used to extract the envelope information within each filter band. The per-channel stimulation rate is uniform across all channels and can go up to 1500 pps in the CIS+ strategy and up to 3000 pps in the HDCIS strategy (Magnusson, 2011).

1.4.3.5 Med-El's Fine Structure Processing FSP

FSP is very similar to the HDCIS strategy with the exception of the lower 1-3 channels which use "channel specific sampling sequence" (CSSS). Unlike envelope-based processing strategies, these CSSS channels were designed so that FSP provides envelope information as well as fine structure. The fixed sampling rate is substituted by CSSS, where stimulation pulses start only at each positive zero crossing within each frequency band's filter output (Arnoldner et al., 2007 and Magnusson, 2011). The stimulation pulses for these CSSS channels are also interleaved with the other electrodes to avoid unwanted interaction. The FSP strategy usually covers the frequency range 100-8500Hz (Magnusson, 2011).

1.4.4 N of m strategies

The spectral peak (SPEAK) and advanced combination encoder (ACE) are n of m strategies, where (n) is the number of electrodes that is stimulated for each cycle and (m) is the number of filters and usually n<m. The main differences between a CIS strategy and an n of m strategy are: (1) the n of m strategy has a greater number of pass band filters than the CIS and (2) n of m is based on explicit temporal frames typically between 2.5-4 ms whilst the CIS strategy does not have an explicit frame (Zeng et al., 2008). In each frame an 'n' number of bands with the largest amplitude are selected, then envelopes of those selected bands are logarithmically compressed and used to determine the pulse's current level for each band. Each of these biphasic pulses is interleaved from other bands' pulses while the frame rate determines the per-channel stimulation rate. If n = m then the strategies such as SPEAK and ACE are not so different from a CIS strategy (Zeng et al., 2008). Among the CI manufacturers, Cochlear employs SPEAK and ACE strategies and Neurelec also employs an n of m

processing strategy. See Figure (1.13) demonstrating how the n of m strategy works.

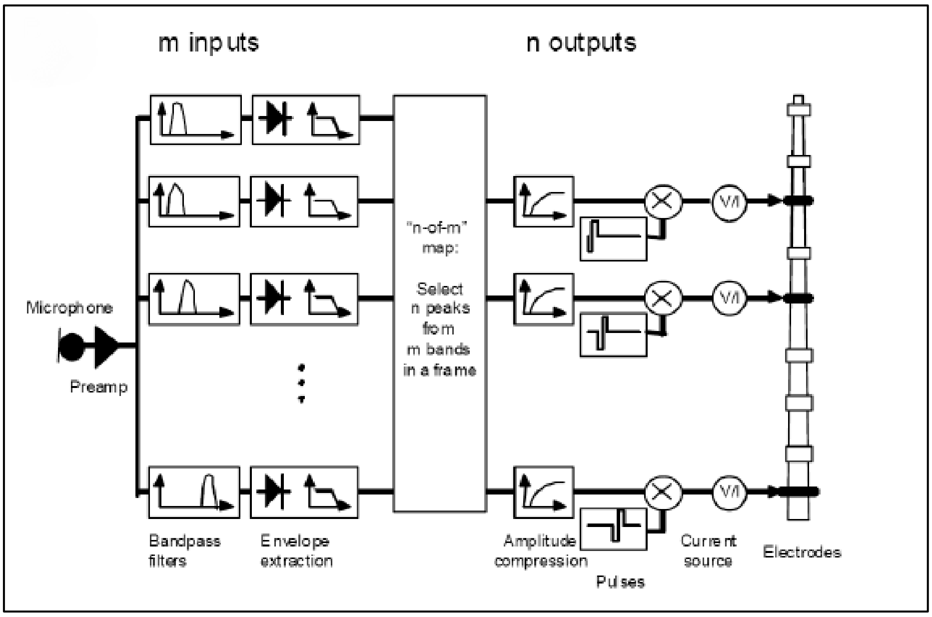


Figure 1.13 Block diagram of n of m strategy; courtesy of Zeng et al. (2008).

1.4.4.1 Spectral peak (SPEAK) strategy

This strategy was developed and used by Cochlear, it uses 20 filters covering the centre frequencies from 200 to 10,000 Hz; each filter has a corresponding electrode on the array with the lowest frequency band assigned to the most apical electrode (Skinner et al., 1994 and Skinner et al., 1996). Depending on the acoustic input, the number of spectral maxima will differ so that only those electrodes representing filters that have speech components with the highest amplitudes are stimulated in each cycle. In the SPEAK strategy maxima can take the values between 6 and 9 (Skinner et al., 2002). The SPEAK strategy has a fixed per-channel stimulation rate of 250Hz and a fixed inter-pulse interval (IPI) of 45 µsec; the relatively high IPI was chosen to decrease thresholds and current requirement (Shepherd and Javel, 1999 and Skinner et al., 2002).

The SPEAK, in comparison to the CIS, strategy provides more spectral details but less temporal details due to the relatively low per-channel stimulation rate of 250 Hz (Zeng et al., 2008).

1.4.4.2 Advanced combination Encoder (ACE) strategy

ACE is a strategy also employed by Cochlear and is very similar to the SPEAK strategy but it has a higher range of peak selection (maxima can take the values between 1 and 20) and a higher rate of stimulation thus preserving more temporal details than SPEAK (Skinner et al., 2002). The per-channel stimulation rate can go up to 2400 Hz, however the total rate of stimulation is limited to 14,400 Hz. This is accomplished by automatically limiting the number of maxima with higher per-channel stimulation rate (the total rate of stimulation is equal to the per-channel stimulation rate times the number of maxima). In an ACE strategy the filter bank has 22 filters rather than 20 filters which could offer better frequency resolution than that provided by a SPEAK strategy (Skinner et al., 2002; Zeng et al., 2008). In ACE the IPI is fixed at 8 µsec which is lower than that for SPEAK, since thresholds are usually lower with higher per-channel stimulation rate (Skinner, Holden, Holden, and Demorest, 2000 and Skinner et al., 2002).

1.5 Summary

The CI device is probably one of the greatest innovations of the 20th century in the field of Otorhinolaryngology, providing hearing restoration to the severe-to-profoundly hearing impaired. It has two major components: the implantable internal part and the external speech processor. Both have gone through great developments in terms of design and function to ensure the safe delivery of a consistent clear signal. The speech processor controls receives the auditory sound, processes it and transforms it into electrical signals that stimulate the auditory nerve *via* the electrical contacts implanted in the cochlea. It is critical to carefully programme the speech processor to ensure that the delivery of the electrical signal is optimally mapped into each CI recipient’s electrical dynamic range. Optimisation of the acoustic to electrical mapping must have an impact on speech perception and performance for the CI user. CI The fitting of the device is not the only factor that has an impact on performance, other factors to be considered are outlined in Chapter 2.

Chapter 2

Factors affecting performance with CIs

Speech perception abilities of adult CI users vary widely from those with very little or no "open set" (not from a closed set and without cues including visual cues) speech understanding when listening without lip-reading to those that have open set speech understanding, even in the presence of competing noise. This disparity in performance can be attributed to several factors, some of which are related to individual characteristics (referred to as subject dependent factors from here on in) (e.g. Waltzman et al., 1995; Blamey et al., 1992; Friedland et al., 2010 and Blamey et al., 2013) and others that are device related or dependent upon surgical insertion (e.g. Finley and Skinner, 2008). The importance of identifying these factors is apparent at both the pre-implantation stage when considering candidacy of an individual and post-implantation for patient management and fitting (Summerfield and Marshall, 1995). During the pre-implantation evaluation candidacy may be affected by prediction of prognosis with CI or it may guide counselling of potential candidates to have realistic expectations and could assist the clinical team when choosing which ear to implant (Friedland et al., 2003). In the post-implantation management process, if factors affecting performance are identified it can help clinicians derive performance expectations and intervene with rehabilitation of fitting modifications when outcomes do not reach the expected level. (Zwolan et al., 1997).

2.1 Subject dependent factors

Some individual characteristics such as age, cognitive abilities, duration of deafness and aetiology of deafness can have an impact on performance.

2.1.1 Age

There have been several studies looking at the effect of age at implantation (AAI) on post CI performance among adults; they mainly compared the performance of younger adults versus that of older adults. However, the “elderly” age-group was defined differently across the studies; for example it was above 55 years in Chan et al.’s study (2004), just above 60 years in Shin et al.’s study (2000), equal to or more than 65 years in Labadie et al’s study (2000) and Friedland et al.’s study (2010), greater than 65 years in Pasanisi’s study (2003) and above 70 years in Chatelin et al. (2004), Blamey et al. (2013) and Lenarz et al. (2012) studies. Despite the different criteria adopted to define the “older” group across the different research studies conducted in this area and the diversity in the performance measures used in the different studies, most studies have found that there was a significant improvement in speech perception for the majority of implantees in the older group after receiving their CI CI(Labadie et al., 2000; Shin et al., 2000; Pasanisi et al., 2003; Chatelin et al., 2004; Orabi et al., 2006; Chan et al., 2007, Friedland et al., 2010 and Lenarz et al., 2012).

Some researchers did not report a difference in post-implantation performance between the older and younger adults (Labadie et al., 2000; Shin et al., 2000; Pasanisi et al., 2003 and Chan et al., 2007). However closer inspection showed that some had a relatively small sample size; Shin et al. (2000) had a sample of 27; both Labadie et al. (2000) and Pasanisi et al. (2003) had 16 elderly individuals and Chan et al. (2007) had a sample of 14 elderly recipients. Another issue is the fact that the older and younger groups were not matched for duration of deafness and pre-implantation audiological or speech perception levels in those studies. Although the groups were matched for duration in deafness in Chan et al.’s study (2007), however the performance measure used by Chan et al. allowed for a ceiling effect because the highest score given for speech perception was defined as speech recognition >50%; i.e. the highest possible score of 7 out of 7 covered a speech recognition range of 51-100% which will mask any differences across that large range.

Contrary to these findings, there was a significant difference reported between the older and younger adult groups with a larger sample sizes such as Chatelin et al. (2004), Friedland et al. (2010) and Lenarz et al. (2012) who had a sample of 65, 78 and 130 elderly, respectively. In 2010 a case-control retrospective analysis of speech perception performance among 78 elderly CI users whose age of implantation was 65 years or older was conducted by Friedland et al. (2010). They investigated the effect of age of implantation on 1-year post-implantation speech performance. No correlation was found between pre-implantation audiological levels, pre-implantation speech perception measures and AAI nor between AAI and post-implantation Consonant-Nucleus-Consonant (CNC) and Hearing in Noise Test in quiet (HINT-Q) scores. However there was a negative effect of AAI on Hearing in Noise Test in noise (HINT-N) scores. They also conducted a performance-matched implant patient analysis, whereby they compared the performance of the elderly implantees with that of younger adult implant recipients with an AAI less than 65 years of age. The younger adults were matched with the older adults based on pre-implantation performance on the HINT-Q and on duration of deafness. They found that the elderly group performance on HINT-Q and CNC test was significantly poorer than that of the younger adult group. Pre-implantation speech reception and audiological measures were significantly correlated with post-implantation speech reception performance in both age groups. Lenarz et al. (2012) found a significant difference between the older and younger adults' performance in HSM (German Hochmair- Schulz-Moser) sentence test in noise but not HSM in quiet.

Poorer performance among the elderly could be due to the fact that they require a longer period of adaptation to reach the level attained by the younger group. Another explanation could be the physiological effect of aging on central auditory processing (Jerger et al., 1989), and on cognitive and associative skills which are important factors that may affect post-implantation performance. This may explain the extra difficulty they found in noise (Lenarz et al., 2012).

Other research found that AAI had predictive power of post-implantation speech perception, such as Waltzman et al. (1995) Gantz et al. (1993) and Blamey et al. (1996 and 2013).

Such findings could be of significance when considering implantation of progressive hearing loss cases such as presbycusis where earlier implantation could lead to better prognosis. These findings may provide useful predictive information for the provision of pre-implantation counselling by providing CI candidates with realistic expectations.

2.1.2 Cognitive abilities

For normal hearing individuals, listening in everyday environments usually involves effortless and automated processing. However this is not the case in the presence of a distorted signal due to hearing loss where listening becomes demanding and requires effort. Cognitive processing abilities (in particular verbal processing) will play a role in facilitating the efficient extraction of essential information from the signal.

One cognitive skill that may influence post CI performance is the ability to learn new information, such as making sense of the new electronic signal. This ability is strongly correlated with IQ (intelligence quotient) and could have an impact on performance (Knutson, 2006). However there are inconsistencies between the studies relating overall intelligence when measured by WAIS-R (Wechsler Adult Intelligence Scale-Revised) to post CI performance. For example Waltzman et al. (1995) found a significant correlation between the WAIS-R score and post-implantation speech perception, while Knutson et al. (1991) did not.

Despite those inconsistencies observed in studies evaluating overall intelligence, some specific cognitive measures have been shown to be consistently predictive of post-cochlear implantation speech perception e.g. the Visual Monitoring Task (VMT) (Knutson et al., 1991; Gantz et al., 1993), Sequence Learning Task (SLT; Simon and Kotovsky, 1963), the Pat Associate Test [(PAT) a non-verbal memory test; Knutson et al., 1991]. These findings support the idea that specific cognitive abilities underpin the ability to extract and process information from a degraded or distorted signal, are related to post-implantation performance. Cognitive measures such as VMT, SLT and Raven Progressive Matrices (RPM; Raven et al., 1977) have been found to be predictive of post-implantation timbre recognition (Gfeller et al., 2002a and Gfeller et al., 2008), appraisal of musical instruments (Gfeller et al., 2002b), appraisal of complex songs (Gfeller et al., 2003), and appraisal of music and performance on a pitch ranking task (Gfeller et al., 2008). Among the cognitive measures, VMT had the most predictive power of post-implantation performance on music perception tasks (recognition and appraisal); this could be because VMT is more demanding than the other measures. However, VMT additionally requires associative memory, working memory and correct processing of quickly changing signals. Speed of processing could be necessary to avoid “bottle neck effects” while receiving and interpreting possibly distorted signals.

Explicit investigation of verbal cognitive abilities lend yet further support to the importance of working memory and fast processing capabilities in the performance with CIs. Internal speech functioning (use of an internal speech code), working memory and speed of verbal information processing were found to be critical predictors of post-implant performance (Lyxell et al., 1996).
Working memory is important since the implanted individual might miss some pieces of information and would require the ability to temporarily store information while filling in the missing information (Lyxell et al., 1996 and Lyxell et al., 2003). Working memory has also been found to be associated with speech reading and audio-visual understanding of speech (Lyxell, 1994 and Rönnberg, 1993).

Internal speech functioning requires the ability to match between the audible signal with an internal representation of sound/speech which is important in interpreting the sounds and speech delivered *via* the CI (Lyxell et al., 1996). Duration of deafness was found to be negatively associated with internal speech (Lyxell et al., 1994).

In summary, all cognitive measures that affected performance require the ability to quickly extract information from sequentially presented stimuli and match it to an existing internal representation. This ability is required for good post-implantation perception of both speech and music.

2.1.3 Duration of deafness

Duration of deafness is considered to be the strongest pre-implant predictor of post-implant performance, with those having the longer the durations of deafness achieving lower levels of post-implantation outcome. Duration of deafness has been shown to have a significant negative correlation with or is a significant predictor of post-implantation performance for a variety of speech perception measures: (a) the Central Institute of Deafness (CID) everyday sentence test score (Blamey et al., 1992); (b) Consonant Nucleus Consonant (CNC) word scores (Rubenstein et al., 1999; Friedland et al., 2003 Gomaa et al., 2003; Yukawa et al., 2004 Leung et al., 2005 and Roditi et al., 2009); (c) CNC phoneme scores and City University of New York (CUNY) sentences in noise score (Yukawa et al., 2004); (d) achieving an open set speech understanding (Battmer et al., 1995); (e) a composite index on 5 categories: 1- prosodic features, 2- lip reading enhancement, 3- phonetic level, 4- spondee tests and 5- open-set speech recognition (Waltzman et al., 1995); (f) lip reading, spondee tests and open set speech recognition (Waltzman et al., 1995); (g) the Iowa Sentence Test Without Context-Sound only, the Iowa Videodisc Vowel Test, the Iowa Videodisc Medial Consonant Test, the Spondee 4-Choice In Noise Test and the Northwestern University Auditory Test No. 6 (NU-6) Word Understanding- Sound only (Gantz et al., 1993); (h) composite outcome measure (COMPERF) which was obtained by averaging scores on the Bamford-Kowal-Bench (BKB) in a sound only condition, Vowel Consonant Vowel (VCV) in sound only condition and common environmental sounds (ENV)

(Summerfield and Marshall, 1995); (i) BKB sentence score (Green et al., 2007) and (j) VCV and phrase speech intelligibility tests (Hiraumi et al., 2007).

These findings could be explained by the effect of the duration of deafness on the residual auditory nerve viability and the integrity of the auditory cortex and memory for sound. Other supporting evidence was provided by Nadol et al. in 1989; they found a correlation between spiral ganglion cell count and the duration of deafness.

Spiral ganglion cell survival may affect the spectral resolution of the electrical signal perceived by the CI recipient. In addition, spiral ganglion cell survival has been hypothesised to be important for retaining the integrity of the central auditory pathway (Rubenstein et al., 1999). Gomaa et al. (2003) found a correlation between pre-implantation CID sentence perception and post-implantation CNC scores, these findings lend support to the hypothesis that residual speech perception “act as a trophic factor” that protects the viability of the ganglion cells and subsequently the auditory pathway.

However these findings should be treated cautiously, especially if we consider studies that have demonstrated that the effect of duration of deafness on post-implantation speech perception is not ear specific but rather reflects the overall auditory function; residual hearing in the non-implanted ear has a positive effect on post-implantation speech perception (Friedland et al., 2003; Francis et al., 2004). These findings may imply that the effect of duration of deafness on performance is due to the importance of the central auditory pathway integrity and memory for sound rather than spiral ganglion survival.

The above findings can provide guidance during the evaluation process for candidacy for cochlear implantation, help predict prognosis and determine which ear to implant.

2.1.4 Aetiology of deafness

A limited number of studies looking at factors affecting performance with CIs have evaluated the aetiology of deafness as a possible factor. They either found no significant relationship between the cause of deafness and performance (Blamey et al., 1992; Green et al., 2007 and Nikolopoulos et al., 2012) or reported a relatively weak effect (Battmer et al., 1995 and Blamey et al., 1996). However, there were numerous studies that have evaluated post-implantation performance in sub-groups with specific aetiologies such as meningitis (Philippon et al., 2009 and Durisin et al., 2010), otosclerosis (Rotteveel et al., 2010), Cogan's syndrome (Bovo et al., 2011; Kontorinis et al., 2010; Pasanisi et al., 2003; Wang et al., 2010), Ménière's disease (Lustig et al., 2003). They found that aetiology does not affect performance per se; however when pathological changes secondary to the aetiology of the hearing loss such as cochlear ossification occurred, those changes had a negative impact on post-implantation performance. Fibrous or bone obliterations of the cochlea in Cogan's syndrome, cochlear ossification in meningitis, osteospongiosis and sclerosis in otosclerosis may lead to difficulties in the surgical insertion of the array resulting in partial insertions which reduces the number of active electrodes; these in turn may affect performance (Cohen and Waltzman, 1993; Hartrampf et al., 1995; Rotteveel et al., 2005 and Rotteveel et al., 2010). These pathological changes may also alter the CI current distribution (Rotteveel et al., 2010). Nadol and Hsu (1991) found a strong inverse relationship between the degree of calcification and spiral ganglion cell count in 6 temporal bones of people who had suffered from severe sensorineural hearing loss secondary to meningogenic labyrinthitis. Aetiology of deafness can shed some light on post-implantation prognosis and can affect programming of CIs mainly due to the underlying pathology secondary to aetiology, for example the deactivation of electrodes in cases of facial nerve stimulation in otosclerosis (Rotteveel et al., 2010).

2.2 Surgical placement of the electrode array

Recent evidence suggests that optimum placement of the electrode array in the cochlea may positively affect the outcome with a CIs (Finley and Skinner, 2008). When addressing placement of the electrode array, two related issues are considered: surgical aspects and electrode array design. Surgical techniques and considerations have developed over recent years however placement of the array in the cochlea is still influenced by the array design (e.g. Rebscher et al., 2008).

In the following sections these surgical (Sections 2.2.1 – 2.2.3) and design issues (Section 2.2.4) are explored further.

2.2.1 Scala tympani versus scala vestibuli surgical placement

The standard surgical approach in cochlear implantation is to insert the electrode array into the scala tympani. However there are situations where the surgeon intentionally places the electrode array in the scala vestibuli (SV), typically where the scala tympani (ST) is not patent. This includes obstruction due to fibrosis or ossification after temporal bone fracture, meningitis or severe otosclerosis. Typically the outcomes in these cases are comparable to those obtained when the electrode is placed in the scala tympani (Barrettini et al., 2002; Kiefer et al., 2000 and Lin, 2009). However, the same is not true when the intended position of the array is the ST but cross-over of the array to the SV occurs during insertion. This typically leads to poorer speech perception scores (Skinner et al., 2007 and Finley and Skinner, 2008). Explanations include mechanical damage causing spiral ganglion cell loss, disruption of the basilar membrane (BM) or cross-turn stimulation. Finley and Skinner (2008) found a relationship between decreased speech perception (CNC word recognition scores) and deeper insertion of the electrode array. They also found deeper insertions to be associated with confused pitch of the apical electrodes in an electrode discrimination task. Gantz and Turner (2003) and Turner et al. (2004) emphasize the importance of surgical procedure, especially the positioning of the hybrid electrode array within the scala tympani so as not to interfere with the normal mechanical function of the basilar membrane and the travelling wave.

They took care in not damaging the round window membrane and avoiding loss of perilymph to preserve residual natural hearing.

2.2.2 Depth of insertion

There have been numerous studies that have evaluated the effect of insertion depth of CI arrays on speech perception. These include simulation studies on normally hearing individuals (Fu and Shannon, 1999a and Rosen et al., 1999) and in vivo studies of post-implanted individuals (Blamey et al., 1992; Yukawa et al., 2004; Skinner et al., 2007 and Finley and Skinner, 2008). Simulation studies mainly focused on the importance of matching the frequency of the electrical stimulation to the natural frequency of the stimulated auditory fibre. In order to estimate the insertion depth in implanted individuals, researchers have initially used an estimate based on the surgeon's report of the number of electrode bands introduced in the cochlea; subsequent researchers used post-operative radiographic images to estimate insertion depth. Three metrics have been used to define insertion depth radiologically: (1) angular depth of insertion, (2) the length of the intra-cochlear electrode array and (3) the number of active electrodes used by the speech processor. When estimates based on surgeons' reports were used, insertion depth was reported to have no significant effect on speech perception (Blamey et al., 1992 and Hodges et al., 1999). However, surgeons' estimates may not be as accurate as radiological measures. In 2004 Yukawa et al. investigated the effects of insertion depth on speech perception with the possibility that one of the radiologically based estimators could be more particularly relevant to speech perception. Thus they evaluated the effects of insertion depth based on angle, length and number of active electrodes estimates on the post-operative CNC words scores (for 48 subjects), CNC phonemes (for 48 subjects) and CUNY sentences in noise (for 26 out of 48 subjects). Duration of deafness, hearing aid usage, preoperative CID sentences scores and pure tone average (PTA) together with insertion depth were used as independent variables in a multiple regression analysis. Among the three insertion depth estimates, the angular depth of insertion was reported as the best predictor of post-implantation speech perception score, especially when

CUNY sentences in noise were used as the speech perception measure. They reported better performance with deeper insertion with the Cochlear device (Nucleus 22 and Nucleus 24). Some advocate the deeper insertion with the assumption that it ensures the stimulation of a wider spectral range of frequencies down to lower frequencies at the apical end of the cochlea, thus improving speech discrimination in noise (Hochmair et al. 2003). There is some evidence to suggest that better frequency matching between the normal cochlear tonotopic organization and the electrical stimulation of the CI (Baskent and Shannon, 2003 and 2005) is more critical for optimising performance. However, other researchers argue that deep insertion increases the possibility of mechanical trauma (Finely and Skinner, 2008) and that frequency specificity is lost due to cross-turn stimulation towards the apex (Gani et al., 2007 and Finley and Skinner, 2008). In addition there have been studies indicating that the CI user habituated to the frequency mapping of their CI program with respect to pitch perception (Reiss et al., 2008); thus matching the frequency of electrical stimulation to the normal tonotopic frequency organization may become unnecessary. More information about insertion trauma due to depth of insertion is provided below in Section (2.2.3.5) when it is considered with respect to “soft surgery”.

2.2.3 Soft CI surgery

In the last few years, the concept of “soft surgery” has become more common practice and is an area that has received a great deal of attention. One of the intended goals is to preserve residual hearing in the implanted ear. With this approach it allows for the extension of the candidacy criteria to hearing-impaired individuals who are not “totally deaf”. The soft surgery approach is essential for systems such as electroacoustic stimulation, which combines electrical stimulation of high frequencies in the basal region sometimes by using a short CI array whilst using acoustic auditory stimulation of low frequencies in the apical region. This necessitates the preservation of hearing at lower frequencies to be able to use the low frequency hearing. Soft surgery is not a new concept; it was first introduced by Lehnhardt in 1993, when the preservation of hearing was considered as a backup for cochlear implantation if CI failed. In order to achieve soft surgery, the technique must ensure the avoidance of any mechanical trauma and the reduction of any factors that may cause adverse cochlear reactions (Friedland et al., 2009). These factors may include the route of insertion, location of the cochleostomy, avoidance of blood or bone dust entry into the cochlea, application of corticosteroid to the cochleostomy, application of Healon ® (a lubricant) to the cochleostomy and electrode array, electrode array size and depth of insertion.

2.2.3.1 The route of insertion

There are two main access approaches to the scala tympani for electrode array insertion, *via* a cochleostomy in the cochlear basal turn or through the round window, which is considered by some to be less traumatic causing less damage to basal turn structures (Adunka, 2004). However, contrary evidence exists suggesting that for some electrode arrays there is a different pattern of results; perimodiolar electrodes were observed to cause significantly more damage in the basal structures with round window insertion (Adunka et al., 2006 and Souter et al., 2011). Round window insertion resulted in preserved low frequency residual hearing by Skarzynski et al. in 2007 with the use of partially inserted MED-EL COMBI 40+ straight electrode array. However, Berrettini et al. in 2008 produced contrary evidence with a reported significant decrease in residual hearing caused by round window insertion though not all the soft surgery precautions were taken with the round window approach in this study. Erixon et al. (2012) provided further evidence that hearing preservation can be accomplished with round window insertion and the use of the flexible MED-EL FLEX^{EAS} electrode array.

2.2.3.2 Location of the cochleostomy

The location of the cochleostomy (a drilled small opening into the cochlea) is thought to have an impact on the potential for damage to the spiral lamina and intracochlear structures. Based on the examination of 27 temporal bones, a cochleostomy in an anterior-inferior location in relation to the round window has been shown to be less likely to cause damage to the spiral lamina (Briggs et al., 2005). This was also true with the use of three-dimensional modelling of the hook region in the cochlea; Li et al. (2007) demonstrated that an anterior-inferior cochleostomy allows direct access to the scala tympani without contact with critical structures. Additional evidence for this approach comes from the literature on preservation of residual hearing where the anterior-inferior cochleostomy was compared to a strictly anterior cochleostomy (Garcia-Ibanez et al., 2008 and Berrettini et al., 2008) or a strictly inferior one (Garcia-Ibanez et al., 2008).

2.2.3.3 Avoidance of intra-cochlear reaction

There is some evidence that links blood entry in the scala tympani with residual hearing damage. Franco-Vidal et al. (2007) looked at sudden hearing loss that coincided with haemorrhage into the cochlea. Other reports included sudden hearing loss that coincided with high intracochlear signal on 3D-FLAIR MRI imaging that could be indicative of haemorrhage (Otake et al., 2006 and Yoshida et al., 2008). Although it is difficult to establish a direct link between bone dust entering the cochlea and residual hearing loss as well, some researchers have found that using bone pate to seal the cochleostomy can promote bone and scar formation (McElveen et al., 1995). Intra-cochlear reaction to blood in the scala tympani or bone dust in the cochlea may adversely affect residual hearing. Thus the avoidance of intra-cochlear exposure to these factors is attempted during soft surgery. Electro-cautery and topical vasoconstrictors such as epinephrine can be used to minimise bleeding from surrounding soft tissue (Bas et al., 2012) while irrigation to flush away bone dust prior to the cochleostomy is advisable to prevent bone-dust entering the cochlea (Kiefer et al., 2004; Friedland and Runge-Samuelson, 2009 and Bas et al., 2012).

2.2.3.4 Application of drugs at the cochleostomy and/or electrode array

Corticosteroids are commonly used in the management and prevention of hearing loss. In CI surgery, corticosteroids are hypothesized to inhibit adverse intracochlear inflammation and molecular reactions towards the cochleostomy and electrode array (Friedland et al., 2009). Animal experiments have demonstrated that corticosteroids can protect the cochlea from insertion damage and cochleostomy with intra-scalar administration of corticosteroids (triamcinolone Volon A®) in guinea pig ears (Kiefer et al., 2007 and Ye et al., 2007). Within four weeks, triamcinolone partially prevented hearing loss secondary to cochleostomy. When considering the use of corticosteroids for hearing preservation during CI surgery, two factors have to be considered. Firstly, only intra-scalar administration showed protective effects in animals but the apical portion of the cochlea received little corticosteroids (Plontke et al., 2008) minimising the corticosteroid effect on hearing preservation at lower frequencies. Secondly, the topical corticosteroid effect lasts less than 24 hours (Hargunani et al., 2006). Rather than applying corticosteroids at the cochleostomy in soft surgery, sodium hyaluronate gel (Healon ®) may be used. In Lehnhardt's original description of soft CI surgery (1993) Healon ® (hyaluronic acid) was recommended to be used in the cochleostomy and on the electrode array. Hyaluronic acid is normally found in the extracellular matrix: it is used as a lubricant when inserting electrode arrays (Friedland et al., 2009 and Laszig et al., 2002). As a translucent viscous substance it may prevent perilymph leakage and prevent cochlear contamination with blood and bone dust without affecting visualization (Friedland et al., 2009). It has been reported to reduce the formation of scar tissue in the middle and inner ear (Huang et al., 2007). Research indicates that Healon ® is most probably not an ototoxic substance that may help preserve hearing in humans (Skarzynski et al., 2002).

2.2.3.5 Depth of insertion

As discussed in Section 2.2.2, the risk of trauma has been reported to increase with deep insertion of the electrode array (Adunka et al., 2006; Finley and Skinner, 2008 and Wardrop et al., 2005a). However, this can be avoided if the electrode array is not inserted beyond the point of first resistance whilst accomplishing full insertion of the electrode array (Gstoettner et al., 1997 and Lenarz et al., 2006). In soft surgery, surgeons have either used partial insertion of electrode arrays (James et al., 2005 and Skarzynski et al., 2007), short electrode arrays (Gantz and Turner, 2003; Turner et al., 2004 and Lenarz et al., 2006) or full insertions of standard-length arrays (Skarzyski et al., 2002;

Baumgartner et al., 2007; Prentiss et al., 2010; Bruce et al., 2011 and Erixon et al., 2012). The objective in soft surgery is to reach a balance between accomplishing an insertion depth that provides the required cochlear coverage and avoiding trauma to the cochlea.

2.2.4 Electrode array design

Electrode array design has advanced dramatically, not only in terms of number of electrodes but also in terms of size, shape, specificity of stimulation, efficiency in the use of current and the material used. Another challenge that faces the manufacturers is optimizing the electrode array design in order to minimize trauma during insertion; this is of particular importance when using the CI in electro-acoustic stimulation (Rebscher et al., 2008). The properties of the array design also influences depth of insertion due to length, thickness and flexibility. In the following section the various electrode physical attributes that may influence array placement, and outcome, will be discussed.

2.2.4.1 Size of the electrode array

The influence of both the length and the diameter of the array will be considered in the following sections.

Electrode array length

The length of the array varies among the different CIs and even between the different models for each manufacturer. The longer arrays are usually designed for deeper insertion, such as MED-EL’s standard 31.5 mm arrays, while shorter arrays were sometimes designed for electro-acoustic stimulation (EAS) where there is residual hearing at the low frequencies and the CI provides electric stimulation to the high frequencies only. An example of such an EAS array is Cochlear’s Hybrid-S CI 10 mm array (Gantz and Turner, 2004). The Gantz and Turner research highlighted the importance of the position of the electrode array in the cochlea and the necessity to maintain a tonotopic relationship between the residual acoustic hearing and the electric stimulation provided by the CI. However, Reiss et al.'s research in 2006 showed that pitch perception through Hybrid CIs can change over time; this may undermine the importance of tonotopicity when it comes to CI electrode insertion. In contrast to Cochlear's Hybrid-S short array (Gantz and Turner, 2004) Cochlear later introduced the Hybrid-L24 16 mm array and hearing conservation was possible with the use of a round window approach (Lenarz et al., 2009). Other researchers have also stressed the importance of the electrode array design (e.g. flexibility) and the use of an atraumatic electrode insertion procedure (soft surgery) even with an insertion depth of up to 18-24 mm when it came to EAS (Gstoettner et al., 2004).

Electrode array diameter

The diameter of the electrode is a design issue as well; EAS systems have thinner electrode arrays e.g. the Iowa/Nucleus Hybrid Implant, Cochlear's Hybrid-L24 and MED-EL's PULSAR$_{CI}^{100}$ Flex^{EAS} (Gantz and Turner, 2003; Turner et al., 2004; Lenarz et al., 2009 and Helbig et al., 2011). Their design used a thinner electrode array in order to minimize injury to hair cells and the Organ of Corti.

CI manufacturers such as MED-EL and Neurelec promoted deeper insertion and reduced the diameter of the array to make it less traumatic.

Some electrode arrays have a larger diameter (e.g. AB HiFocus II) and therefore may carry a greater risk of cochlear trauma during insertion (Eshragi et al., 2003; Aschendorff et al., 2003 and Wardrop et al., 2005a). However, these arrays were designed to (1) ensure increased efficiency of electrical stimulation by decreasing the volume of the surrounding conductive fluid and to (2) enhance frequency specificity by increasing the proximity of the electrodes to the spiral ganglion. In this case finding the right balance would be the target of future designs.

The electrode array's cross-sectional dimensions must not exceed that of the Scala Tympani otherwise there would be a high incidence of trauma

(Aschendorff et al., 2003, Eshraghi et al., 2003, Wardrop et al., 2005a, Rebscher et al., 2008).

2.2.4.2 Preformed curved electrode arrays versus straight arrays

Electrode array designs that allow the contacts to sit in closer proximity to the modiolus are intended to increase electrical stimulation efficiency and promote frequency specificity by positioning the electrodes closer to the auditory neurons. Cords et al. (2000) compared an AB modiolus-hugging position of the array with the use of a preformed silastic positioner to push the array closer to the modiolus and a straight array in six adult cats. Electric Auditory Brainstem Response (EABR) testing showed a significant reduction in thresholds with the positioner; and this was associated with shallower amplitude growth slopes indicating a wider dynamic range, this was most evident in the basal region. Early research on pre-curved arrays in humans (Taikocinski et al.,2001) such as Cochlear’s Contour implants found that T and C levels decreased with the use of the pre-curved perimodiolar array compared to the straight array; this finding was also replicated by (Saunders et al., 2002, Parkinson et al., 2002). Other supporting evidence included the observed decrease in EABR thresholds, shorted latencies and an increase in the amplitudes of waves III and V after the removal of the stylet with the use of Nucleus Contour implant (Pasanisi et al., 2009). Some argue that electrode array designs that position the array closer to the modiolar wall of the scala tympani can risk damaging this thin wall; thus directly damaging the spiral ganglion and increasing the risk of spreading infection from the middle ear to the CSF (cerebro-spinal fluid) (Rebscher et al., 2008).

2.2.4.3 Electrode array stiffness

The stiffness of the electrode array may have an effect on the insertion of the array, the final position of the array in the cochlea and the incidence of insertion trauma. Rebscher et al. (2008) measured the overall stiffness and the stiffness on the vertical and horizontal planes of different electrode arrays from AB, Cochlear and Nurobiosys (a Korean CI manufacturer). They then correlated stiffness to results reported in previous studies reporting insertion trauma (Wardrop et al., 2005a and Wardrop et al., 2005b).They found that there was no correlation between the overall stiffness of the arrays and insertion trauma. However, they did show that arrays with greater stiffness on the vertical plane were less likely to perforate into the scala vestibuli or scala media than those with isotropic stiffness (equal stiffness on the vertical and horizontal planes) or with stiffness greater on the horizontal plane. Baumgartner et al. (2007) found that the MED-EL FLEX^{soft} electrode array with increased flexibility allowed deep insertion while preserving hearing for half of the 16 implanted up to one month and for a quarter of them up to one year post implantation. The MED-EL FLEX^{soft} produced comparable speech reception and life quality questionnaire results to those of COMBI 40+ and PULSAR$_{CI}^{100}$.

2.3 Factors dependent on the CI electrodes/channels

The electrode array contacts themselves may also play a role in affecting performance by altering spectral selectivity or the efficiency with which current is delivered. Despite the disparity in the number of electrodes that the CI devices from the different manufacturers have, they all provide comparable post-implantation results (e.g. Friesen et al., 2001 and Green et al., 2007).

It is presumed that increasing the number of electrodes would increase the number of perceptual channels, this would only be the case if they provided distinct information to increase specificity; this however may not be the case (e.g. Friesen et al., 2001). Some problematic electrodes may cause distortion to the signal delivered *via* the implant which may actually lead to greater numbers of electrodes causing degradation in performance. Identifying these electrodes and finding a fitting solution to overcome the effects that they have on perception might have an impact on post-implantation performance.

2.3.1 Number of channels stimulated by the active electrodes

Different CI systems have a different number of possible active physical electrodes in their devices ranging from 12 to 22. But the number of physical electrodes does not necessarily correspond to the number of spectral channels provided by the implant (Blamey et al., 1992; Zwolan et al., 1997; Fu et al., 1998 and Friesen et al., 2001). Friesen et al. (2001) investigated speech perception as a function of electrodes/channels in implanted [Nucleus 22 users and AB CI (8 electrodes)] and normally hearing adults (using a noise band vocoder). They found that CI recipients were not able to fully utilise the spectral information provided by the full number of electrodes. They did not improve in terms of speech perception in noise when the number of electrodes increased beyond seven or eight. However normal hearing individuals continued to improve up to at least 20 channels. They also reported that the best implanted individuals performed as well as the normal hearing individuals up to 7/8 electrodes/channels only. However, these results have to be considered with caution, since around half of the implanted individuals (9 of 19) had the CI Clarion implant that stimulated only up to 8 channels when all possible electrodes were switched on. In addition to that, there was a marginal significant difference in speech perception between the research conditions with seven active channels versus ten in implanted individuals with Nucleus 22 (the device with 20 possible active electrodes). Another factor that was not accounted for in this study was the discriminability of the electrodes; there was a possibility that non-discriminable electrodes did not add spectral information when switched on, in contrast to discriminable ones. Additionally CI recipient may benefit from a larger number of channels with more recent CI devices and strategies. Nonetheless, there was discrepancy between the number of electrodes and the number of useful perceptual channels (Blamey et al., 1992; Zwolan et al., 1997; Fu et al., 1998 and Friesen et al., 2001). One possible explanation for that is the stimulation of overlapping populations of auditory neurons by different electrodes (Fu and Nogaki, 2004 and Dorman and Spahr, 2006), which could be caused by so called dead regions in the spiral ganglion or “holes in hearing”

(Shannon et al., 2001) or secondary to placement issues whereby electrodes are placed relatively far from the spiral ganglion (Wilson and Dorman, 2008).

This discrepancy may affect performance, since studies have shown a positive relationship between the number of perceptually distinct channels and speech perception for both adults (Collins et al., 1997; Henry et al., 1997; Nelson et al., 1995; Friesen et al., 2001) and children (Dawson et al., 2000).

Besides increasing the number of physical electrodes, CI manufacturers explored other possibilities to increase the number of distinct pitch percepts (perceptual channels). Current steering (described earlier in Section 1.4.3.3) was introduced to create virtual channels to allow the channels to be placed in the correct characteristic frequency region rather than at a fixed electrode site (e.g. Donaldson et al., 2005; Firszt et al., 2007; Koch et al., 2007; Bonham and Litvak, 2008 and Wilson and Dorman, 2008). Tripolar and partial tripolar coupling (described earlier in Section 1.2.5.) aimed to reduce current spread by concentrating stimulation (e.g. Bierer et al., 2005; Bonham et al., 2005; Litvak et al., 2007; Zhu et al., 2012) and thus creating less overlap between channels.

Electrodes that do not provide distinct information could lead to poor perception because cycles of information in a CIS or n of m strategy would be wasted delivering duplicate information rather than unique information to enhance perception, these electrodes could be considered problematic and may require intervention.

2.3.2 Problematic electrodes

It is routine clinical practice that some CI electrodes are deactivated. In a retrospective study Stoddart and Cooper (1999) examined electrodes that showed complications and were subsequently deactivated in 100 adult CI recipients. Reasons for de-activating those electrodes within routine clinical practice were: (1) non-auditory stimulation mainly facial nerve stimulation and sometimes throat sensations, (2) poor sound quality, (3) reduced dynamic range or absence of loudness growth, (4) pain, (5) vibration, (6) absence of auditory stimulation and (7) dizziness. However, in this section, problematic electrodes refer to electrodes with sub-optimal function that may not be deactivated in routine clinical practice.

The identification of problematic CI electrodes has been explored by different methods. Such as frequency discrimination approaches to determine if the electrodes provide distinct pitch information (e.g. Zwolan et al., 1997) or threshold measurement with the use of focussed stimulation to identify what was called “poor electrode-neuron interface” (e.g. Bierer et al., 2011). Some researchers have used direct testing *via* a research interface (e.g. Zwolan et al., 1997) while others explored indirect testing approaches, using consonant and vowel confusion matrices (Remus et al., 2007). The following section provides an overview of different methods used for identifying problematic electrodes with adults, including main findings and indications for possible solutions to improve speech perception.

2.3.2.1 Testing methods for problematic electrodes

2.3.2.1.1 Using electrode differentiation (discrimination)

Several procedures have been described to test for electrode differentiation (discrimination). Some used a pitch ranking task (e.g. Nelson et al., 1995), while others determined the frequency difference limen of each electrode (Zwolan et al., 1997) or used a multidimensional scaling procedure (McKay and Henshall, 2001). These procedures described below required manufacturer specific research interfaces that require programming and lengthy procedures rendering them clinically non-viable.

Pitch ranking

Nelson et al. (1995) described an electrode pitch ranking test administered in a two-interval two-forced-choice (2I-2AFC) task with the use of direct stimulation at loudness balanced “medium loudness” level. They used 500 ms bursts of current pulses and an inter-stimulus interval (ISI) of 500 ms. Stimulation was delivered through the Cochlear corporation research interface to collect the percent correct responses for electrode pairs that were 0.75, 1.5, 3.0, and 4.5 mm apart. Additional electrode separations of 6.0 and 7.5 mm were also tested if subjects did not achieve near perfect scores when the electrodes were 4.5 mm apart. They found great variability in performance on the electrode pitch ranking task among the 14 Nucleus-22 adult users. They also reported that electrode ranking improved with increased spatial separation and suggested increasing the spatial separation between electrodes for subjects with poor ranking at smaller spatial separation; “the reduction in the number of active electrodes might provide a better representation of place pitch across electrodes for these subjects”. Later Donaldson and Nelson (2000) used the same procedure and found a positive relationship between place-pitch sensitivity, as assessed by the electrode pitch-ranking and consonant recognition in 12 post-lingually deafened adults, all of whom were experienced Nucleus 22 implant SPEAK users.

Frequency Difference Limen (FDL)

In 1997 Zwolan, Collins and Wakefield investigated the possibility of identifying indiscriminable (problematic) electrodes based on electrode discrimination in 11 adult post-lingually deafened CI users. Two procedures were employed to evaluate the discriminability of each electrode at loudness balanced comfortable levels: (1) an adaptive 2I-2AFC procedure to determine the discrimination limen (DL) for each electrode; i.e. the closest discriminable electrode to a reference electrode in the basal or apical direction and (2) a fixed-level procedure to verify results from the first procedure and to provide finer estimates of the electrode DL. Each electrode served as a reference electrode in a DL task in at least one block of trials. They provided their participants with research programs based on the electrode differentiation results which improved speech perception for seven out of nine participants, for details of the research programs see Section (2.3.2.2).

Electrode discrimination

Henry et al. (2000) used speech intelligibility index (SII) procedures to investigate the amount of speech information received by CI users in five different frequency bands and associated it with electrode discrimination in each band. They also compared the speech perception abilities of 15 adult post-lingually deafened CI users with that perceived by normal hearing individuals. The normal hearing listeners listened to filtered speech filtered into five frequency bands (170–570, 570–1170, 1170–1768, 1768–2680, and 2680–5744 Hz) and the CI users listened with sequences of electrodes turned down to cut out those spectral components. Electrode discrimination between the adjacent electrodes corresponding to each frequency band was tested in a 4 interval forced choice (4IFC) procedure in which three intervals containing stimulation of the more apical reference electrode and a fourth interval containing stimulation of the test electrode were randomly presented and separated by a 500 ms ISI . The participants were asked to identify the stimulation of the test electrode. Results indicated that the amount of speech information perceived by CI users was significantly less than that of normal hearing individuals in the low to mid frequencies 170-2680 and there was a significant correlation between electrode discrimination ability and the speech information perceived in that frequency range (170-2680 Hz) . This correlation was greatest with the speech information perceived in the frequency band 1768-2680 Hz. Speech information at this frequency band was also shown to be more difficult to perceive by poor performers. Thus it is the most important band for predicting overall speech perception (i.e. whether the CI user was a good or a poor performer), suggesting this band (which corresponds to the region of the second formant) to be one of the most important perceptual regions in speech.

Multidimensional scaling (MDS) procedure

McKay and Henshall (2001) used a multidimensional scaling (MDS) procedure to choose the most discriminable electrodes which were used in their (10 electrode) experimental programmes. The stimulus consisted of a 250 Hz pulse train with a 500 ms duration; all possible pairs were tested at loudness balanced comfort levels. The subject was asked to judge the dissimilarity of the two electrodes across a scale from "exactly the same" to "the most different". Then the scale was converted to a numerical scale and each response was given a number between 0 and 100. This was done twice and two matrices were acquired for each individual, a repeated measure nonparametric multidimensional scale was applied later for analysis. The three experimental programmes were two ten-electrode maps, one of which had a high resolution for frequencies below 2.708 kHz, where 9 electrodes were assigned to that range and only one electrode was assigned to the higher frequency range (2.708-10.513 kHz), while the other 10-electrode map had evenly distributed frequency filters across the electrodes. The third experimental map utilized all possible electrodes as that in the original clinical map, but it had the same analysis filter as that used in the 10-electrode maps which differed from the usual frequency to electrode allocation used the original clinical map.

Results demonstrated that the number of electrodes required for good speech perception may differ between high and low frequencies. In this study, nine electrodes were better than five for the perception of information below 2.6 kHz, and five electrodes were better than one and equivalent to nine for the perception of frequencies above 2.6 kHz; in other words, for optimum perception of speech information by CI users with Nucleus 22 systems 14 channels of information were required. However, it should be noted that there was a large variability among tested individuals.

Although the design of the study did not directly investigate the effect of the less discriminable CI electrodes on speech perception, it served to highlight the importance of spectral resolution at a specific frequency range (less than 2.6 kHz) in order to achieve good speech perception, a finding supported by studies simulating “holes in hearing” or missing spectral information in both the implanted populations (Henry et al., 2000 and Shannon et al., 2001) and the normal hearing individuals *via* noise vocoders (Shannon et al., 2001).

2.3.2.1.2 Using electrically evoked compound action potential (ECAP)

As described previously, channel interaction where different electrodes across the array stimulate overlapping regions of auditory neurons may negatively affect performance with a CI. Abbas et al. (2004) investigated the use of ECAP (an objective measure) to evaluate these channel interactions in Nucleus 24M or 24R implant users with the use of the NRT software (which provides objective measures of the auditory-neural response to the CI electrodes' see Section 1.2.1.1). They used a "forward-masking stimulus paradigm" where the masker and probe pulses were delivered through different electrodes. The position of the masker electrode was varied for each probe electrode which affected the amplitude of the neural response to the probe. The amplitude of the neural-response to the probe depends on the extent of overlap between the stimulated neural regions by the masker and probe electrodes. They found that the ECAP revealed varying degrees of channel interaction across the different CI users and within-subject differences across the different electrodes. They also found that ECAP has the potential to identify regions with little stimulable neurons, but they did not correlate ECAP results with speech perception. Later, Hughes and Abbas (2006) tried to correlate between results of the objective ECAP spread of excitation (SOE) and the psychometric 2I-2AFC electrode pitch ranking, but they found no significant relationship between the width of the ECAP and the slope of the electrode pitch ranking function for the electrodes. However, later re-evaluation of the original ECAP and electrode pitch ranking data revealed a significant strong positive relationship between ECAP SOE and electrode pitch ranking for the electrode pairs (Hughes, 2008). In the re-analysis ECAP SOEs were normalised to the highest amplitude of all the ECAPs within the electrode array, in contrast to the first analysis where ECAP for each electrode was normalised individually. This allowed within subject comparison between the different electrodes in the re-analysis. The re-analysis also used the electrode pitch ranking score for each electrode pair rather than the slope of the electrode pitch ranking function (where the reference electrode was tested with several electrodes and a slope was calculated). Further research is warranted to associate ECAP SOE with speech perception. It is important to note that the NRT used in this research is specific to Nucleus devices, although AB and MED-EL both have their own ECAP systems

2.3.2.1.3 Using single electrode thresholds and electric auditory brainstem response (EABR) thresholds

Variability in single-channel thresholds with the use of bipolar or tripolar (more focussed) stimulation techniques across the electrode array was found to be associated with poor speech perception (Pfingst and Xu, 2004; Pfingst et al., 2004 and Bierer, 2007). Bierer and Faulkner (2010) and Bierer et al. (2011) used the more spatially focused partial tripolar stimulation (described in 1.2.5) to investigate the use of single-channel thresholds and EABR thresholds as a means of identifying poorly-differentiated electrodes. Electrodes with higher thresholds had steep wave V growth function and a degraded spatial/spectral selectivity (wave V is usually the clearest wave and has the largest amplitude). It was suggested that these problematic electrodes have a “poor electrode-neuron interface” and negatively impact on performance with CI. The tripolar and partial-tripolar stimulation applied in this research is currently only available in AB devices because multiple current sources are required to deliver the simultaneous stimulation.

2.3.2.1.4 Modulation detection threshold (MDT)

The detection of frequency modulation at specific CI electrodes was investigated as a possible tool to predict performance with CI and to identify possibly problematic electrodes. Fu 2002 explored the relationship between temporal processing and speech perception with CI. An adaptive, three-alternative, forced-choice procedure was used; two presentations of a 300ms long non-modulated steady-state biphasic pulse train and the same pulse train modulated by a 100 Hz sinusoid. The depth of modulation was adaptively varied and the threshold for detecting the modulation (modulation detection threshold) was established at seven different presentation levels (ranging between 10%-90% of the dynamic range) for the middle electrode pair (10 and 12). He found that the mean modulation detection threshold strongly correlated with the phoneme recognition score. This finding was further supported by Luo et al. (2008), and Garadat et al. (2012). Luo et al. (2008) found a positive relationship between mean MDT (at 5 different stimulation levels for electrode 10) and tone, consonant and sentence recognition scores in Mandarin but not with vowel recognition scores. The lack of correlation with vowel recognition could have been due to the use of one central electrode that does not represent the lower frequencies (vowel formants region). Garadat et al. (2012) reported significantly better speech perception with a research program that used the ten electrodes with the best MDT as compared to a research program that used the ten electrodes with the worst MDT; no comparison was made with the clinical program because they did not control all program settings.

2.3.2.1.5 Using consonant and vowel confusion matrices

Remus et al. (2007) proposed the use of an indirect approach employing vowel and consonant confusion matrices to identify indiscriminable electrodes. Their analysis of Zwolan et al.’s (1997) data (electrode discrimination) in addition to consonant and vowel confusion matrices data from six CI recipients showed that they can potentially identify anomalous channels (problematic electrodes) “above chance level”. However, the development of confusion matrices requires stimuli that will allow testing of each channel and the identification of problems associated with each particular channel. This could be especially challenging and prohibitively time consuming in clinical practice, especially because it would need to be adapted for different devices and different frequency configurations that each device allows.

2.3.2.2 Deactivation of problematic electrodes to improve CI performance

Using electrode differentiation (ED)

Zwolan et al. (1997) identified indiscriminable (problematic) electrodes for 11 post-lingually adult CI recipients. Indiscriminable electrodes were deactivated and participants were provided with experimental programs that employed discriminable electrodes only, thus reducing the number of active electrodes which is in concordance with the Nelson et al. (1995) recommendations mentioned above. Stimuli used for speech testing included a medial vowel recognition test, a medial consonant recognition test, the NU6 Monosyllabic Word Test (scored for words and phonemes) and the CID Everyday Sentence Test. Two implanted individuals showed perfect electrode discrimination, thus were not given experimental programs and were not included in further testing and analysis.

Results indicated that seven out of the nine implanted individuals showed significant improvement in at least three out of the five measures with the use of the experimental program, as compared to performance with the clinical program. Two implanted individuals showed a significant decline in performance in at least one of the tests with the experimental programme. However, it must be noted that one of those individuals' experimental programmes included three discriminable electrodes only. It could be argued that the three electrodes provided very limited speech information to the point that reprogramming cannot improve his performance.

Using modulation detection threshold (MDT)

Zhou and Pfingst (2012) used MDT with eight bilaterally implanted post-lingually deafened adults and provided them with three experimental programs. MDT was measured for each electrode at a presentation level of 50% of the electrode’s dynamic range in a four-alternative forced-choice (4AFC) with the use of a research interface. Four 500ms pulse trains with inter-stimulus-interval of 500ms were presented in each trial; one of the pulse trains was modulated by a 10 Hz sinusoid. MDT was measured with and without masking; the masker was presented on the adjacent electrode which was apical to the test electrode except for electrode 22 (basal) at 50% of the masking electrode’s dynamic range. Speech reception threshold (SRT) with the use of CUNY sentences was acquired for each ear with the clinical program. The MDT in masking was used to identify poor sites (electrodes) unless mean MDT in masking was poorer in the ear with the better SRT; in that case MDT in quiet was used if it agreed with the SRT results. In research program A, the MDT for the 22 corresponding electrodes (e.g. electrode 1 in the left and electrode 1 in the right CI) were compared, the electrode with the higher MDT was deactivated and the corresponding (contralateral) electrode was kept active. Frequencies were not redistributed following deactivation, which meant that each frequency range was represented by the CI in one ear only and both ears complemented each other in dichotic programs; i.e. the program had spectral holes in one ear that was compensated by the corresponding contralateral site. In research program B, the electrodes were divided into five segments and the two electrodes with the highest MDT in each segment were deactivated, again without frequency redistribution (dichotic programs). Program C was similar to program B with the exception that frequencies were redistributed across the electrodes which meant that each frequency range was represented by both ears. All participants showed improved speech perception in noise with at least one research program, program B produced the best results but participants may have required some adaptation/training period to adjust to the new frequency relocation in program C. Program B was a dichotic program that did not have any channels with mismatched pitch across ears. However measures of localisation were not applied.

2.3.2.3 Comparison between the different methods

2.3.2.3.1 The identification of problematic electrodes

As mentioned in Section (2.3.2.1.2), there was a strong statistically significant association between ED and SOE using ECAP (Hughes, 2008). Chatterjee and Yu, (2010) evaluated the relationship between ED and MDT in 13 implanted adults with Cochlear devices, ED and MDT were measured for the centrally located electrode 10 only at 20%, 30% and 40% of the dynamic range with the use of monopolar and bipolar modes of stimulation. The maximum stimulation level of 40% was chosen because their subjects were performing at ceiling levels when higher stimulation levels were used which could be due to restricting testing to one electrode; a possible limitation in the study. MDTs were measured at two modulation frequencies; 100 Hz and 10 Hz. They found statistically significant correlation between ED and MDT at the lower levels of 20% and 30% only with the use of the bipolar mode of stimulation and only at the 20% level with the use of the monopolar mode of stimulation. Weaker associations at higher levels could be due to measures approaching ceiling (especially for MST) thus masking inter-subject variability in performance at the tested electrode (10). The ED was better with the more focussed bipolar stimulation than monopolar stimulation. Considering that MDT testing requires the use of temporal cues while ED requires the use of spectral cues, the most likely explanation is that these tests uncovered a common underlying reason for both poor ED and worst MDT. Poor localised neuronal survival of the spiral ganglion (dead regions) would affect local sensitivity to temporal and spectral cues. Further support is provided by the fact that the correlation was stronger with the more restricted excitation patterns associated with lower presentation levels and with the more focussed bipolar stimulation. More restricted excitation can evaluate more localised regions and increase the sensitivity of the tests (especially MDT in this study) for local dead regions.

A common underlying cause for poor ED, worst MDT (poor detection of frequency modulation) and wider SOE (stimulation of overlapping neural population by more than one electrode) is the most plausible explanation for the positive associations found. Cochlear regions with poor neuronal survival “dead regions” can cause loss of temporal and spectral cues thus affecting MDT and ED respectively. Such regions will also be associated with the need to increase stimulation levels to reach T levels (subjective and EABR) and M levels because they necessitate higher levels of stimulation to reach audibility. Higher levels of stimulation can also stimulate surrounding regions with better neural ganglion survival. This in turn will cause more channel interaction and the stimulation of overlapping neural populations by different electrodes thus affecting ED and SOE, which would relate increased T and M levels with poor ED and a wider SOE.

Dead regions usually refer to “Regions in the cochlea with no (or very few) functioning inner hair cells and/or neurons.” (Moore, 2004). In sensorineural hearing loss these dead regions may have damaged inner hair cell or auditory neurons. However since the cochlear implant device bypasses the damaged cochlear hair cells and stimulates the auditory nerve fibres, when referring to” dead regions “in cochlear implants, these refer to regions with no or few spiral ganglion (Shannon et al., 2001 and Baskent and Shannon, 2006). Reference to “dead regions” in this thesis thereafter will be in that context; i.e. regions with no or poor spiral ganglion survival.

Another factor that may increase the T and M levels and widen the activation pattern of neurons (increase SOE) could be increased electrode-neuron distance within the cochlea which affects the electrode-neuron interface. With the increased electrode-neuron distance higher levels of stimulation are required to reach T and M levels thus spreading the width of excitation. This is in line with a model proposed by Goldwyn et al. (2010) where they suggested that along with cochlear dead regions, increasing the electrode-neuron distance may also increase the T and M levels especially with the use of a more focused mode of stimulation.

In summary, the different methods used so far to identify problematic electrodes are affected by common underlying causes for decreased performance on those measures, mainly the presence of dead region in the cochlea or poor electrode-neuron interface.

2.3.2.3.2 Practical application with the different CI devices

When comparing between the different methods for the identification of problematic electrodes, correlation between results is not sufficient. The results provided by each method and the analysis involved to identify problematic electrodes has to be considered when choosing a testing method. Additionally issues concerning practical application and clinical viability have to be taken into account.

MDT has been used in the identification of the best electrodes (stimulation sites) relative to the other electrodes, however this can be an issue for CI recipients with no problematic electrodes. Deactivating electrodes with higher MDT in comparison to other electrodes for those recipients may not enhance their performance, contrary to that it may negatively affect their performance due to reduced spectral resolution. This holds true when applying ECAP to measure SOE and when using T and M levels as a means to identify problematic electrodes. Obtaining a score with a cutoff point that determines whether a particular electrode is problematic or not with the use of a preset pass versus fail criterion is preferable; it would allow a CI recipient to pass all electrodes. It can also allow for comparison with other electrodes if necessary. Testing electrode-pairs for ED in a 2 interval-2 alternative forced choice pitch ranking task could provide such a score where binomial distribution could be used to establish the pass cut off point.

Other practical considerations may include the method’s flexibility to accommodate devices from different CI manufacturers without the use of special manufacturer-specific research interfaces or stimulation modes (e.g. use of partial tripolar stimulation which is available only to AB in measuring T and M levels). Delivering the test stimuli to the speech processor *via* pure-tones with the use of software designed to allow such flexibility can be a practical option that overcomes the need for research interfaces.

Feasibility of use in clinical settings would also necessitate that the duration of testing does not exceed that routinely allocated to programming CI. The test method is also required to demonstrate a relationship with different speech perception measures, thus relating test results with performance indicating potential for use as a clinical tool to enhance performance with CI.

A possible method for testing that meets the above considerations is pure-tone ED (PTED) which tests for ED by presenting pure-tones at the electrodes' centre frequencies. The use of "STAR" software *via* the "STAR box" [Medical Research Council Institute of Hearing Research (MRC IHR), Nottingham] in a pitch ranking task can be optimised for the application of PTED. In Chapter 3, PTED is described and tests of reliability, validity and clinical use feasibility are reported. Furthermore, Chapter 5 explores the relationship between PTED and speech perception and Chapter 7 applies PTED results to provide CI recipients with research programs and evaluates speech perception with those programs.

2.3.2.4 Interim summary

In summary problematic CI electrode contacts may affect performance, either indirectly because they interface with a neuronal dead region or directly by functioning sub-optimally. The identification of those problematic electrodes which are not usually identified in routine clinical practice may actually be worth finding and de-activating. If those problematic electrodes are identified, intervention targeting them through re-programming of the CI device to improve performance might be possible. A possible solution for those problematic electrodes was offered by Nelson et al. (1995); they suggested that de-activating electrodes in subjects with poor electrode discriminability thus increasing spatial separation might lead to improvements in speech perception. This was followed by Zwolan et al.'s (1997) attempt to deactivate indiscriminable electrodes which improved speech perception for seven of nine implanted individuals. Zhou and Pfingst (2012) also demonstrated improvement in speech perception when the electrodes with poorer MDT were deactivated. Since the methods used so far have been clinically non-viable due to equipment and time restraints and/or are manufacturer specific, exploring other testing methods such as PTED may have great impact on post-implantation performance.

2.4 Second CI

Wilson and Dorman (2008) considered that bilateral electrical stimulation as one of the recent advances that “produced significant improvements in the overall (average) performance of implant systems”. It is argued that the second CI would provide the CI recipient with additional benefit mainly by providing binaural hearing and improved spatial listening. These in return would translate to the real world with improved localisation skills (e.g. Kerber and Seeber, 2012) and better speech perception especially in noise (e.g. Litovsky et al., 2006). Localisation is also important for CI users to aid them in the identification and orientation towards a specific talker among several talkers. The impact of having a second implant is clear if we consider how crucial sound localisation is for safety reasons, in order to avoid hazardous situations especially for the deaf and blind. It also guarantees that the better ear receives an implant, which maybe vital in post-meningitic cases for instance, where urgent intervention before ossification occurs could greatly improve prognosis.

2.4.1 Speech perception with bilateral CIs

In normal hearing listeners, speech perception is greatly enhanced in binaural versus monaural hearing in noise and in quiet (e.g. Bronkhorst and Plomp, 1992). Hence, speech perception is expected to improve in both quiet and noise when listening through bilateral CI in comparison to unilateral (monaural) CI. Although some of the studies comparing bilateral CI with unilateral CI listening conditions have reported improvement in speech perception in quiet (Mosnier et al., 2009; Tyler et al., 2007; Eapen et al., 2009; Dunn et al., 2010 and Litovsky et al., 2006) and in noise when both speech and noise were presented from the front (at 0° azimuth) (Schleich et al., 2004; Ramsden et al., 2005; Eapen et al., 2009 and Wackym et al., 2007). This was not always true; some have found that speech perception did not necessarily improve in quiet (Ramsden et al., 2005 and Laszig et al., 2004) or in noise when both speech and noise were presented from the same direction (at 0° azimuth) (Laszig et al., 2004; Litovsky et al., 2006). This discrepancy could be explained by the lack of a strong "binaural summation" effect which is found in normal hearing due to redundant information from both ears. In normal hearing binaural summation improves speech perception in quiet and in noise even when both (speech and noise) are presented from the same direction. On the other hand, evidence shows that there seems to be consistent improvement in speech perception with bilateral CI in noise when speech and noise are spatially separated; i.e. speech and noise are not coming from the same direction (Laszig et al., 2004; Schleich et al., 2004; Eapen et al., 2009; Litovsky et al., 2006 and Ricketts et al., 2006). This could be explained by the "head shadow" effect which is a purely physical advantage whereby the head shadows one of the ears to the sound or noise coming from the contralateral side. The head shadow effect does not require binaural integration of the signal to occur. In summary, there is a bilateral advantage in adults when it comes to speech perception, most of which is secondary to the head shadow effect with only some of the bilaterally implanted individuals showing evidence of binaural summation. See Table (2.1) for summary of major studies comparing unilateral CI with bilateral CI in adults and have a sample large enough to allow comparison and generalisation ($N \geq 6$ was chosen).

2.4.2 Localisation with bilateral CIs

If spatial listening improves with the provision of bilateral implantation, it's expected to lead to better localisation when both implants are active in comparison to monaural conditions. There were several studies that have found better sound source localisation among implanted individuals in the bilateral versus the monaural condition (Kerber and Seeber, 2012; Laszig et al., 2004; Mosnier et al., 2009; Neuman et al., 2007; Schleich et al., 2004; Seeber et al., 2004 ; Tyler et al., 2007 and Verschuur et al., 2005). This advantage was reported for localisation with the use of different stimuli and tasks in both quiet and noise (Table 2.1 for summary). It must be noted that localisation abilities varied greatly among bilaterally implanted adults (Mosnier et al., 2009) and that no correlation was found between localisation and speech perception in noise (Kerber and Seeber, 2012).

2.4.3 Interim summary

In summary a second CI should have a positive impact on perception, especially in terms of localisation and speech perception in noise. The benefit will not enable perception similar to that of normal binaural hearing, for example there is evidence suggesting that little or no binaural summation occurs for adults with bilateral CI. Variability in performance among the bilaterally implanted is also an issue; some clues of why that is the case were offered by Ramsden et al. (2005) "Most subjects were able to integrate the two signals, but there was an issue with some subjects reporting very large overall pitch differences between the ears. Subjective reports also indicate that initially, if the performance of the second ear is poor, it takes time to learn to ignore it and can be quite distressing."

If we consider the lack of a strong summation effect and the difficulties of pitch mismatches between the ears it may well point to the need for better matched implants for bilateral CI users in an attempt to help them use the important timing and level cues that are available for good binaural listening. Using pitch perception to match electrodes between the two implants might improve performance by facilitating integration of the two signals among the bilaterally implanted. Matching the bilateral CIs for pitch can be accomplished either *via* direct stimulation or *via* pure tone presentations. In Chapter 9 a study evaluating the effects of matching the bilateral CIs for pitch with both methods is described.

Table 2.1 Comparison between unilateral and bilateral CI performance.

Study	Sample	Testing measures	Findings/ conclusions
Dunn et al. (2010)	*30 unilaterally implanted* *30 bilaterally implanted*	Speech perception in noise: Speech reception threshold (SRT) with Cuing-the-Listener and Multiple- Jammers and Cognitive loading.	Bilaterally implanted significantly better on all measures
Eapen et al. (2009)	*9 bilaterally implanted*	Speech perception of (CNC) in quiet and (CUNY) sentences in noise.	Bilateral CI condition better speech perception than unilateral CI.
Kerber and Seeber (2012)	*6 normal hearing* *4 unilaterally implanted* *10 bilaterally implanted*	Speech reception thresholds (SRT) with the use of HINT. Localisation of sonorous source with the use of pulses in noise “spatial resolvability” (SR) was used as a measure.	Normal hearing performed best followed by the bilaterally implanted followed by the unilaterally implanted individuals for SRT and localisation. No significant correlation between speech perception and localisation.
Laszig et al. (2004)	*37 bilaterally implanted*	Speech perception in quiet and in noise with Freiburger monosyllabic words, Oldenburger sentences (OSLA), and the Hochmair-Schulz-Moser (HSM) sentences. Localisation of speech.	No significant difference between bilateral and unilateral condition (with better ear) in quiet or noise when both noise and speech presented from the front with HSM. Significant difference between bilateral and unilateral condition (with better ear) when both noise and speech presented from the front with OSLA and when speech and noise spatially separated (reported head shadow effect with bilateral CI). Localisation better for bilateral CI condition than unilateral CI

Table 2.1 (continued) Comparison between unilateral and bilateral CI performance

Study	Sample	Testing measures	Findings/ conclusions
Litovsky et al. (2006)	*34 bilaterally implanted*	Speech perception in quiet: HINT sentences and (CNC). Speech perception in noise: BKB-SIN test (BKB-Speech In Noise) for SRT. Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire.	All subjects showed benefit in at least measure. Main benefit from head shadow effect. Reported benefit in questionnaire.
Mosnier et al. (2009)	*27 post-lingually deafened bilaterally implanted adults*	Comparison between monaural (left and right) and bilateral. Speech perception of disyllabic words in quiet and noise. Localisation of speech in noise.	Bilateral CI condition significantly better than unilateral CI with the better ear for speech perception in quiet and in noise and for localisation.
Neuman et al. (2007)	*8 bilaterally implanted*	Localisation of speech and pink noise.	Localisation better for bilateral CI condition than unilateral CI.
Nopp et al. (2004)	*20 bilaterally implanted*	Localisation of speech-shaped noise bursts.	18/20 localisation better for bilateral CI condition than unilateral CI. The other 2 had long duration of deafness.
Ramsden et al. (2005)	*29 post-lingually deafened bilaterally implanted adults*	Speech perception in quiet: CUNY sentences and (CNC). Speech perception in noise: CUNY sentences.	Bilateral CI condition significantly better than unilateral CI for group. Not all showed benefit (noise not spatially separated from speech).

Table 2.1 (continued) Comparison between unilateral and bilateral CI performance

Study	Sample	Testing measures	Findings/ conclusions
Ricketts et al. (2006)	*16 post-lingually deafened bilaterally implanted adults*.	Speech perception in noise: SRT with HINT and connected speech test (CST) at fixed SNR.	Bilateral CI condition significantly better than unilateral CI (noise spatially separated from speech).
Schleich et al. (2004)	*21 bilaterally implanted*	Speech perception in noise: SRT with Oldenburg sentences.	Bilateral CI condition significantly better than unilateral CI. Statistically significant head shadow and binaural summation. Small benefit from squelch.
Tyler et al. (2007)	*7 bilaterally implanted*	Speech perception of (CNC) in quiet and (CUNY) sentences in noise. Localisation of everyday sounds.	Bilateral CI condition better speech perception than unilateral CI in 4/7. Localisation better for bilateral CI condition than unilateral CI.
Wackym et al. (2007)	*7 bilaterally implanted*	Speech perception in quiet: CNC and HINT sentences. Speech perception in noise: HINT and speech perception in noise (SPIN). APHAB questionnaire.	Bilateral CI condition better than unilateral CI for all measures, statistical comparison not applied due to “limited number and variance in performance”.
Verschuur et al. (2005)	*20 post-lingually deafened bilaterally implanted adults*	Localisation of five stimuli (speech, tones, noise, transients, and reverberant speech).	Bilateral CI condition significantly better than unilateral CI.

2.5 Summary

- Central cognitive and central auditory processing is integral for good post CI performance; this is apparent when examining the effect of AAI and cognitive abilities.
- Among subject dependent factors, duration of deafness seems to have the strongest impact on performance with CI; this could be secondary to spiral ganglion cell loss.
- The duration of deafness effect on CI performance isn't ear specific, providing yet further support for the importance of the integrity of the central auditory pathway and processing.
- The aetiology of deafness can affect performance with CI because of the underlying pathological disease process associated with some conditions and can cause ossification or fibrosis, and may affect surgical insertion of the CI and post-implantation audiological management.
- Optimum surgical placement of the CI array is crucial, in terms of ST versus SV insertion or crossing over between them, depth of insertion, proximity to the modiolus and insertion trauma with its impact on hearing preservation.
- Soft CI surgery was introduced with hearing preservation as a priority, which is essential in cases of EAS. It requires the CI electrode array to meet certain specification as well including size and flexibility to avoid insertion trauma.
- The number of perceptual channels may be different to the number of active electrodes; this could be due to the inherent limitations of the electric stimulation or due to neuronal dead regions or secondary to problematic or indiscriminable electrodes.
- Some electrodes are deactivated in routine audiological practice but there might be some problematic electrodes that remain active; identifying them and deactivating them might improve performance.

- Several methods and procedures have attempted to identify those potentially problematic electrodes, but none of them were clinically viable and compatible with the different CI devices.
- Electrodes which are indiscriminable and potentially problematic might be so due to neuronal loss “dead region” causing them to stimulate overlapping auditory neurons or due to electrodes sub-optimally functioning.
- Zwolan et al’s study (1997) Zhou and Pfingst (2012) were the only studies that not only identified the indiscriminable electrodes but also explored a possible solution, which was to deactivate them. This is in line with Nelson et al.’s (1995) suggestion to increase spatial separation between electrodes in regions of poor discrimination.
- A clinically viable procedure is still not available, but such a procedure has potential to influence clinical management of CI if proven beneficial; this necessitates exploring possible intervention or solutions after identifying the problematic/indiscriminable electrodes.
- For some CI recipients the situation is further complicated because they have bilateral CIs. The second implant should provide the CI recipient with great advantages in localisation and speech perception, especially in noise.
- The bilateral advantage of the second CI so far does not match that of binaural hearing, which may indicate the need for investigation.
- Programming of bilateral CIs may require modification to incorporate matching across the ears for pitch and loudness level to maximise results and potentially improve outcomes.

2.6 Conclusion

It is important for the CI team to know the factors that may impact on post CI implantation performance and understand how they affect it. Generally, these factors interact with each other: a too deep surgical insertion of the CI array for example can cause damage to the cochlea and/or the electrode array.

When faced with a sub-optimally performing CI user, one must investigate possible underlying reasons in order to target them with a possible intervention that may rectify or partially relieve the problem. Radiological evaluation may be indicated to examine electrode placement, for example, to confirm a kink in the electrode array or the number of electrodes lying inside the cochlea in cases of partial insertion of the array. These electrodes would be usually deactivated, thus radiological evaluation can affect programming of the CI device. The same is true when we understand how the pathological changes associated with meningitis or otosclerosis can affect the spread of electrical current hence influencing the programming of the CI. Again de-activation of some problematic electrodes in those cases can prevent facial nerve stimulation for instance or enhance performance.

Thus a review of the literature has exposed some problems with achieving optimal performance with CI. Pitch perception analysis might be a valid tool in determining electrode discrimination. Poorly functioning electrodes, if deactivated might improve overall speech perception in CI users. However, testing methods in the unilaterally implanted so far have been clinically non-viable due to equipment and time constraints thus the PTED pitch ranking test can be a clinically viable option. Reprogramming of the CI with the use of tonotopic electrodes only may provide improvement. Among the bilaterally implanted using pitch perception to identify problematic electrodes must take into consideration matching pitch across ears since mismatch in pitch perception across ears can negatively affect performance. Reprogramming with the use of electrodes which are tonotopic in relation to the other ear as well may provide benefit. To measure performance with CI the widely used BKB sentence test in quiet and in noise (provides contextual cues that allows participants to fill in the blank) in addition to the Coordinate response measure [(CRM) an adaptive speech in speech test that introduces both energetic and informational masking and does not provide contextual cues] will be used to assess speech perception additionally localisation will be assessed in the bilaterally implanted individual.

This thesis will address the following research questions:

$Q_{1:}$ The main research question "Can testing for pitch perception guide programming of CI to improve performance?" which will be mainly addressed in Chapters 7, 8 and 9.

Q_2: Is PTED a valid, reliable and clinically viable test? (Chapter 3)

Q_3: What is the minimum clinically significant change in CRM in the normal hearing and CI users? Is it different between these two groups? (Chapter 4)

Q_4: Is there a relationship between the percentage of discriminable electrodes as identified *via* PTED and speech perception (BKB in quiet and in noise and CRM threshold)? If so, is the relationship stronger at specific frequency ranges (is good spectral resolution at certain frequencies more important for good speech perception)? (Chapter 5)

Q_5: Are there other factors that contribute to speech perception with CI? (Chapters 5 and 6)

Q_6: Are deeper insertions of the CI electrode array associated with better or worst speech perception? If so, is there a relationship between speech perception and the mismatch between the characteristic frequency stimulated by the most apical electrode and the electrically stimulated frequency? (Chapter 6)

Q_7: Are deeper insertions of the CI electrode array associated with poor ED of the most apical electrodes? (Chapter 6)

Q_8: Can cone beam computed tomography (CBCT) be used to estimate scalar placement of individual CI electrodes? If so, does scalar placement affect speech perception or ED? (Chapter 6)

Q_9: Will deactivating indiscriminable electrodes as identified *via* the PTED in the unilaterally implanted improve speech perception? (Chapter 7)

Q_{10}: Is there a difference in using pitch information (number of discriminable intermediate frequencies) between regions of discriminable versus indiscriminable electrode-pairs? If so, do participants showing benefit after deactivating indiscriminable electrodes demonstrate a different pattern as compared to those showing no benefit following the deactivation of indiscriminable electrodes? (Chapter 8)

Q_{11}: Is there a difference in using pitch information (number of discriminable intermediate frequencies) between regions of indiscriminable electrode-pairs before and after deactivation? If so, do participants showing benefit after deactivating indiscriminable electrodes demonstrate a different pattern as compared to those showing no benefit following the deactivation of indiscriminable electrodes? (Chapter 8)

Q_{12}: Will deactivating electrodes which are indiscriminable or non-tonotopic in relation to the contralateral ear in the bilaterally implanted improve speech perception and/or localisation? (Chapter 9)

Chapter 3

Validity and reliability of the pure-tone electrode differentiation in CIs

Abstract

The pure-tone electrode-differentiation (PTED) test is potentially a clinically viable test for determining electrode differentiation (ED). It is based on a pitch ranking task using pure-tone presentation. Each pure-tone is presented at the estimated centre frequency of one of the CI filters, such that each frequency should predominantly stimulate a different CI electrode. The validity, reliability and feasibility of clinical use of the PTED were evaluated in this study. The PTED's validity was determined by comparing the results to a direct-stimulation electrode differentiation approach that used the same response procedure but the stimuli were delivered using the CI fitting station. The results showed that the PTED has good validity ($\gamma = 0.88$, $n = 104$, $p < 0.001$). PTED demonstrated good test-retest reliability ($\gamma = 0.95$, $n = 108$, $p < 0.001$) and was clinically viable in terms of equipment and time requirements.

3.1 Introduction

One of the goals of CI development is to increase the number of distinct pitch percepts for the CI recipient. To date, the approach adopted has been to increase the number of physical electrode contacts on the array, or to create virtual channels by trying to focus electrical stimulation between electrode contacts (Donaldson et al., 2005; Firszt et al., 2007; Koch et al., 2007; Bonham and Litvak, 2008; Wilson and Dorman, 2008). Additional approaches have been made to reduce current spread by concentrating the stimulation, using bipolar or tripolar stimulation techniques (Bierer et al., 2005; Bonham et al., 2005; Litvak et al., 2007).

As discussed in Chapter 2 (see Section 2.3) for many CI users, the number of perceptually-distinct channels can differ greatly from the number of active electrodes, or channels, on their implanted device (Blamey et al., 1992; Zwolan et al., 1997; Fu et al., 1998 and Friesen et al., 2001). In adult listeners, a positive relationship exists between the number of perceptually-distinct channels and speech perception scores (Collins et al., 1997; Henry et al., 1997 and Nelson et al., 1995). There is some evidence that the same is true in children despite the inherent difficulties in assessing electrode differentiation (Dawson et al., 2000). This discrepancy between the number of channels and number of active electrodes could be attributed to problematic or indiscriminable electrodes. As discussed in Section 2.3.2.3 the indiscriminable electrodes may arise as a consequence of placement of electrodes relatively far away from the spiral ganglion cells (Wilson and Dorman, 2008) or the existence of neuronal dead regions “holes in hearing” (Shannon et al., 2001). With CIs, dead regions usually refer to regions with no or few spiral ganglion (Shannon et al., 2001 and Baskent and Shannon, 2006).

In summary, a range of methods have been employed to demonstrate a strong, positive relationship between ED and speech recognition, and there is some evidence that an improvement in performance occurs when only discriminable electrodes were used in the CI programme (Zwolan et al., 1997 and Zhou and Pfingst 2012). Despite this, methods employed to date (described in Section 2.3.2.1) are largely inappropriate in a clinical setting due to time constraints and their reliance on a research interface to make the assessment. Hence there is a need for a clinically viable test for ED; PTED is proposed as a potential clinically viable test for identifying problematic electrodes which could be indicative of problematic neural regions.

The study described in this chapter was conducted to validate a new potentially clinically viable testing procedure (PTED) for the identification of problematic electrodes *via* ED and to assess its clinical viability.

3.1.1 The development of the PTED test

The PTED test was developed with collaboration between the UCL Ear Institute and the Medical Research Council Institute of Hearing Research (MRC IHR), Nottingham. Development involved the author, Dr. Debi Vickers, Dr. Victor Chilekwa and Prof. David Moore. The author was the software's beta tester and worked very closely with the programmer (Dr. Victor Chilekwa) in choosing the test tasks and the test protocol administered in each task and in ensuring that the software ran those tasks as required without crashing (debugging of the program).

The number of trials per electrode pair and the pass/fail criteria were determined based on binomial distribution. The testing protocols and the starting presentation levels used in the test protocols were modified based on pilot testing to reduce testing time (e.g. if the comfort level was determined at 65dB for the first electrode, the initial loudness level of the adjacent electrode used in the loudness balance task was not as low as 40dB).

In the pilot phase, eight CI recipients from the three CI manufacturers (AB, Cochlear and Med-El) underwent both pitch ranking and pitch discrimination testing at various degrees of roving.

The pitch ranking in a 2 interval-2 alternative forced choice (2I-2AFC) task was chosen for PTED rather than pitch discrimination in an odd one out 3I-3AFC task because it requires that the CI recipients identify each presentation's pitch while pitch discrimination does not. CI recipients (in the pilot phase) reported that some tone presentations (at electrodes' centre frequencies) were distorted and sounded like noise while other presentations sounded like tones with specific pitches associated with them. In those cases a CI recipient passed the pitch discrimination task but not the pitch ranking task. These distortions could be associated with malfunctioning electrodes or electrodes stimulating regions of poor spiral ganglion cell count (dead regions) hence the pitch ranking task is superior to the pitch discrimination task. Additionally some CI recipients reported that the 3I-3AFC used in pitch discrimination had a higher demand for auditory memory than the 2I-2AFC used in ranking and that they could not remember the first presentation which adds an additional variable (i.e. auditory memory).

An ‘adjacent reference method’ (further described in Section 3.2.2.2) was chosen for loudness balancing because it ensures –as much as possible- that presentations of adjacent electrode-pairs (which will be tested for pitch ranking) are balanced for loudness to reduce loudness cues, in addition to that roving was added to further control for loudness cues. A 2 -dB- level rove (ranging from -1 to +1dB with a 1 dB step resolution) was chosen because some CI recipients (in the pilot phase) complained that a range of -2 to +2dB and of -3 to +3dB was too confusing.

3.1.2 Aims and hypothesis

The aim was to determine if the PTED was a valid and reliable tool for assessing pitch-ranking (direction) ED (PTED) and whether it was sufficiently quick for use in clinical practice. The accepted standard approach for determining ED based on pitch ranking has been direct-electrical-stimulation [direct electrode discrimination (DED)] (Collins et al., 1997; Henry et al., 1997; Nelson et al., 1995; Dawson et al., 2000 and Zwolan et al., 1997) An approach utilising DED was used to validate the pure-tone method PTED. In addition, test-retest reliability of the PTED was measured, and the testing time and ease of testing of the PTED were also evaluated.

The rationale of PTED was that the acoustic stimuli (pure tones at the centre frequency of each electrode’s filter) should stimulate the appropriate electrode. Concurrent validity of the PTED procedure was established by comparing the results to those of the DED procedure testing the same electrodes in the same person. Concurrent validation is demonstrated when there is significant correlation between scores on two measures that test the same construct (e.g., Shuttleworth, 2009). Results of the PTED and DED were compared for all tested electrode pairs.

The PTED was tested during two different test sessions, PTED’s test-retest reliability was carried out, and PTED’s scores were compared across sessions for all tested electrode pairs.

PTED’s clinical use feasibility was assessed; testing duration of all tasks involved were measured and both average and maximum possible testing durations for the different devices were calculated based on the median, the 25th quartile and 75th quartile of testing times per electrode pair.

Main research hypotheses:

H_1: There will be a relationship between PTED and DED.

H_2: There will be a relationship between PTED in first and second sessions.

Sub-hypotheses are:

H_1: There will be a relationship between PTED and DED in classification of electrode-pairs into pass versus fail.

H_2: There will be a relationship between PTED and DED in classification of electrodes into problematic versus non-problematic.

H_3: There will be a relationship between PTED in the first and second sessions in classification of electrode-pairs into pass versus fail.

H_4: There will be a relationship between PTED in the first and second sessions in classification of electrodes into problematic versus non-problematic.

It was considered that if the testing duration for the PTED tasks for the different devices would not exceed the 1 hour clinical slot allocated for routine CI programming that this would be clinically appropriate if the results are useful.

3.2 Method

NHS ethical approval (09/H0714/17) and Research and Development agreement were obtained for this project from the Royal Free Hampstead NHS Trust. All participants gave written consent and received reimbursements for the cost of travel.

3.2.1 Participants

Participants were recruited from the Royal National Throat Nose and Ear Hospital (RNTNEH) and through the National Cochlear Implant Users Association (NCIUA) by advertisement in its newsletter. One participant (participant 2) had a history of cochlear ex-plantation and re-implantation and one participant (participant 5) had a rolled over electrode array tip at insertion.

15 adult CI recipients with acquired deafness were recruited.

The inclusion criteria were that the participants had:

1. A minimum of six months CI experience.
2. An aural-oral mode of communication.
3. English as a first language.

Participants' demographics are shown in Table (3.1). Details for determining some of the individual categories and summary of demographics were as follows:

(1) Duration of deafness was calculated for each participant from the date of diagnosis of a bilateral profound sensorineural hearing loss, it ranged from 2 to 53 years. (2) Age at testing ranged between 24 to 83 years with a mean of 63 years (± 14). (3) The aetiology of the hearing loss was unknown in 7 out

of the 15 participants. (4) Cochlear implant experience was calculated from date of switch on of the currently used implant; this ranged from 6 to 168 months with a mean of 66 months and median of 48 months. (5) The hearing loss was progressive for all of the participants. (6) All were post-lingually deafened except participants 3, 4 and 8 who had progressive onset from childhood. (7) Participants recruited had CI devices from Advanced Bionics (AB), MED-EL™ and Cochlear®.

Table 3.1 Participants' demographics

Participant	Aetiology	Progressive	Age in years	Age at implant in years	Duration of Deafness in years	Implant experience in months	Type of implant
1	Post general anaesthesia in 3rd decade	Yes	63	61	12	18	MED-EL™ SONATA$_{TI}^{100}$
2	Unknown	Yes	68	57	19	18	AB HiRes 90K
3	Pyrexia at 8 months	Yes	53	49	?	48	Nucleus® Freedom
4	Head injury, age 5 years	Yes	56	46	3	6	MED-EL™ PULSAR$_{CI}^{100}$ standard
5	Unknown	Yes	50	48	2	24	AB HiRes 90K
6	Sickle cell anaemia	Yes	24	20	9	48	MED-EL™ PULSAR$_{CI}^{100}$ standard
7	Typhoid Otosclerosis	Yes	72	61	40+	132	MED-EL™ Combi 40+
8	Measles, age 5 years	Yes	66	59	25	89	MED-EL™ Combi 40+
9	Unknown	Yes	71	70	5	13	MED-EL™ PULSAR$_{CI}^{100}$ standard
10	Unknown	Yes	78	64	53	168	Nucleus® 22
11	Hereditary	Yes	62	57	6	62	AB HiRes 90K
12	Unknown	Yes	63	57	5	60	MED-EL™ PULSAR$_{CI}^{100}$ standard
13	Unknown	Yes	64	51	33	153	MED-EL™ Combi 40+
14	Unknown	Yes	71	69	9	25	MED-EL™ Combi 40+
15	Noise induced and otosclerosis	Yes	83	72	40+	123	Nucleus® CI 24M

3.2.2 Test battery

The PTED was validated against the DED approach; details of both procedures are shown below.

3.2.2.1 Direct electrode differentiation (DED)

The DED was measured by directly stimulating electrodes using standard CI fitting software. The procedure examined all adjacent active electrodes, to assess which were discriminable. Identical methods were used for all adjacent electrode pairs at loudness-balanced levels, with subjects having to judge which presentation (electrode) had the higher pitch. All pairs were presented 5 times in random order. Pairs scoring ≤ 80% were tested 5 more times to give a score for 10 trials, if they scored greater or equal to 80%, this was seen as significantly different (binomial $p<0.05$; Skellam, 1948). Although the DED procedure was believed to be effective in identifying problematic electrodes, it was not deemed clinically useful because it required two clinicians to conduct testing and calculate scores. However, the approach was considered to be effective test for ED and it was therefore used to validate the PTED which employs pure tone ED testing.

3.2.2.2 Pure tone electrode differentiation (PTED)

To assess ED without direct stimulation, pure tones that corresponded to the centre frequencies of the processing filters within a participant's individual CI program were presented through a specifically designed sound box [Medical Research Council Institute of Hearing Research (MRC IHR), Nottingham, 'STAR box']. The purpose of this USB-connected box was to present high fidelity sounds that bypassed the host computer's sound card. All filter centre frequencies associated with switched-on electrodes were used. The audio and graphical presentation was controlled through STAR software (MRC IHR; Barry et al., 2010; Halliday et al., 2012).

Measurements of electrode activation spread were made for the Advanced Bionics (at M-level) and MedEl (at C-level) systems by directly measuring the outputs from all channels on a multi-channel oscilloscope. Stimuli were presented at 60dBSPL. For both systems the stimuli were presented through a speech processor which went to a "dummy" implant in a box attached to a load board with outputs permitting direct measurements of the activation in different channels. A criterion level of 6dB down was used as a cut-off for considering that current had spread to adjacent electrodes from the main stimulating electrode. For both of these implants there was some spread to the very next electrode above and below the stimulating electrode but no further than that, this was considered acceptable. For the Cochlear device, stimuli were routed through an experimental speech processor, the sound processing strategy was set to use only one maxima. The output was verified using a dummy cochlear implant and a research interface with an "Electrodogram" programme developed by Cochlear Corporation that creates a frame-by-frame listing of the output of the implant transmitter coil and generates an electrodogram illustrating visually the output of each electrode within a specific time window. The results of the electrodogram analysis demonstrated that the stimuli only activated one channel at a time for the cochlear device when using the single maxima sound processing programme.

The duration of the pure tones was 400 ms with 50 ms onset and offset cosine ramps and an inter-stimulus interval of 500 ms. The stimuli were presented directly to the speech processor as an auxiliary audio input with a 2 -dB- level rove (ranging from -1 to +1dB with a 1 dB step resolution) in order to remove the impact of loudness cues without unduly disturbing pitch perception. Verification of accuracy of frequency, duration of stimulation and level of presentation was determined using an Oscilloscope (model: Philips PM 3070, 100 MHz) prior to testing.

Stimuli were delivered at a comfortable level from a desktop PC *via* the IHR soundbox to the participant's CI 'auxiliary' input lead. Comfort level was established for one frequency representing the centre electrode in the CI electrode array. Loudness matching was then conducted at both increasing and decreasing test frequencies (across the electrodes) to ensure that stimuli were all equally loud. An 'adjacent reference method' for loudness balancing

(Throckmorton and Collins, 2001) was used where each electrode was sequentially balanced to its adjacent, previously balanced electrode. A two interval forced choice task was used, in which the participant was presented with two pure-tones representing two adjacent electrodes and had to say whether the second tone was louder, softer or same loudness level as the first tone. A simple up-down staircase adaptive procedure was followed. Step size started at 5 dB and was halved after the second reversal, testing stopped after the participant indicated that the second tone had same loudness level as the first tone for three times. The average loudness level of those three responses judged as having the same loudness was taken as the loudness balanced level.

The pitch-ranking task employed a 2I-2AFC paradigm in which the listener responded to the statement “which sound has the higher pitch?” A visual cue was given with each pure-tone presentation; two animated figures representing the two tones are presented on the computer monitor (see Figure 3.1) and one figure would jump up on the screen with each pure-tone presentation (see Figure 3.1). A mouse was used to click on the animated figure representing the pure-tone presentation with a higher pitch. Each pair of adjacent active electrodes was tested for a minimum of 5 consecutive trials. If the participant scored 80% or lower (i.e. was correct on 4 or fewer trials), a further five trials were carried out giving ten successive trials in total. As mentioned earlier, this was based on binomial distribution calculation of minimum correct responses required to achieve significance at the $p<0.05$ level (Skellam, 1948). The STAR software provided automated delivery and scoring (percent correct and pass or fail categorization) for each electrode pair, thus avoiding bias.

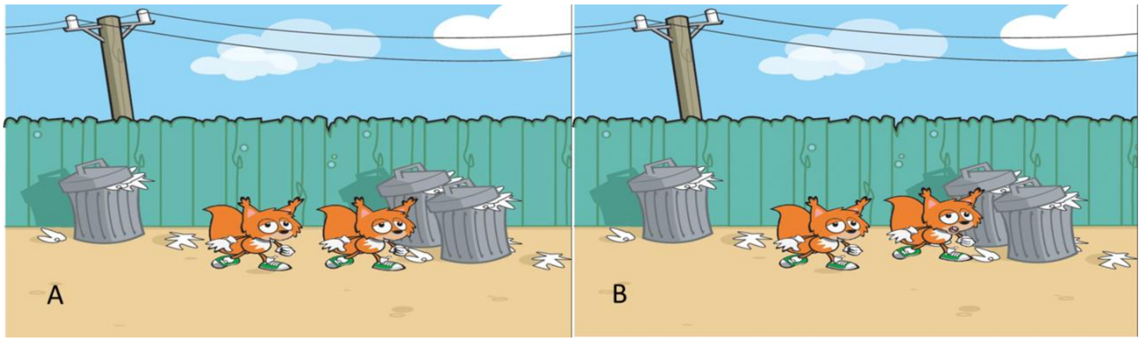
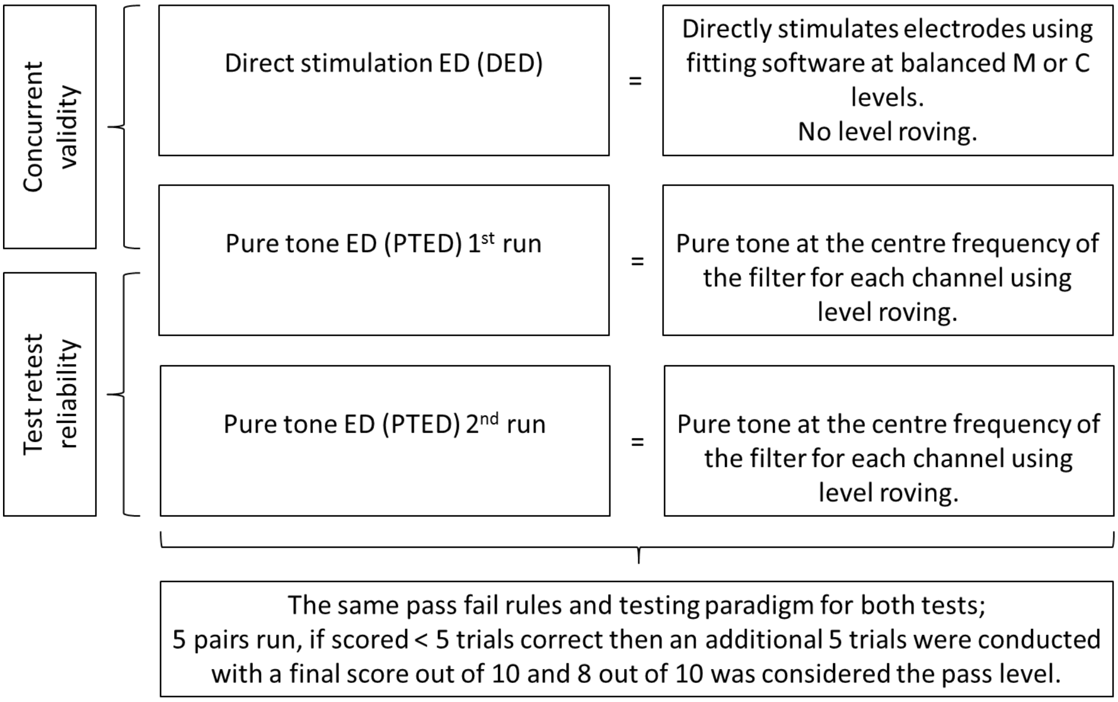


Figure 3.1 The animated figures (foxes) used for testing and collecting responses, which appeared on the monitor during testing for PTED. A) The two animated figures before pure-tone presentation. B) The two animated figures (foxes) during the second pure-tone presentation, the second fox is jumping up and opening its mouth during pure-tone presentation.

3.2.3 Procedure

All testing was performed in a 2×2.5 m double-walled sound booth. Scoring for the PTED was automatically calculated *via* the testing software and the DED and PTED calculations were derived independently to ensure that the testers were blind to the results of the other test. Certain adjustments to the speech processor’s program settings (see Section 1.3.2 for speech processor programming) had to be applied before administering the PTED test. See Figure (3.2) for outline of the study protocol.



Direct stimulation ED (DED)

Directly stimulates electrodes using fitting software at balanced M or C levels.
No level roving.

Pure tone ED (PTED) 1st run

Pure tone at the centre frequency of the filter for each channel using level roving.

Pure tone ED (PTED) 2nd run

Pure tone at the centre frequency of the filter for each channel using level roving.

The same pass fail rules and testing paradigm for both tests;
5 pairs run, if scored < 5 trials correct then an additional 5 trials were conducted with a final score out of 10 and 8 out of 10 was considered the pass level.

Figure 3.2 Outline of the study protocol to evaluate validity and reliability of the PTED.

3.2.3.1 Adjusting the speech processor for testing PTED

The program used when running the PTED tasks was the participant's preferred clinical program. For participants with Cochlear® devices, the number of maxima (see Section 1.3.2.3) was adjusted and set to the value of 1 to ensure that only one electrode, the test electrode, was stimulated. Both the threshold and highest comfort level were increased with this maxima setting by 15% in the participant's testing program. Care was taken that levels did not cause non-auditory stimulation and were comfortable before conducting loudness balancing and pitch ranking. ADRO (Adaptive dynamic range optimization) (James et al., 2002) was deactivated because it may affect testing loudness levels. Mixing between the auxiliary and the microphone was set on a maximum mixing ratio for the auxiliary input. For the AB devices, testing was administered with a program having an audio output setting of "AUX" only, in line with manufacturers' recommendations.

For both the AB and MED-EL™ devices it was not possible to avoid stimulation spreading to adjacent electrode sites.

3.2.3.2 Validation of the PTED procedure

Eight participants (2 with Cochlear®, 3 with MED-EL™ and 3 with AB implants) were tested with both the DED and the PTED test for the same electrode configurations and frequency tables (frequency to electrode allocation in the CI program; Section 1.3.2). The pass/fail scores for all electrode pairs that were tested with both procedures were compared, using a pass level of 80%. Furthermore all individual electrodes were categorised into problematic versus non-problematic and comparison was made across procedures.

3.2.3.3 Reliability of the PTED procedure

Inter-session test-retest reliability of the PTED was established using the same electrode pairs, the same programs and the same frequency tables (for program and frequency table see Section 1.3.2). Ten participants conducted two test sessions each that were at least one month apart. All electrode pairs and electrodes were compared across sessions and the ED pass level was, again, 80%. Furthermore all individual electrodes were categorised into problematic versus non-problematic and comparison was made across sessions.

3.2.3.4 Clinical use feasibility of PTED *via* STAR software

To evaluate potential feasibility of PTED in a clinical setting in terms of testing time, the median duration of testing per frequency pair was measured for both the loudness matching and the pitch ranking task. Loudness matching data for 2458 trials of 351 frequency pairs and pitch ranking data for 6927 trials were collected and used in the analysis. In contrast to the fixed number of trials per electrode pair in the pitch ranking task (five or ten), the number of trials per electrode pair in the loudness matching varied more widely and thus affected testing time. Therefore, number of loudness matching trials per electrode pair was also measured.

3.3 Analyses

Statistical analysis was conducted to assess the following:

1. Whether there was a significant relationship between DED and PTED results for the tested electrode pairs and for identification of indiscriminable electrodes.
2. Whether there was a significant relationship between the test-retest PTED results for the tested electrode pairs and for the identification of indiscriminable electrodes without demonstration of a learning effect.
3. Whether the testing duration of both PTED tasks (loudness matching and pitch ranking) renders PTED a clinically practical/feasible procedure.

IBM SPSS STATISTICS 21 for windows was used to carry out the analyses, *p* values are two tailed and significance is reported when $p<0.05$.

3.3.1 Validation of the PTED procedure

3.3.1.1 Categorisation of electrode-pairs into pass or fail

All PTED and DED scores for all electrode pairs were categorized as pass or fail; resulting data was categorical ordinal data with one category (pass) more common than (fail), hence Goodman-Kruskal Gamma (a test of association that can be used with categorical ordered data (Agresti and Finlay, 1997) was used with the group results to determine agreement. Group and individual agreement results in addition to the upper and lower quartiles of agreement per participant were also calculated.

3.3.1.2 Categorisation of individual electrodes into problematic versus non problematic

Since the goal of developing a tool to assess the ED of the CI device is to identify indiscriminable/problematic electrodes, the categorical data was further analysed. Each electrode was identified as either non-problematic or problematic, The Goodman-Kruskal Gamma was then used to evaluate for agreement between DED and PTED on problematic versus non-problematic electrodes.

In an indiscriminable electrode pair, the electrode was considered problematic according to the following criteria:

1. If an electrode is common to two failing electrode-pairs.
2. Both electrodes in an indiscriminable pair if both have the same score with the adjacent electrodes on either side.
3. The poorer electrode in an indiscriminable pair; the electrode with a poorer score with the adjacent electrode.
4. The electrode at the end of electrode array in an indiscriminable pair.

3.3.2 Test-retest reliability of the PTED procedure

3.3.2.1 Categorisation of electrode-pairs into pass or fail

PTED scores for all electrode-pairs from both sessions were categorized as pass or fail; resulting data was categorical ordinal data with one category (pass) more common than (fail), hence Goodman-Kruskal Gamma was used with the group results. Group and individual agreement results, in addition to the upper and lower quartiles of agreement per participant, were also calculated. To exclude a learning effect, a Wilcoxon signed test was administered with the use of the actual scores (percent correct) obtained in both PTED testing sessions.

3.3.2.2 Categorisation of electrodes into problematic versus non problematic

As mentioned earlier, the aim of an ED test is to identify indiscriminable/problematic electrodes. Each electrode was identified as either non-problematic or problematic, and the Goodman-Kruskal Gamma was used to evaluate for test-retest agreement. The categorisation criteria of indiscriminable/problematic electrodes described in Section (3.3.1.2) were used.

3.3.3 Clinical use feasibility of the PTED *via* STAR software

Total testing duration and testing duration per PTED task was reported for each participant, median, lower quartile (Q_1) and higher quartile (Q_3) and interquaurtile (IQ) range was calculated for the group. The median, Q_1, Q_3 and IQ range was also calculated for per test-trial testing duration of both PTED tasks, loudness balance and pitch ranking. Estimates of average and maximum testing durations required for the different CI devices were calculated based on median, Q_1 and Q_3 values and the number of tested electrode pair in each device.

3.4 Results

3.4.1 Validation of the PTED procedure

Results obtained with both DED and PTED procedures were compared for the same electrodes that were tested in both procedures in the same person based on the pass/fail categorisation.

3.4.1.1 Categorisation of electrode-pairs into pass or fail

Group results (all electrode pairs of the eight participants as one group): Goodman-Kruskal Gamma, revealed a significant strong correlation between the DED and PTED ($\gamma = 0.88$, $N = 104$, $p < .001$), thus the hypothesis H_1 was accepted.

The percentage of electrode pairs that fell in the same category (pass versus fail) across the two procedures (DED and PTED) was 80% (Table 3.2). There were 21 electrode-pairs that showed disagreement between DED and PTED, closer evaluation revealed no trend in the direction of disagreement; 10 pairs passed PTED and failed DED while 11 pairs failed DED and passed PTED.

Individual results: The percentage of electrode pairs that fell in the same category across the two procedures (DED and PTED) for each participant was calculated to derive the individual agreement score (Table 3.2, median = 81%, interquartile range = 9.75, Q1 = 75, Q3 = 85, N = 8). See Figure (3.3) for an example of one data set.

Table 3.2 The percentage agreement (pass versus fail) of all tested electrode-pairs between DED and the PTED and for all participants.

Participant	**No. Electrode pairs**	**No. electrode pairs agreement**	**No. electrode pairs disagreement**	**% agreement of electrode pairs**
2	11	9	2	82%
3	21	16	5	72%
4	7	6	1	86%
5	12	11	1	92%
6	11	9	2	82%
7	8	6	2	75%
10	19	14	5	74%
11	15	12	3	80%
Total	104	83	21	80%

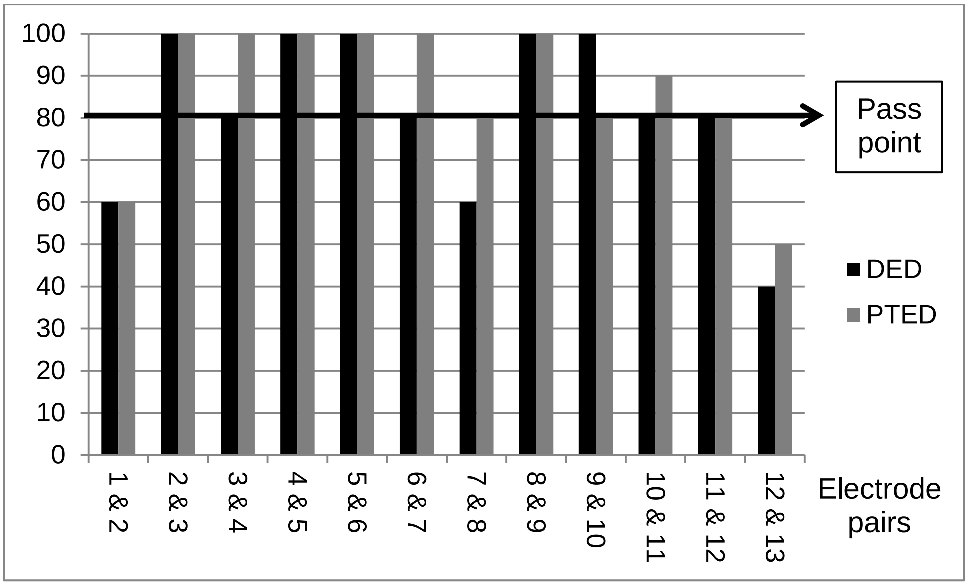


Figure 3.3 Example of raw percentage DED and PTED pitch ranking scores for each electrode pair in participant 9 to show agreement. The passing cut off point at 80% to show agreement in terms of pass versus fail. All electrode pairs are in agreement except pair 7 and 8.

3.4.1.2 Categorisation of electrodes into problematic versus non problematic

Group results (all electrodes of the eight participants): Goodman-Kruskal Gamma, revealed a significant strong association between the DED and PTED ($\gamma = 0.85$, $N = 112$, $p < .001$), thus the hypothesis H_2 was accepted.

In summary, the validation results showed that the PTED scores were highly associated with DED scores with respect to identifying indiscriminable CI electrodes.

3.4.2 Test-retest reliability of the PTED procedure

Test-retest of the PTED results for the same subject and the same electrodes at two different test sessions one month apart were compared.

3.4.2.1 Categorisation of electrode-pairs into pass or fail

Group results (all electrode pairs of the ten participants as one group): Goodman-Kruskal Gamma analysis revealed a highly significant association between the two test sessions ($\gamma = 0.95$, $n = 108$, $p < 0.001$), thus the hypothesis H_3 was accepted.

The percentage of electrode pairs that fell in the same category (pass versus fail) across the two test sessions for all tested electrode pairs was also calculated and was 90% (Table 3.3).

Individual results: Individual test-retest agreement score are shown in Table 3.3 (median = 88.5%, interquartile range = 18, Q1 = 82, Q3 = 100, N = 10).

Table 3.3 The percentage agreement (pass versus fail) of all tested electrode pairs between the test-retest sessions with the PTED -while using the same test map and frequency table- for all participants.

Participant	**No. Electrode pairs**	**No. electrode pairs agreement**	**No. electrode pairs disagreement**	**% agreement of electrode pairs**
1	8	6	2	75%
5	12	10	2	83%
6	11	9	2	82%
7	8	7	1	88%
8	9	8	1	89%
9	11	9	2	82%
12	11	11	0	100%
13	11	11	0	100%
14	9	8	1	89%
15	18	18	0	100%
Total	108	97	11	89%

Examining those electrode pairs where discrepancies occurred, 8/11 were as a result of improvements in discrimination performance in the second session. A Wilcoxon signed test was applied to the raw scores obtained for all electrode pairs in both sessions to determine if there was a learning effect. There was no significant difference between the two sessions (Z = -1.55, N = 108, $p = 0.122$), which indicated that in general a learning effect was not apparent.

3.4.2.2 Categorisation of electrodes into problematic versus non problematic

Group results (all electrode pairs of the ten participants): Goodman-Kruskal Gamma, revealed a significant strong association between the DED and PTED ($\gamma = 0.98$, N = 118, $p < .001$), thus the hypothesis H_4 was accepted.

In summary, the test-retest reliability of the PTED was high and no significant learning effect was seen.

3.4.3 Clinical use feasibility of the PTED *via* STAR software

A clinically-viable test must be able to be carried out within the time frame of a typical CI fitting session and the test must be sufficiently easy to use with CI users with different devices and settings. The testing and scoring was automated once the frequency test settings were entered. All participants were able to follow instructions and complete the tasks without difficulty. Testing duration of both tasks together (loudness balancing and pitch ranking) for all participants was recorded and are shown in Table (3.4).

Table 3.4 Testing duration per participant for each of the PTED tasks (loudness matching and pitch ranking) and the total testing duration; values are rounded up to the nearest minute.

Subject	Loudness matching testing duration	Pitch ranking testing duration	Total testing duration in minutes
1	10	7	17
2	13	14	27
3	32	25	57
4	10	9	19
5	13	11	24
6	10	12	22
7	19	10	29
8	12	9	21
9	4	11	15
10	15	20	35
11	15	9	24
12	5	7	12
13	19	9	28
14	11	8	19
15	16	15	31

The duration taken to conduct the loudness matching task ranged from 4 to 32 minutes and for the PTED's pitch ranking task ranged from 7 to 25 minutes. Total testing duration for both tasks ranged from 12 to 57 minutes (see Table 3.5 for descriptive statistics).

Table 3.5 Descriptive statistics of testing duration per participant for each of the PTED tasks (loudness matching and pitch ranking) and the total testing duration; values are rounded up to the nearest minute.

Task	Median	IQ range	Q_1	Q_3
Loudness matching (LM) in minutes	13	6	10	16
Pitch ranking (PR) in minutes	10	5	9	14
LM and PR in minutes	24	10	19	29

An estimate of test duration per electrode pair was calculated with the use of group values. Based on which further estimations of the average and the maximum possible duration it would take to test participants with different CI devices were made. Further analysis of duration per trial (one presentation of two stimuli for one electrode pair and the associated response) detailed data showed that: (a) for loudness matching, the median duration for balancing each electrode pair was 40.3 seconds, and the median number of trials that was required to match the loudness of an electrode pair was 6.5 trial (see Table 3.6 for descriptive statistics). The average and maximum testing duration of all adjacent electrodes was calculated for each CI device and is shown in Table (3.7), (b) for pitch ranking, 17 response time measurements were removed due to participants stopping the task and restarting after a break. This reduced the total number of the pitch ranking trials used in analysis from 6927 to 6910. The median duration for running each trial was 4.37 seconds (see Table 3.6 for descriptive statistics). Based on the median per-trial testing duration, the average and maximum expected testing duration of all adjacent electrodes was calculated for each CI device and is shown in Table (3.8).

Table 3.6 Descriptive statistics of testing duration per electrode pair for each of the PTED tasks (LM and PR) and number of LM trials per electrode pair. Durations are shown in seconds.

Variable	Median	IQ range	Q1	Q3	N
LM duration per electrode pair (EP) in seconds	40.3	43.7	24.3	68	351
Number of LM trials per EP in number of trials	6.5	5.8	3.8	9.6	351
PR duration per test trial in seconds	4.37	2.1	3.8	5.9	6910

Table 3.7 Average and maximum testing duration in minutes for PTED's loudness matching task in the different devices based on the lower 25th and upper 75th quartile (Q_1 and Q_3) in minutes; average is calculated with the assumption that each electrode pair will be tested in five trials which is the minimum number of trials and the maximum is calculated with the assumption that each electrode pair will be tested in ten trials which is the maximum number of trials.

Device	Maximum number of electrodes	Maximum number of electrode pairs (MNEP)	Average test duration in minutes (Q_1 x MNEP)	Maximum test duration in minutes (Q_3 x MNEP)
MED-EL™	12	11	4.5	12.5
AB	16	15	6.1	17
Cochlear®	22	21	8.5	23.8

Table 3.8 Average and maximum testing duration in minutes for PTED's pitch ranking task in the different devices based on the lower 25th and upper 75th quartile (Q_1 and Q_3); average is calculated with the assumption that each electrode pair will be tested in five trials which is the minimum number of trials and the maximum is calculated with the assumption that each electrode pair will be tested in ten trials which is the maximum number of trials.

Device	Maximum number of electrodes	Maximum number of electrode pairs (MNEP)	Average test duration in minutes (Q_1 x MNEP)	Maximum test duration in minutes (Q_1 x MNEP)
MED-EL™	12	11	3.5	11
AB	16	15	4.75	14.75
Cochlear®	22	21	6.65	20.65

3.5 Discussion

PTED was shown to have the potential to be a clinically-useful testing approach for CI users. To be able to have confidence in the results of a procedure it has to be valid, show good reliability, and be clinically practicable.

3.5.1 Validation of the PTED procedure

To validate the PTED it was compared to the DED, a test which used direct-electrical-stimulation. Results of this direct stimulation ED (DED) procedure were shown by Vickers et al. (in preparation) to be highly correlated with speech perception scores using the BKB sentences both in quiet and in noise (speech-spectrum shaped noise at 10dB signal-to-noise ratio). This finding was in keeping with the previous literature using procedures based on direct stimulation using a research interface (e.g. Collins et al., 1997; Henry et al., 1997; Nelson et al., 1995 and Dawson et al., 2000). Improvements in performance were also observed for some listeners who had poorly differentiated electrodes deactivated (Vickers et al., in preparation). This study demonstrated that the PTED is a valid method of stimulus delivery to test for ED, based on a strong and significant correlation between ED across DED and PTED and both hypotheses H_1 and H_2 were accepted.

The PTED has advantages over the DED because it allows for amplitude roving of presented stimuli without the requirement of a research interface. Furthermore, it requires just one person to perform the task. Additionally, the STAR software randomizes stimuli presentation and follows the pre-defined rules for pass/fail criteria and stimuli presentation, thus avoiding human error.

3.5.2 Test-retest reliability of the PTED

For PTED to be employed clinically it must be reliable across test sessions. More importantly it must consistently identify the same electrodes as problematic or indiscriminable. The test-retest inter-session reliability showed a strong and significant agreement across sessions for tested electrode pairs and for identification of indiscriminable electrodes and both H_3 and H_4 were accepted.

Although the PTED categorisation of electrode pairs into pass or fail was highly correlated across sessions, the PTED’s nomination of problematic electrodes was even more so. The reason for that is because problematic electrodes are common to two test electrode pairs, an adjacent electrode on each side. So it may pass with one adjacent electrode but fail with the other, or it may fail with both neighbouring electrodes. There were cases (5 of 11 discrepancies) where a problematic electrode was consistently (in both sessions) indiscriminable with one adjacent electrode but showed disagreement (pass versus fail) when tested with the adjacent electrode on the opposite side of the electrode array. For example, electrode 9 in participant 16; the participant failed to differentiate between electrode pair 9 and 10 in both sessions but correctly differentiated between electrode pair 8 and 9 in one session and failed in the other sessions (causing disagreement between sessions for electrode pair 8 and 9). Despite the apparent disagreement, the same poorly-differentiated electrode (electrode 9) was identified in both sessions. Hence, PTED was found to be a highly reliable tool in identifying indiscriminable electrodes.

3.5.3 Clinical use feasibility of the PTED

For this procedure to be employed as a clinical tool to identify electrodes with poor pitch differentiation and guide programming, it is necessary to ensure that the tested subjects are able to perform the task and can correctly rank pitch. Amongst the participants tested here, all were able to rank pitch and none of them reported finding the approach difficult. Consequently, participants at this stage were not regularly provided with a training trial.

It is also essential that the procedure be time efficient. Total testing duration for loudness matching and PTED’s pitch ranking tasks ranged from 12 to 57 minutes and would therefore not exceed the time currently allocated in the NHS for a routine CI fitting session (around 60 minutes). Finally, the procedure also requires sufficient flexibility to accommodate the different frequency tables used by different CI recipients. Frequency tables are the frequency range and frequency-electrode mapping in the CI program which differ between manufacturers and fitting settings. The results of this study showed that the PTED provided sufficient flexibility. The PTED can thus be used clinically for ED without undue prolongation of clinical visits.

3.6 Conclusion

The present study demonstrated that presenting ED test stimuli *via* STAR software provides a clinically-viable solution that allows a valid, practical and flexible procedure for mapping the frequency table. It also provides a tool that could potentially help us improve performance with CIs, guided by ED results. However, it is important to prepare the test programme settings, speech processor settings and software settings to ensure the testing of ED of the CI electrodes rather than a general ability to rank pitch.

3.7 summary

- Several studies have employed different testing methods to identify indiscriminable/problematic electrodes. They were clinically non-viable due to time and/or equipment requirement.
- The standard test for the identification of indiscriminable electrodes has been direct stimulation of the CI electrodes.
- PTED, a new test for electrode differentiation employing pure tones at the electrodes centre-frequencies was evaluated for validity and reliability.
- PTED’s validity was assessed by comparing it to a direct-stimulation electrode differentiation test, the DED and proved to be a valid test.
- PTED’s test-retest reliability was evaluated and it showed high reliability.
- PTED’s clinical use feasibility was evaluated, testing duration (both recorded and estimated) were within the time routinely allocated for programming CI. Everyone was able to perform the tasks and the software (STAR) was flexible enough to accommodate the different devices and settings.

- PTED was found to be a valid and reliable clinically viable test for the identification of indiscriminable electrodes.

Chapter 4

Test-retest reliability of the Coordinate Response Measure (CRM) speech perception test

Abstract

The coordinate response measure (CRM) is an adaptive speech perception test with competing speakers as the masker. This study determined the test-retest reliability of the CRM with normal hearing (NH) and adults with CIs. The replicability, variability and stability of the CRM were evaluated for the two groups separately. CRM had a better replicability, stability and lower variability for the CI adults compared to NH adults.

4.1 Introduction

After establishing the PTED's validity and reliability in Chapter 3, before applying it to identify problematic electrodes and reprogramming based on its results, the speech perception test battery had to be developed. One consideration was that different types of masking have distinct effects on speech perception and some make the test more sensitive for picking up small changes in performance. In order to evaluate the efficacy of reprogramming based on pitch perception (including PTED), the coordinate response measure [(CRM) a speech on speech test] was used in addition to the widely used BKB sentence test that contains strong contextual cues. The CRM evaluates speech perception in the presence of a competing talker and is potentially more sensitive to changes in the spectral resolution (Stickney et al., 2004). Additionally CRM is not influenced by learning effects to the same extent that the more context heavy more predictable speech perception tests are. Prior to using the CRM the test-retest reliability and the minimum clinically significant difference had to be established because this information was not available for the test.

Speech perception in noise is especially challenging for CI recipients, but it is of vital importance if we consider everyday listening situations which are rarely quiet (e.g. Friesen et al., 2001). Background noise and conflicting speech cause some of the information in the target speech signal to be masked, making it very difficult to recognise and understand speech. Competing speech is especially difficult because of the combined effect of energetic and informational masking (e.g. Freyman et al., 1999 and Kidd et al., 1998; Arbogast et al., 2002; Brungart, 2001a and 2001b). Energetic masking occurs at a more peripheral level when both the masker (e.g. noise) and speech simultaneously carry energy at the same critical frequency bands rendering portions of speech inaudible. Informational masking occurs at a more central higher level when both the masker and target speech are audible but the listener is unable to segregate the elements of the target speech from that of the “similarly sounding” masker (e.g. Doll and Hanna, 1997; Kidd et al., 1994; Kidd et al., 1995; Watson, Kelly, and Wroton, 1976). Speech perception tests are used clinically to evaluate speech recognition for the hearing impaired and the CI users, as a means to evaluate functional listening and to gain a good understanding of an individual’s everyday listening ability. Some tests such as the BKB and the CUNY sentence tests are routinely used. These sentence tests can be administered in both quiet and in noise, and allow the listener to use contextual cues because the sentences are meaningful and the listener can fill in the part they miss by using the context of the words that they do detect. Typically the speech perception tests are conducted in the presence of an interfering noise such as a white, pink or speech shaped noise. The effect of using different types of masking on speech perception has been highlighted by some studies (e.g. Hawley et al., 2004; Arbogast et al., 2005; Stickney et al., 2004 and Qin and Oxenham, 2003). For some people with good listening skills it could be beneficial to test in the more challenging listening situations for example with one or more competing speakers. This competing masker not only provides some energetic masking from the excitation of the masker but also could potentially provide informational masking. Energetic masking is widely defined as peripheral masking that occurs because of energy overlap between the target and masker both spectrally and temporally while informational masking is widely thought of as a competition between the target and the masker at a central level of processing (Brungart, 2001b). Hornsby et al. (2006) found that speech on speech masking had a greater masking effect than speech-modulated noise for both NH and hearing impaired individuals using hearing aids. They contributed the increased difficulty to the combined effect of informational masking and energetic masking. The CRM is administered to evaluate speech perception in the presence of a competing talker; it is an adaptive test that requires limited vocabulary which makes it suitable for listeners that do not have English as their first language. The noise is adapted for positive signal-to-noise ratios (SNR) and once 0dB SNR is reached the speech is adapted for the negative SNRs. It can be used in conjunction with other speech perception measures where each test can evaluate different aspects and provide a more complete picture of the performance of the CI recipient.

4.1.1 The CRM speech perception test

The CRM was initially developed by the American Air Force Research Laboratory (Moore, 1981) to test speech intelligibility in a multi-talker environment. Stimuli consisted of low redundancy phrases in the following form ‘’Ready call sign go to colour number now’’, e.g. “Ready Charlie go to Green Four now”. A target “call sign” which participants listened for was selected and the participant had to respond by correctly identifying the colour and number following the target “call sign”. However it has been used as a speech recognition test outside of its initial military context (Brungart, 2001a and 2001b; Brungart et al., 2001 and Kitterick et al., 2010). Brungart (2001a), investigated the relationship between the CRM stimuli (corpus) and the articulation index (AI) and found that within extremely difficult listening environments (noisy environments), CRM has high sensitivity to small intelligibility changes. Kitterick et al. (2010) tested 41 NH adults and used an array of 13 loudspeakers at 15° separation and found that CRM SRT (speech reception threshold) was better when each talker spoke one at a time in comparison to two talkers speaking in pairs. They also found that knowing “who” the talker saying the target phrase is, “where” the target phrase will be presented and “when” the target phrase will be presented improved CRM SRTs when pairs of talkers started speaking at the same time. When each talker started speaking one at a time only knowing “who” was marginally beneficial. They concluded that masking and attention are important factors in listening in multi-talker environments. However when testing CRM with two talkers simultaneously presented (both from the same speaker), knowing “where” or “when” do not become variables and knowing “who” does not affect performance (Brungart et al., 2001). This may indicate that using two talkers presented simultaneously from the same speaker may reduce the effect of attention; a listener attending to the wrong talker can simply switch to the second talker after hearing the wrong “call sign” used.

It must be noted that it was found that in the NH, reducing the intensity of the target in comparison to the masker (negative signal to noise ratio) improved speech perception in CRM because the listener was able to tune their attention to the softer sound (Brungart, 2001b). In other words, the difference in intensity provided a cue to distinguish between the target and masker which outweighed the advantage provided by a larger SNR (signal to noise ratio). This advantage may not be available to the CI recipients because their speech reception thresholds are unlikely to be at a negative SNR (i.e. speech at a lower presentation level to the noise).

Competing speech maskers have a more detrimental effect on speech perception for listeners with a CI when compared with other maskers such as modulated (speech-spectrum-shape) noise or steady state noise (Stickney et al., 2004). This same effect has been demonstrated in simulations with the use of noise-vocoders, with NH individuals (Qin and Oxenham, 2003 and Stickney et al., 2004). They found that a competing talker negatively affects speech perception with a CI when compared with NH and more than other maskers would (Stickney et al., 2004). These results were also replicated in the simulated condition (Qin and Oxenham, 2003 and Stickney et al., 2004). They concluded that this happened because of a combined effect of energetic and informational masking in addition to the reduced spectral resolution and fine structure of the speech signal provided by the CI. The reduced spectral resolution provided by the CI might have impaired the listeners' ability to distinguish between components of the target speech and those of the competing speech. If so, then enhancing spectral representation of the signal provided by the CI might improve speech perception in the presence of a competing talker; this could be measured by a test such as the CRM. An added benefit of using CRM in the evaluation of CI recipients would be the introduction of new test material and avoidance of learning effects.

CRM can potentially be used as a clinical tool but it is necessary to establish the test-retest reliability and the minimum clinically significant change in the CRM speech reception threshold (SRT) if it were to be used as a speech perception assessment test.

4.1.2. Aims and hypothesis

This study evaluated the test-retest reliability of the CRM test for NH adults and CI recipients. The aim was to collect data and determine the minimum clinically significant difference for the CRM SRT by establishing replicability, variability and stability, so it could be later used to analyse individual performance changes in studies looking at reprogramming of the CI speech processor. Both NH and CI users were tested to determine whether the increased difficulty faced by CI users (Qin and Oxenham, 2003 and Stickney et al., 2004) can affect test-retest reliability.

Main research hypotheses:

H_1: NH will have significantly different CRM SRTs in comparison to CI recipients.

H_2: CRM SRTs will correlate across sessions for both the NH and the CI recipient groups.

4.2 Method

4.2.1 Participants

The CI recipients were recruited from the RNTNEH and through the NCIUA.

13 adult (CI) recipients with acquired deafness were recruited, four of whom were male and nine were female.

The inclusion criteria were that the participants had:

1. A minimum of 18 months CI experience.
2. An aural-oral mode of communication.
3. English as a first language.

Age at testing ranged between 27 to 77 years with a mean of 60 years (± 12). Among the participants recruited 4 had AB, 4 had MED-EL™ and 5 had Cochlear® devices.

The NH adult volunteers were native English speakers recruited from University College London (UCL). 33 adults aged 24 to 59 years with a mean of 38 years (± 10) were recruited; they had pure-tone thresholds $\leq$ 15 dB HL at octave frequencies between 0.25 and 8 kHz, inclusive, measured using the British Society of Audiology guidelines (1981). There were 19 females and 14 males. All the volunteers had their hearing evaluated on the day of CRM testing to confirm normal thresholds at the time of testing; this means that their hearing was tested twice once at the original test session and once at the re-test session.

4.2.2 Test battery

Coordinate Response Measure (CRM)

The CRM with two talkers was used. This test was used within our standard test battery when a participant scored over 50% in the BKB sentences in speech-spectrum shaped noise at 10dB SNR. CRM was a more difficult task than the BKBs because it avoided contextual cues. The CRM sentence corpus used consisted of 128 phrases spoken by eight native British English speakers, four of which were female and four were male. Stimuli consisted of low redundancy phrases in the following form ‘‘Ready call sign go to colour number now’’, e.g. “Ready Charlie go to Green Four now”. The target “call sign” which participants listened for was “Baron”. In each trial two talkers; one male and one female uttered the stimuli which were presented from the same speaker, directly ahead of the participant (at 0˚ azimuth). There were seven possible distractor call signs ‘‘charlie,’’ ‘‘arrow,’’ ‘‘eagle,’’ ‘‘hopper,’’ ‘‘laker,’’ ‘‘ringo,’’ ‘‘tiger’’. There were four colour options ‘‘blue,’’ ‘‘green,’’ ‘‘red,’’ ‘‘white’’, and four numbers (one, two, three and four) which were randomly assigned. The participant had to listen to the phrase containing “Baron” and choose the colour and number combination presented in that phrase by selecting from a button on the touch screen; e.g. “Ready Baron go to Red Four”, the participant was required to choose “Red Four” for the response to be considered correct. The test started at a SNR of 30dB (target phrase presented at 60 dB SPL, non-target phrase presented at 30 dB SPL). Positive SNR was achieved by attenuating the noise and negative SNR by attenuating the target phrase thus the maximum presentation level of the target phrase was reached at 0dB SNR. A simple up-down staircase adaptive procedure was followed to determine the CRM SRT, in which three reversals occurred before obtaining the threshold. Step size started at 10dB and was halved twice after a reversal occurred to reach the smallest step size of 2.5dB. The threshold was estimated based on the SNR of the 15 trials following the third reversal and the outcome score was a threshold in dB at which the colour and number in the target phrases were correctly chosen at a 50% accuracy level.

4.2.3 Procedure

Testing took place in a 3.7×3.25 m double-walled sound booth where the participant was seated 1 metre in front of an ear level loud speaker (Plus XS.2, Canton) from which the speech and noise were presented. The stimuli were stored (16 bits), sampling rate (44.1 kHz), presented using the AB-York

Crescent of Sound (Kitterick et al., 2011). The participants used a touch screen monitor to respond, and the software ran the test presentation and scoring in an automated fashion.

The participants underwent two testing sessions at least one month apart; participants were tested twice for CRM in each session and an average CRM SRT was obtained in each session for each participant. The CI recipients were experienced CI users who have been using their CI program used during testing for a minimum of two months prior to testing.

4.2.4 Analyses

The analyses aimed to establish:

1. Whether there was a significant difference in the CRM SRT between NH participants and participants with a CI.
2. Whether there is a strong relationship between CRM SRTs across sessions for both groups; the NH and the CI recipients (as part of the test-retest reliability analysis).
3. Minimum clinically significant change which was calculated as part of establishing the test-retest reliability.

IBM SPSS STATISTICS 21 for windows was used to carry out the analyses. CRM SRT average per session for each participant was used for analysis. According to Shapiro-Wilk’s test, all CRM SRTs for both groups were normally distributed so parametric statistical tests were used.

An independent *t*-test was used to compare CRM SRTs between groups and the Pearson product-moment correlation coefficient was used to establish the relationship between scores obtained in the two sessions for each group.

4.2.4.1 Test-retest reliability

Three measures were used to evaluate test-retest reliability, which were proposed by Summerfield et al. (1994). Not only do they evaluate the relationship between the test-retest CRM SRTs but they also provide a value of the minimum clinically significant difference.

Replicability: measured as the correlation coefficient between pairs of CRM SRTs, which establishes whether the second score can be predicted from the first.

Variability: measured as the within-subjects standard deviation (σ) of across-sessions scores. When an individual is tested twice by the same tool in similar conditions, a reliable test would produce the same results giving rise to a smaller σ. In this case we are more interested in the group results; hence a mean within-subjects standard deviation (σ_W) was calculated. The following equation adopted from Summerfield et al. (1994) was used.

$$\sigma_w = \sqrt{\frac{\sum_{i=1}^{k}\sum_{j=1}^{n}\left(x_{ij} - \mu_i\right)^2}{k(n-1)}}$$

Where k is the number of the participants, n is the number of test trials, x_{ij} is the j^{th} CRM SRT of the i^{th} participant and μ is the mean threshold for the i^{th} participant. Any score for any randomly chosen participant should lie within ±1.96 σ_W of that participant's mean score with a $p \geq 95$; i.e. the 95% confidence interval.

Stability: measured as the standard deviation of the difference (σ_δ) in thresholds collected twice under similar conditions. If the difference between thresholds is equal or more than 1.96 σ_δ then it is significant with $p \geq 95$.

4.3 Results

4.3.1 Difference between NH and CI recipients

All CRM SRTs obtained in both sessions were used in the comparison. The group results of the CRM SRTs of the NH and CI recipients are shown in Figure (4.1). When thresholds from both sessions were clustered per group, the between-subjects variance was greater in the CI recipients' group, indicating a disparity in performance among the CI recipients as compared to the NH and the assumption of homogeneity of variances was violated, as assessed by Levene's Test for Equality of Variances ($p < 0.001$). The NH performed significantly better than the CI recipients t (31.16) = -23.91, p<0.001 (Table 4.1) and H_1 was accepted. Since CRM SRTs for both populations are normally distributed, a 95% interval was calculated for each group, mean ± 1.96 SD. Based on the mean and standard deviation values, there is a 95% possibility that thresholds for the NH would fall in the range (-23.65 to -22.17 dBA) and thresholds for the CI recipients would fall in the range (2.28 to 6.6 dBA).

Table 4.1 Descriptive statistics of the CRM SRTs for each group; mean and standard deviation in dBA.

Group	Mean	Standard deviation	N
NH	-22.91	.37	66
CI recipient	4.44	1.08	26

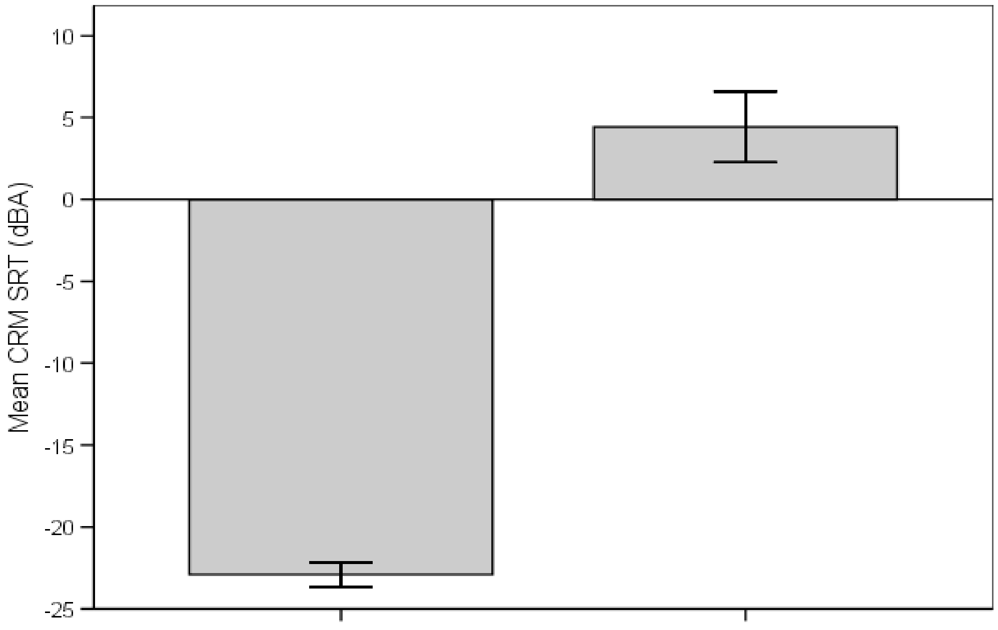


Figure 4.1 Results of the CRM test in dBA for each group, the NH and the CI recipients. Values above 0dB line indicate thresholds at a positive SNR and values below 0dB line indicate thresholds at a negative SNR. The bars show mean scores, error bars show ± 2SE.

4.3.2 Test-retest reliability of the CRM

There was a significant positive relationship between the test-retest CRM SRTs for both groups, which was moderate (r=0.5, p<0.005, N=33) for the NH and strong for CI recipients (r=0.95, p<0.001, N=13). See Figure (4.2) for results of the NH and the CI recipients groups. Hence the H_2 was accepted for both groups.

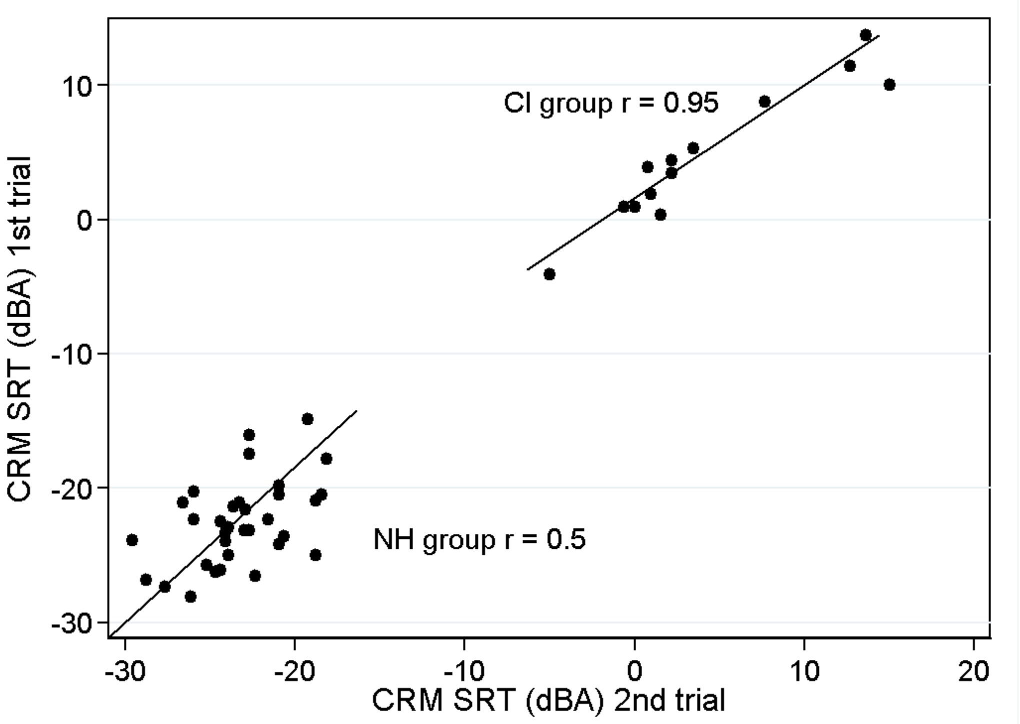


Figure 4.2 The relationship between CRM SRTs in dBA in the first trial and the second trial among the NH and CI recipients. CRM SRT in dBA in the first trial on the y axis versus the CRM SRTs in dBA in the second trial on the x axis showing a positive relationship between the CRM SRTs across sessions.

All the test-retest reliability statistics are shown in Table (4.2). As previously explained, a single threshold from a randomly chosen CI recipient should lie within $\pm 1.96\sigma_w$ (in this case 2.12dB) of that recipient's true mean threshold with a probability ≥ 0.95. If a CI recipient was tested under two different conditions (e.g. two different programs) a change in CRM is considered significant (at $p<.05$) if the change is greater than $1.96\ \sigma_\delta$ (in this case 4dB).

Table 4.2 Test-retest statistics of the CRM test for the NH and the CI recipients groups. The Pearson product-moment correlation coefficient (r), the within-subjects standard deviation of thresholds (σ_w), the standard deviation of the differences between participants' first and second thresholds (σ_δ) and the sample number for each group.

Measure	Groups	
	NH	CI recipients
Reproducibility (r)	0.5	0.95
Variability σ_w (dB)	2.24	1.44
1.96σ_w (dB)	4.39	2.8
Stability σ_δ (dB)	3.06	2.05
1.96 σ_δ (dB)	6	4.03
Number of sample	33	13

4.4 Discussion

The NH group performed significantly better than the CI recipients on the CRM test, which is expected particularly in this situation using speech on speech masking (Qin and Oxenham, 2003 and Stickney et al., 2004). Due to the poor spectral resolution of CI users the task is not necessarily an informational masking task but most likely an energetic masking task in which the CI users are unable to benefit from listening in the gaps of the interfering speech signal in the same way that NH listeners can. Hence the hypothesis H_1 was accepted.

As hypothesised (H_2) there was a significant correlation between CRM SRT across-sessions for both NH and CI recipients. The larger between-subjects variance in the CI group as compared to the NH listeners is in line with previous reports of variability in performance among the CI population (see Chapter 2). Another important finding is that there is a 95% probability for the CI user to have a CRM SRT in the range (2.28 to 6.6 dB); i.e. the threshold will most likely be at a positive SNR. In this case it will be highly unlikely for CI recipients to be able to use the intensity cue, which a negative SRM could provide the NH (see 4.1.1) where CRM improved because the listener was able to tune their attention to the softer signal (Brungart, 2001b).

In contrast to the CI group, the ability of the NH to utilise the intensity cues at a negative SNR could add an extra variable that may account for the higher within-subject variability in the NH group. This may help explain the larger within-subject variability as displayed by a lower correlation coefficient and a higher variability (σ_w) and stability (σ_δ) values for that group. The minimum clinically significant change (at $p < 0.05$) in CRM SRTs among CI users was found to be > 4dB, and > 6 dB for the NH if an individual were to be tested under two different conditions.

CI recipients exhibited less within-subject variability than the NH group, potentially due to not being able to utilize the intensity cues effectively. Hence, it was decided that for the minimum significant CRM SRT change for CI users would be based purely on the data obtained from the CI recipients within this study.

4.5 Conclusion

The trends in the CRM results are consistent with previous literature; the NH had significantly lower thresholds than the CI recipients t (31.16) = -23.91, $p<0.001$. There was higher between-subject variability among the CI recipients as compared to the NH. In addition, loudness cues at negative SNR increased within-subjects variability among the NH. The minimum clinically significant change (at $p < 0.05$) in CRM SRTs among CI users was found to be > 4dB, and > 6 dB for the NH.

4.6 Summary

- CRM is an adaptive speech perception test that utilises speech on speech masking, which resembles real life listening situation and is especially difficult for CI users.
- CRM test-retest reliability was measured in NH and CI recipients groups.
- CRM SRTs are lower and have higher within-subject variability among the NH in comparison to CI recipients.
- The CI users are more likely to have CRM SRTs at positive SNR in contrast with the NH group whose CRM SRTs were at negative SNR.
- The higher within-subject variability in CRM SRT among the NH could be due to the additional variable added by the intensity cue at negative SNR.
- The minimum significant change (at $p < 0.05$) in CRM SRT among CI users is > 4dB, if a CI user were to be tested under two different conditions.

Chapter 5

The relationship between PTED and speech perception

Abstract

The association between ED measured *via* PTED (described in Chapter 3) and speech perception scores (BKB in quiet and in pink noise and the CRM test) was evaluated. In line with earlier literature, there was a positive relationship between the percentage of discriminable electrodes and the different speech perception measures (R^2 ranging from 0.36 – 0.55). Stronger associations were found between the percentage of discriminable electrodes at the lower frequency range (≤ 2600 Hz) than at higher frequencies. Multiple regression tests revealed that the percentage of discriminable electrodes especially at the low frequency range (< 1000 Hz) is a significant predictor of speech perception performance and the models accounted for up to 68% of variance in CRM SRTs. Findings from this study along with findings from Chapter 3 provide evidence of the validity for the PTED test as a test for ED.

5.1 Introduction

CI recipients hope to hear, listen and make sense of what is being heard, be it speech or everyday sounds. As discussed there in Chapter 2, there is a wide variance in the speech perception ability of the CI recipient population. Among the factors discussed, the number of perceptually distinct channels is considered to be a contributor to performance level (see Section 2.3.1). Studies have shown better speech perception with a higher number of perceptually distinct channels (Collins et al., 1997; Henry et al., 1997; Nelson et al., 1995; Friesen et al., 2001 and Dawson et al., 2000). It would therefore be expected that any valid and reliable test of ED would show a positive relationship with speech perception. After establishing the validity and reliability of the PTED in Chapter 3 and the reliability of the speech perception test CRM in Chapter 4, the PTED results were correlated with the speech perception tests. A relationship between the PTED and speech perception would indicate the validity of the measure PTED as an ED test. Additionally many authors (Skinner et al., 1995; Henry et al., 2000; Fourakis et al., 2004 and Fourakis et al., 2007) have shown that the lower frequency range (frequencies ≤ 2600 Hz) and in particular the first formant region ≤ 1000 Hz requires a larger number of electrodes to convey the information than is required for the higher frequency regions for good speech perception. This suggests that ED and spectral resolution in the low frequency range may have a greater impact on speech perception than they do in the high frequency range. Thus a valid test of ED that reflects the spectral resolution of the signal provided by the CI should demonstrate the need for better spectral resolution at low frequencies.

A study addressing the relationship between ED results as measured *via* PTED in three different frequency ranges and speech perception is described in this chapter. Additionally, the effect of other factors that may affect speech perception with CI (in Chapter 2) is evaluated.

5.1.1 Aims and Hypotheses

The data collected in the first session of the studies described in Chapters 7 and 8 were analysed specifically to look at the association between the estimated ED results obtained from the PTED procedure and the different speech perception measures. Analysis of ED results was conducted using estimates across the entire electrode array (at all frequencies) and in three frequency ranges (≤1000Hz, 1000 Hz - 2600 Hz and >2600Hz). These frequency ranges were chosen because of the different contributions that they have on speech perception (Miller and Nicely, 1955; Shannon et al., 2001; Skinner et al., 1995; Henry et al., 2000; Fourakis et al., 2004 and Fourakis et al., 2007).

Main research hypotheses:

H_1: There will be a correlation between the percentage of discriminable electrodes identified by the PTED test and speech perception with CI (BKB in quiet and in noise and CRM-SRT).

H_2: The correlations with speech perception (BKB in quiet and in noise and CRM-SRT) will be different across the three different frequency regions for the ED results.

H_3: The percentage of discriminable electrodes identified by the PTED especially at frequencies below 1000 Hz test will be a significant predictor of speech perception with CI (BKB in quiet and in noise and CRM-SRT).

Previous studies in the field identifying the number of perceptually distinct CI channels and associating it with speech perception employed direct stimulation and used lengthy procedures. Finding an association between the clinically-viable procedure described in Chapter 3 (PTED) and speech perception would provide further support to PTED's potential functional use.

5.2 Method

5.2.1 Participants

Participants were recruited from the RNTNEH and through the NCIUA.

36 adult CI recipients with acquired deafness were recruited.

The inclusion criteria were that the participants had:

1. A minimum of six months CI experience.
2. An aural-oral mode of communication.
3. English as a first language.

Participants' demographics that were collected were:

(1) Duration of deafness which was calculated for each participant from the date of diagnosis of a bilateral profound sensorineural hearing loss, it ranged from 1 to 53 years. (2) Age at testing ranged between 19 to 83 years with a

mean of 59 years (± 15.86). (3) The aetiology of the hearing loss was unknown in 16 out of the 36 participants. (4) CI experience was calculated from date of switch on of the present implant; it ranged from 8 to 204 months, with a mean of 67 months (± 47) and a median of 57 months. (5) The hearing loss was progressive for all of the participants. (6) Among the participants there were 11 AB, 12 MED-EI™ and 13 Cochlear® CI recipients.

Five participants had a pre or peri-lingual onset of hearing loss (before 5 years old) (participants 3, 4, 9, 26 and 31). Two participants (2 and 7) had a history of cochlear explantation and re-implantation and participant 5 had a “rolled over” electrode tip at insertion. Table (5.1) provides details of participants’ demographics. Participant 34 was excluded due to being diagnosed with dementia.

Table 5.1 Participants' demographic details; duration of deafness was calculated from the date of diagnosis of a bilateral profound sensorineural hearing loss to time of receiving an implant.

Participant	**Aetiology**	**Progressive**	**Age in years**	**Age at implant in years**	**Duration of Deafness in years**	**Implant experience in months**	**Type of implant**
1	Post general anesthesia in 3rd decade	Yes	63	61	12	18	MED-EL™ SONATA$_{TI}^{100}$
2	Unknown	Yes	68	57	19	18	AB HiRes 90K
3	Meningitis at 8months	Yes	53	49	?	48	Nucleus® Freedom
4	Head injury, age 5 years	Yes	56	46	3	120	MED-EL™ PULSAR$_{CI}^{100}$ standard
5	Unknown	Yes	50	48	2	24	AB HiRes 90K
6	Unknown	Yes	65	61	?	48	AB HiRes 90K
7	Hereditary started at age 7 years	Yes	54	44	4	1st implant 24 2nd implant 104	MED-EL™ Tempo+
8	Unknown	Yes	80	78	25	24	MED-EL™ SONATA$_{TI}^{100}$
9	Unknown at age 9mths?	Yes	41	40	15	17	Nucleus® CI 512
10	Endolymphatc Hydrops	Yes	48	47	6	8	Nucleus® CI 512
11	Sickle cell anemia	Yes	24	20	9	48	MED-EL™ PULSAR$_{CI}^{100}$ standard
12	Typhoid and Otosclerosis	Yes	72	61	40+	132	MED-EL™ Combi 40+
13	Unknown	Yes	52	47	?	57	AB HiRes 90K
14	Meniers	Yes	71	70	5	13	MED-EL™ PULSAR$_{CI}^{100}$ standard
15	Unknown	Yes	31	22	15	100	Nucleus® CI 24R(CS)
16	Unknown	Yes	64	52	6	172	Nucleus® 22
17	Measles, age 5 years	Yes	66	59	25	89	MED-EL™ Combi 40+

Table 5.1 (continued) Participants' demographics.

Participant	**Aetiology**	**Progressive**	**Age in years**	**Age at implant in years**	**Duration of Deafness in years**	**Implant experience in months**	**Type of implant**
18	Unknown	Yes	75	70	1	57	MED-EL™ PULSAR$_{CI}^{100}$ standard
19	Unknown	Yes	78	64	53	168	Nucleus® 22
20	Hereditary	Yes	62	57	6	62	AB HiRes 90K
21	Unknown	Yes	63	57	5	60	MED-EL™ PULSAR$_{CI}^{100}$ standard
22	Unknown	Yes	64	51	33	153	MED-EL™ Combi 40+
23	Unknown	Yes	71	69	9	25	MED-EL™ Combi 40+
24	Noise induced and otosclerosis	Yes	83	72	40+	123	Nucleus® CI 24M
25	Genetic started at age 20 years	Yes	77	73	7	48	AB HiRes 90K
26	Measles, age 5.5 years	Yes	62	57	6	62	Nucleus® CI 24R(CS)
27	Typhoid	Yes	27	15	5	144	AB CI
28	Unknown	Yes	67	66	?	12	Nucleus® CI 512
29	Genetic started at age 40 years	Yes	59	60	7	72	Nucleus® CI 24R(CS)
30	Endolymphatic Hydrops	Yes	42	39	1	34	Nucleus® Freedom (CA)
31	Genetic	Yes	19	2	1	204?	Nucleus® 22
32	Unknown	Yes	60	56	?	42	AB HiRes 90K
33	Otosclerosis	Yes	69	63	7	71	Nucleus® Freedom
34	Genetic	Yes	71	67	10	45	AB HiRes 90K
35	Unknown	Yes	69	63	12	38	Nucleus® Freedom (CA)
36	Otosclerosis	Yes	67	58	2	106	AB HiRes 90K

5.2.2 Test battery

The PTED (described in Section 3.2.2.2) in addition to three speech perception measures were used in testing, the CRM (described in Section 4.2.2) and the BKB sentence test in quiet and in speech-shaped noise at a 10dB SNR (signal-to-noise ratio).

BKB sentence test

The Bamford Kowal Bench (BKB) sentence test (Bench, Kowal, and Bamford, 1979) had 20 possible lists, each containing 16 sentences and 50 key words. The sentences were presented by a male speaker at a level of 70dBA, and participants were asked to repeat the sentences and the number of key words correct was scored. It was administered in quiet for all participants and was also administered in speech-spectrum shaped noise at a SNR of +10dB if the participant's BKB score in quiet was higher than 50%. Two sentences were presented per condition and participants never received the same list twice.

5.2.3 Procedure

Testing took place in a 3.7×3.25 m double-walled sound booth where the participant was seated 1 metre in front of an ear level loud speaker (Plus XS.2, Canton) from which the speech and noise were presented. The stimuli were stored (16 bits), sampling rate (44.1 KHz) presented digitally using the AB-York Crescent of Sound (Kitterick et al., 2011).

For CRM the participants responded using a touch screen monitor and the software ran the test presentation and scoring in an automated fashion as the SNR varied adaptively. During BKB testing, the tester entered the participants’ verbal response by selecting the correct key words on the tester’s monitor.

All participants underwent BKB and PTED testing, CRM SRTs were measured for 19 out of the 35 participants. CRM was added to the testing protocol once the test-retest reliability had been established, it was necessary to incorporate the test because some participants were achieving scores falling within the ceiling range for BKB scores in quiet and in noise. All testing took place in one session with the same CI program which had been used by the participant for a minimum of two months prior to testing.

5.3 Analyses

BKB scores were converted to rationalized arcsine-transform units (RAU) before conducting statistical analysis (Studebaker, 1985) to reduce the impact of floor and ceiling effects. Percentage of discriminable electrode pairs was calculated for each participant using the same pass/fail criteria described in Chapter 3 (Section 3.2.3.2) to categorise all tested electrode pairs *via* the PTED for each participant. This was done to establish the percentage of discriminable electrode pairs for all tested frequencies (overall percentage) and for the frequency ranges (1) frequencies ≤ 1000 Hz, (2) 1000 Hz < frequencies ≤ 2600 Hz (3) frequencies > 2600Hz. For each participant AAI (see Section 2.1.1) was categorised as younger than or older than 65 years (similar to Friedland et al., 2010) and duration of deafness (see Section 2.1.3) was categorised to less than or equal to 15 years and more than 15 years. The aetiology of deafness (see Section 2.1.4) was categorised to either causing possible cochlear pathological changes such as fibrosis or calcification (e.g., meningitis might cause ossification) or aetiology that is not associated with such cochlear pathological changes. The presence or absence of cochlear pathology that could be detected by radiological evaluation (fibrosis, ossification or calcification) was also determined based on radiological evidence (e.g. fibrosis following explantation of a CI before re-implantation) for all participants.

The statistical analysis was conducted to assess the following:

1. Whether there was a correlation between PTED's overall percentage of discriminable electrode pairs for the entire array and speech perception (BKB in quiet and in noise and CRM SRT).
2. Whether there was a correlation between PTED's percentage of discriminable electrode pairs within different frequency bands (≤1000Hz, 1000 Hz - 2600 Hz and >2600Hz) and speech perception (BKB in quiet and in noise and CRM-SRT).
3. Whether there is a significant correlation between PTED's percentage of discriminable electrode pairs at all frequencies (overall percentage) and at each frequency band and CRM-SRT (lower thresholds indicate better results).
4. Whether the percentage of discriminable electrode pairs for the entire array and within different frequency bands (≤1000Hz, 1000 Hz - 2600 Hz and >2600Hz), AAI, duration of deafness, aetiology of deafness or presence of confirmed cochlear pathology can be used to predict speech perception (BKB in quiet and in noise and CRM-SRT).

IBM SPSS STATISTICS 21 for windows was used to carry out the analyses. Shapiro Wilk's test revealed that BKB (RAU) scores in quiet and noise and CRM SRT were normally distributed. It also revealed that PTED scores were normally distributed for the group of 20 participants tested with CRM and for the groups of 29 and 36 tested with BKB (RAU) scores in quiet and noise respectively. Hence Pearson's correlation coefficient was used to determine the relationship between speech perception measures [BKB (RAU) scores in quiet and noise and CRM-SRT] and PTED.

Stepwise multiple regression was used with each of the speech perception measures separately [BKB (RAU) scores in quiet and in noise and CRM] as the dependent variable and the percentage of discriminable electrode pairs for the entire array and within different frequency bands, the AAI, the duration of deafness, the aetiology of deafness and the presence of confirmed cochlear pathology as the independent variables. See Appendix C for data used in analyses.

5.4 Results

The results of the PTED test and the three speech perception tests are shown in Table (5.2) and Figure (5.1). Among the 20 participants, only one participant had a CRM SRT at a negative SNR, representing only 5% of the tested CI population. Performance on 'BKB in quiet' was better than 'BKB in noise'.

Table 5.2 Results of the PTED, BKB (RAU) scores in quiet and in noise and the CRM SRT. Percentage of discriminable electrode pairs reported for PTED, RAU of percentage correct key words reported for BKB (range -23 to +123) and CRM SRT are reported in dBA. The descriptive statistics are the 25th percentile (Q_1), the 50th percentile (median), the 75th percentile (Q_3) and the number of participants contributing the data (N).

Test	Q_1	Median	Q_3	N
PTED	64.16	81.08	100	35
BKB in quiet	68.75	79.41	90.91	35
BKB in noise	48.14	72.21	87.36	29
CRM SRT in dBA	1.45	5.7	9	19

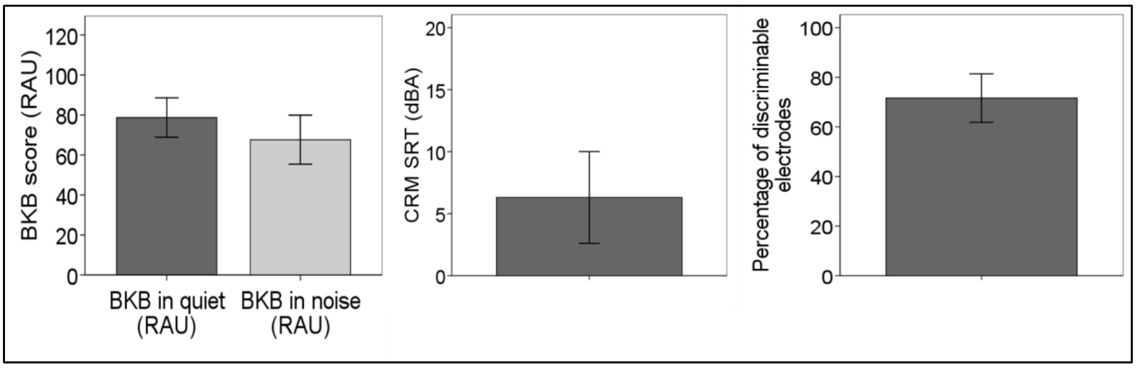


Figure 5.1 Results of the BKB tests in quiet and in noise in rationalized arcsine-transform units (RAU), the CRM SRT in dBA and the percentage of discriminable electrodes. The bars represent mean scores and the error bars show 95% confidence intervals.

There was a significant relationship between the percentage of discriminable electrode-pairs and all speech perception measures, which was strong with 'BKB in quiet' (Pearson's r = 0.6, $p < 0.001$, N=35) (Figure 5.2) very strong with 'BKB in noise' (Pearson's r = 0.74, $p < 0.001$, N=29) (Figure 5.3) and very strong with CRM SRT (Pearson's r = -0.74, $p < 0.001$, N=20) (Figure 5.4). The hypothesis H_1 was accepted and a positive correlation was found between the percentage of discriminable electrode-pairs and all speech perception measures.

See Table (5.3) for correlation results between PTED's percentage of discriminable electrode pairs at each frequency range and each speech perception measure. 'BKB in noise' significantly correlated with the percentage of discriminable electrode-pairs at all frequency ranges however 'BKB in quiet' and CRM SRT significantly correlated with the percentage of discriminable electrode-pairs at the low to mid frequency ranges (≤1000Hz, 1000 Hz - 2600 Hz) but not with the percentage of discriminable electrode-pairs at the higher frequency range (>2600Hz). Thus the H_2 was accepted for 'BKB in quiet' and CRM SRT but not for 'BKB in noise'.

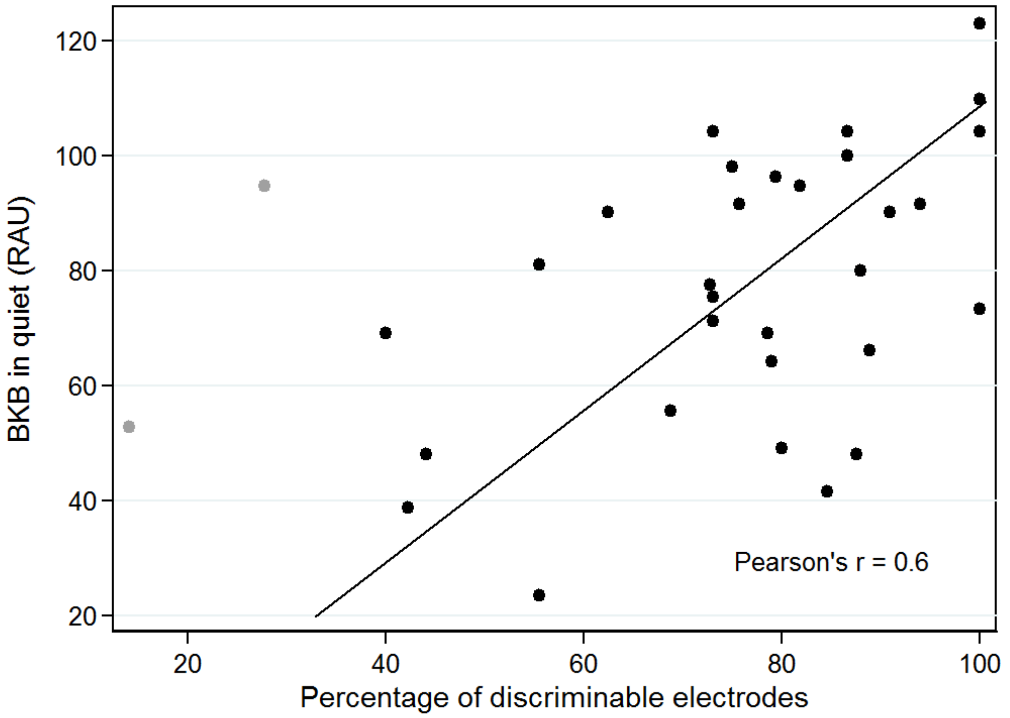


Figure 5.2 The relationship between BKB scores in quiet (RAU) and the PTED's percentage of discriminable electrodes. BKB scores in quiet (RAU) on the y axis versus PTED's percentage of discriminable electrode pairs on the x axis showing a moderate positive relationship. Without the outliers, the Pearson's r = 0.6 *p* < 0.001, N=33.

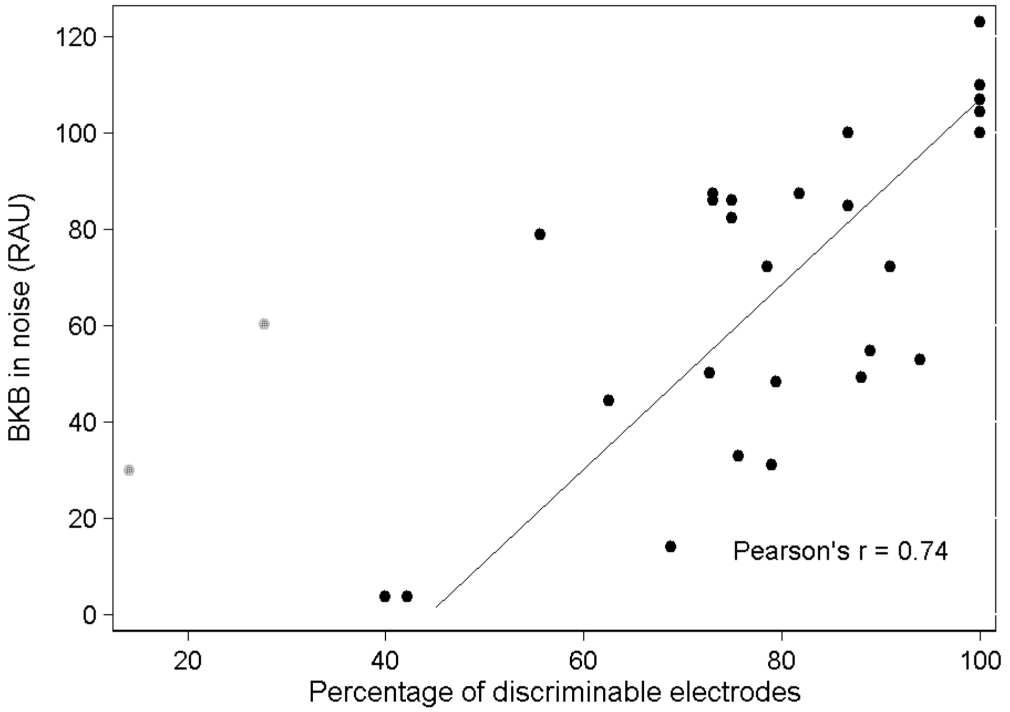


Figure 5.3 The relationship between BKB scores in noise (RAU) and the PTED's percentage of discriminable. BKB scores in noise (RAU) on the y axis versus PTED's percentage of discriminable electrode pairs on the x axis showing a strong positive relationship. Outliers are shown in grey. Without the outliers, the Pearson's r = 0.74 *p* < 0.001, N=27.

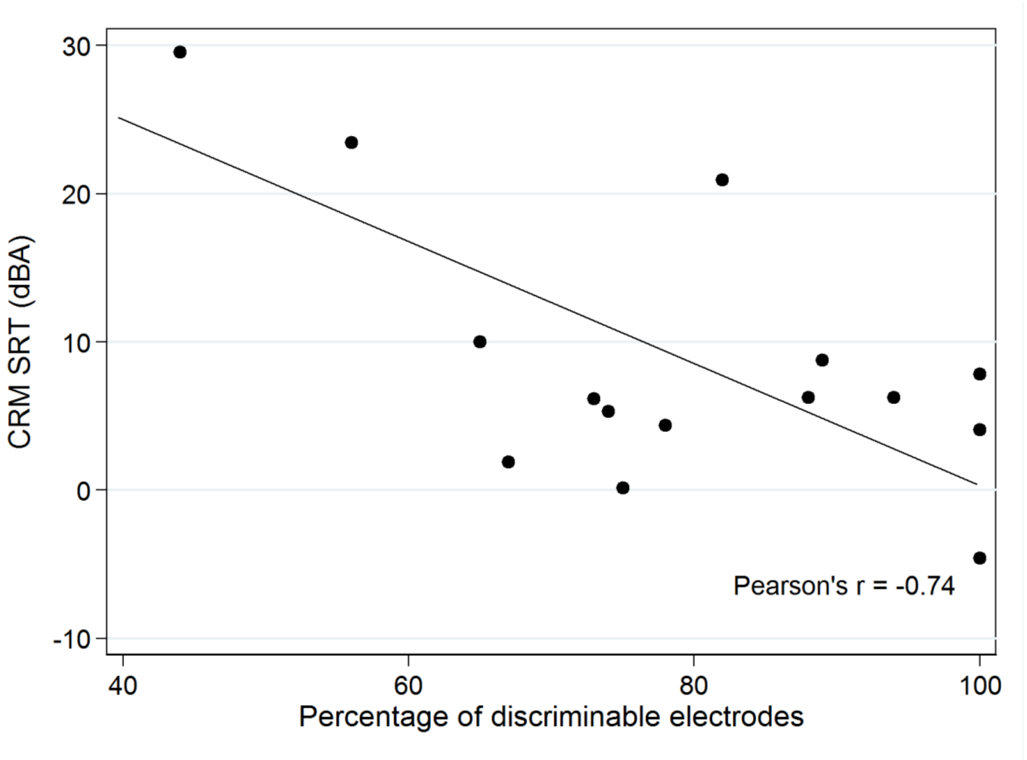


Figure 5.4 The relationship between CRM SRT and the PTED's percentage of discriminable. CRM SRT on the y axis versus PTED's percentage of discriminable electrode pairs on the x axis showing a strong negative relationship between the CRM SRTs across sessions.

Table 5.3 Correlation results between PTED's percentage of discriminable electrode pairs at each frequency range [(1) frequencies ≤ 1000 Hz, (2) 1000 Hz < frequencies ≤ 2600 Hz (3) frequencies > 2600Hz and (4) all frequencies] and each speech perception measure (BKB in quiet and in noise and CRM).

Percentage discriminable electrodes at	BKB in quiet Pearson's		BKB in noise Pearson's		CRM SRT Pearson's	
	r	*p*	r	*p*	r	*p*
Frequencies≤1000Hz	0.6**	< 0.001	0.65**	< 0.001	-0.67**	< 0.005
1000 Hz < frequencies ≤ 2600 Hz	0.58**	< 0.001	0.61**	< 0.001	-0.51*	< 0.05
Frequencies >2600Hz	0.12	0.5	0.49**	< 0.005	-0.28	0.25
All frequencies	0.6**	< 0.001	0.74**	< 0.001	-0.74**	< 0.001

5.4.1 Results of multiple regression models

5.4.1.1 Results of multiple regression models using overall percentage of discriminable electrode pairs as a potential predictor

Stepwise multiple regression analyses were carried out to determine the predictors for ‘BKB in quiet’ (RAU), ‘BKB in noise’ (RAU) and CRM SRT. Factors were added to each model one at a time starting with the best predictor followed by the second best predictor and so on. The emphasis was on finding the best predictors at each stage and the model was tested for significance at each stage. Factors were added to maximize the Pearson r coefficient and the goodness of fit of the model (ANOVA analysis). If two predictors were highly correlated with each other and with the dependent variable, often only one variable was chosen as a predictor in the model and the other variable was not. This indicated that the latter variable did not provide additional contribution to the model.

For ‘BKB in quiet’ (RAU), the independent variables entered were: the percentage of discriminable electrodes for the full electrode array, the presence of pathology, the AAI, the duration of deafness (as a categorical and as a continuous variable) and the aetiology of deafness (as a categorical and as a continuous variable). The only predictors reaching significance level were the percentage of discriminable electrodes and the presence of pathology. The prediction model contained these two predictors and was reached in two steps. The model was statistically significant, F(2, 28) = 15.03, $p < .01$, and accounted for approximately 48% of the variance of ‘BKB in quiet’ (RAU) ($R^2 = 0.52$, Adjusted $R^2 = 0.48$). ‘BKB in quiet’ (RAU) was primarily predicted by the percentage of discriminable electrodes and to a lesser extent by the presence of pathology. The raw and standardized regression coefficients of the predictors are shown in Table (5.4). All other variables (the AAI, the duration of deafness and the aetiology of deafness) were non-significant predictors. The AAI and the duration of deafness were non-significant when included as continuous or categorical variables.

Table 5.4 Results of step-wise multiple linear regression: the dependent variable was BKB score in quiet. The value of the adjusted R^2 for the model was 0.48 ($p < 0.01$).The unstandardised regression coefficient, B (with 95% confidence interval c.i. in parentheses, which indicate that the true coefficient of the predictor falls in this range at a 95% confidence level), and the standardised regression coefficient *β*, are listed for each significant variable in the model.

Dependent variable	*B* (95% c.i.)	*β*	*p*
Percentage discriminable electrode-pairs	0.85 (0.49 to 1.2)	0.65	< 0.001
Pathology	28.58(9.33 to 47.84)	0.40	< 0.01

For ‘BKB in noise’ (RAU), the independent variables entered were: the percentage of discriminable electrodes for the full electrode array, the presence of pathology, the AAI, the duration of deafness (as a categorical and as a continuous variable) and the aetiology of deafness (as a categorical and as a continuous variable). The only predictor reaching significance level was the percentage of discriminable electrodes. The prediction model was statistically significant, F(1, 24) = 26.95, $p < .001$, and accounted for approximately 51% of the variance of ‘BKB in noise’ (RAU) ($R^2 = 0.53$, Adjusted $R^2 = 0.51$). ‘BKB in noise’ (RAU) was predicted by the percentage of discriminable electrodes. The raw and standardized regression coefficients of the predictors are shown in Table (5.5). All other variables (the presence of pathology, the AAI, the duration of deafness and the aetiology of deafness) were non-significant predictors. The AAI and the duration of deafness were non-significant when included as continuous or categorical variables.

Table 5.5 Results of step-wise multiple linear regression: the dependent variable was BKB score in noise. The value of the adjusted R^2 for the model was 0.51 ($p < 0.001$).The unstandardised regression coefficient, B (with 95% confidence interval c.i. in parentheses, which indicate that the true coefficient of the predictor falls in this range at a 95% confidence level), and the standardised regression coefficient *β*, is listed for each significant variable in the model.

Dependent variable	*B* (95% c.i.)	*β*	*p*
Percentage discriminable electrode-pairs	1.15 (0.69 to 1.6)	0.73	< 0.001

For CRM SRT, the independent variables entered were: the percentage of discriminable electrodes for the full electrode array, the presence of pathology, the AAI, the duration of deafness (as a categorical and as a continuous variable) and the aetiology of deafness (as a categorical and as a continuous variable). The only predictors reaching significance level were the percentage of discriminable electrodes and the AAI (as a categorical variable). The prediction model contained these two predictors and was reached in two steps. The model was statistically significant, F(2, 12) = 15.65, $p < 0.005$, and accounted for approximately 68% of the variance of CRM SRT ($R^2 = 0.72$, Adjusted $R^2 = 0.677$). CRM SRT was primarily predicted by the percentage of discriminable electrodes and to a lesser extent by the AAI categorical variable. The raw and standardized regression coefficients of the predictors are shown in Table (5.6). All other variables (the presence of pathology, the duration of deafness and the aetiology of deafness) were non-significant predictors. The duration of deafness was non-significant when included as continuous or categorical variables.

Table 5.6 Results of step-wise multiple linear regression: the dependent variable was CRM SRT. The value of adjusted R^2 for the model was 0.68 ($p < 0.005$).The unstandardised regression coefficient, B (with 95% confidence interval c.i. in parentheses, which indicate that the true coefficient of the predictor falls in this range at a 95% confidence level), and the standardised regression coefficient *β*, is listed for the only significant variable in the model.

Dependent variable	*B* (95% c.i.)	*β*	*p*
Percentage discriminable electrode-pairs	-0.51 (-0.71 to -0.3)	-0.85	< 0.001
AAI	8.84 (1.06 to 16.61)	0.39	< 0.05

5.4.1.2 Results of multiple regression models using the percentage of discriminable electrode pairs at each frequency band as a potential predictor

Stepwise multiple regression analyses were carried out to determine the predictors for ‘BKB in quiet’ (RAU), ‘BKB in noise’ (RAU) and CRM SRT. Factors were added to each model one at a time starting with the best predictor followed by the second best predictor and so on. The emphasis was on finding the best predictors at each stage and the model was tested for significance at each stage. Factors were added to maximize the Pearson r coefficient and the goodness of fit of the model (ANOVA analysis). If two predictors were highly correlated with each other and with the dependent variable, often only one variable was chosen as a predictor in the model and the other variable was not. This indicated that the latter variable did not provide additional contribution to the model.

For ‘BKB in quiet’ (RAU), the independent variables entered were: the percentage of discriminable electrodes within each of different frequency bands (≤1000Hz, 1000 Hz - 2600 Hz and >2600Hz), the presence of pathology, the AAI, the duration of deafness (as a categorical and as a continuous variable) and the aetiology of deafness (as a categorical and as a continuous variable). The only predictors reaching significance level were the percentage of discriminable electrodes at the lower frequency range (≤ 1000 Hz) and the presence of pathology. The prediction model contained these two predictors and was reached in two steps. The model was statistically significant, F(2, 28) = 16.35, $p < .001$, and accounted for approximately 51% of the variance of ‘BKB in quiet’ (RAU) ($R^2 = 0.54$, Adjusted $R^2 = 0.51$). ‘BKB in quiet’ (RAU) was primarily predicted by the percentage of discriminable electrodes at the lower frequency range (≤ 1000 Hz) and to a lesser extent by the presence of pathology. The raw and standardized regression coefficients of the predictors are shown in Table (5.7). All other variables [discriminable electrodes at the mid and at the high frequency range (> 1000 Hz and > 2600 Hz respectively), AAI, duration of deafness and aetiology of deafness] were non-significant predictors. AAI and duration of deafness were non-significant when included as continuous or categorical variables. H_3 was accepted for ‘BKB in quiet’ because the percentage of discriminable electrodes especially at the lower frequency range (≤ 1000 Hz) was a significant predictor of ‘BKB in quiet’.

Table 5.7 Results of step-wise multiple linear regression: the dependent variable was BKB score in quiet. The value of the adjusted R^2 for the model was 0.51 ($p < 0.001$).The unstandardised regression coefficient, B (with 95% confidence interval c.i. in parentheses, which indicate that the true coefficient of the predictor falls in this range at a 9 5% confidence level), and the standardised regression coefficient β, are listed for each significant variable in the model.

Dependent variable	*B* (95% c.i.)	β	*p*
Percentage discriminable electrode-pairs at the low frequency range (≤ 1000 Hz)	0.56 (0.34 to 0.79)	0.67	< 0.001
Pathology	27.65 (8.87 to 46.43)	0.39	< 0.005

For ‘BKB in noise’ (RAU), the independent variables entered were: the percentage of discriminable electrodes within each of different frequency bands (≤1000Hz, 1000 Hz - 2600 Hz and >2600Hz), the presence of pathology, the AAI, the duration of deafness (as a categorical and as a continuous variable) and the aetiology of deafness (as a categorical and as a continuous variable). The only predictor reaching significance level was the percentage of discriminable electrodes at the lower frequency range (≤ 1000 Hz). The prediction model was statistically significant, F(1, 24) = 19.39, $p < .001$, and accounted for approximately 42% of the variance of ‘BKB in noise’ (RAU) ($R^2 = 0.45$, Adjusted $R^2 = 0.42$). ‘BKB in noise’ (RAU) was predicted by the percentage of discriminable electrodes at the lower frequency range (≤ 1000 Hz). The raw and standardized regression coefficients of the predictors are shown in Table (5.8).

All other variables [the percentage of discriminable electrodes at the mid and at the high frequency range (> 1000 Hz and > 2600 Hz respectively), the presence of pathology, the AAI, the duration of deafness and the aetiology of deafness] were non-significant predictors. The AAI and the duration of deafness were non-significant when included as continuous or categorical variables. H_3 was accepted for ‘BKB in noise’ because the percentage of discriminable electrodes especially at the lower frequency range (≤ 1000 Hz) was a significant predictor of ‘BKB in noise’.

Table 5.8 Results of step-wise multiple linear regression: the dependent variable was BKB score in noise. The value of the adjusted R^2 for the model was 0.42 ($p < 0.001$).The unstandardised regression coefficient, B (with 95% confidence interval c.i. in parentheses, which indicate that the true coefficient of the predictor falls in this range at a 95% confidence level), and the standardised regression coefficient *β*, is listed for each significant variable in the model.

Dependent variable	*B* (95% c.i.)	*β*	*p*
Percentage discriminable electrode-pairs at the low frequency range (< 1000 Hz)	0.79 (0.42 to 1.15)	0.67	< 0.001

For CRM SRT, the independent variables entered were: the percentage of discriminable electrodes within each of different frequency bands (≤1000Hz, 1000 Hz - 2600 Hz and >2600Hz), the presence of pathology, the AAI, the duration of deafness (as a categorical and as a continuous variable) and the aetiology of deafness. The only predictors reaching significance level were the percentage of discriminable electrodes at the lower frequency range (≤ 1000 Hz). The model was statistically significant, F(1, 13) = 9.196, $p = 0.01$, and accounted for approximately 37% of the variance of CRM SRT ($R^2 = 0.41$, Adjusted $R^2 = 0.37$). CRM SRT was primarily predicted by the percentage of discriminable electrodes at the lower frequency range (≤ 1000 Hz). The raw and standardized regression coefficients of the predictors are shown in Table (5.9). All other variables [the percentage of discriminable electrodes at the mid and at the high frequency range (> 1000 Hz and > 2600 Hz respectively), the presence of pathology, the AAI, the duration of deafness and the aetiology of deafness) were non-significant predictors. The AAI and the duration of deafness were non-significant when included as continuous or categorical variables. H_3 was accepted for 'CRM SRT' because the percentage of discriminable electrodes especially at the lower frequency range (≤ 1000 Hz) was a significant predictor of 'CRM SRT'.

Table 5.9 Results of step-wise multiple linear regression: the dependent variable was CRM SRT. The adjusted value of R^2 for the model was 0.37 (p < 0.05).The unstandardised regression coefficient, B (with 95% confidence interval c.i. in parentheses, which indicate that the true coefficient of the predictor falls in this range at a 95% confidence level), and the standardised regression coefficient *β*, is listed for the only significant variable in the model.

Dependent variable	*B* (95% c.i.)	*β*	*p*
Percentage discriminable electrode-pairs at the low frequency range (≤ 1000 Hz)	-0.18 (-0.3 to -0.05)	-0.64	< 0.01

5.5 Discussion

There was great variability in the speech perception scores for CI recipients which was reflected in the results of our participants' BKB scores and CRM SRTs, this is in line with previous reports by other research groups (see Chapter 2; e.g. Wiltzman et al., 1995; Blamey et al., 1992; Summerfield and Marshall, 1995 and Friedland et al., 2010). There was also a large variability in the participants' performance on the PTED pitch ranking task, ranging from perfect scores (100%) to extremely poor (24%) indicating that more than a third of the electrodes in the CI electrode array were affected, consistent with previous studies (reported in Section 2.3; e.g. Nelson et al., 1995; Zwolan et al., 1997; Henry et al., 2000).

The CI recipients' performance on the speech perception measures were consistent with previous reports, BKB in quiet scores were better than BKB in noise. Understanding BKB sentences in noise requires the CI recipient to receive the sound with a higher spectral resolution; thus the decrease in performance (e.g. Friesen et al., 2001).

In line with the data in Chapter 4, the majority (95%) of the CI population tested had a CRM SRT at a positive SNR (above 0 dB).

In accordance to earlier studies (Collins et al., 1997; Henry et al., 1997; Nelson et al., 1995 and Dawson et al., 2000), there was a positive relationship between speech perception and the number of perceptually distinct channels stimulated by the CI (H_1 was accepted). The PTED procedure was able to define pitches that could not be discriminated which more likely corresponded to channels that were indistinguishable; hence there was a positive relationship between the number of discriminable electrode pairs and speech recognition scores. This is also in line with Friesen et al. (2001) who reported that CI performers with good speech perception were able to utilise more channels of spectral resolution than poor CI performers, although there might be some dispute on what the limit of channels that the CI recipient can utilise (discussed in Section 2.3.1).

When evaluating the relationship between PTED results at the different frequency ranges (low, mid and high) and speech perception, results were in accordance to previous studies (e.g. Miller and Nicely, 1955 and Shannon et al., 2001; Skinner et al., 1995; Henry et al., 2000; Fourakis et al., 2004 and Fourakis et al., 2007). The association between speech perception as measured *via* BKB in quiet and CRM and the proportion of discriminable electrodes was significant at low and mid frequency range (≤ 2600 Hz) but not at the higher frequency range (> 2600 Hz). This reflects the importance of the lower frequency range (≤ 2600 Hz) to speech perception in comparison to the higher frequency range (e.g. Miller and Nicely, 1955 and Shannon et al., 2001). It’s also in line with (Skinner et al., 1995; Henry et al., 2000; Fourakis et al., 2004 and Fourakis et al., 2007) who found that the CI recipient requires a larger number of electrodes in the lower frequency region; hence a larger proportion of discriminable electrodes in that region (≤ 2600 Hz) was associated with better BKB in quiet and CRM. This concurs with Henry et al. (2000) where a significant association between the ability to discriminate electrodes and the amount of speech information perceived was found in the frequency range in frequencies 170Hz – 2680 Hz but not in the higher frequency range > 2680 Hz.

For good speech perception a larger number of discriminable electrodes is required in the lower frequency range (≤ 2600 Hz) in comparison to higher frequencies (>2600 Hz). This region requires higher spectral resolution not only because it provides vowel formant information but also because it provides information of phonemic voicing, nasal and place of articulation features (e.g. Miller and Nicely, 1955). The region of the first formant (≤ 1000 Hz) is also particularly important for nasal and voicing cues (e.g. Miller and Nicely, 1955). The region (≤ 2600 Hz) is critical for detecting formant transitions, which are acoustic cues involving rapidly changing spectral patterns (Munson and Nelson, 2005). Formant transitions were found to be the most vulnerable speech feature to degradation in noise among CI users (Munson and Nelson, 2005). Additionally the perception of place of articulation for plosives, fricatives and affricates and of the voicing feature is also at least in part dependent on vowel formant transitions (e.g. Cooper et al., 1952; Benki, 2001 and Hedrick and Carney, 1997). Frication (manner of articulation feature) is the only phonemic feature that relies on information usually solely provided by the higher frequency region (> 1000 Hz) spreading up to 8 to 10 kHz. But the detection of “random noise” above 1 kHz is sufficient to perceive this phonemic feature and unlike other phonemic features does not require high spectral resolution (Wright, 1997).

The association between the proportion of discriminable CI electrode pairs and speech perception was stronger for BKB in noise than in quiet, which is most likely due to BKB in noise test’s increased demand for spectral resolution (e.g. Qin and Oxenham and Fu and Nogaki, 2004). This higher demand for spectral resolution was also reflected in the association between BKB in noise and the proportion of discriminable electrodes at different frequency ranges (low, mid and high). Again, this supports the idea that the percentage of discriminable electrodes reflects the degree of spectral resolution that a CI recipient has. This could be related to neuronal survival, electrode placement issues or other device related issues (see Section 2.3).

Results of the multiple regressions showed a similar picture; the PTED's percentage of discriminable electrodes not only correlated with all speech perception measures used, it was the main significant predictor in all models (H_3 was accepted). With the use of the overall discriminable electrodes at all frequencies, the models predicted over 50 % and reaching up to 66 % of the variance in the speech perception measures used (BKB in quiet, in noise and CRM). With the use of the percentage of discriminable electrode pairs at each frequency band in step-wise multiple regression, the models predicted over 41 % and reaching up to 53 % of the variance in the speech perception measures used (BKB in quiet, in noise and CRM). Results showed that the percentage of discriminable electrodes at the low frequency range ($\leq$ 1000 Hz) was the only significant predictor for CRM and BKB in noise and was the main significant predictor for BKB in quiet. Findings of multiple regression testing emphasize the expected importance of low frequency range contribution to speech perception (e.g. Miller and Nicely, 1955; Shannon et al., 2001; Skinner et al., 1995; Henry et al., 2000; Fourakis et al., 2004 and Foukaris et al., 2007). Other contributing variables to the models included the presence of pathology for predicting BKB in quiet, which is consistent with studies evaluating the effect of aetiology on CI performance and found that pathological changes such as calcification led to decreased performance (Cohen and Waltzman, 1993; Hartrampf et al., 1995; Rotteveel et al., 2005 and Rotteveel et al., 2010). This finding is also in agreement with Nadol and Hsu (1991) who reported a negative correlation between calcification and spiral ganglion cell count. The interesting finding here is that pathology (as defined in Section 5.3) did not only include cases of pathological changes (ossification, calcification and fibrosis) to the cochlea secondary to aetiology of the hearing loss but also included cases of confirmed fibrosis following device failure and infection. Despite reports of comparable results for CI performance before and after explantation and reimplantation (e.g. Saeed et al., 1995; Alexiades et al., 2001; Parisier et al., 2001 and Cote et al., 2007) pathological changes such as fibrosis may have a negative impact on performance. In our test population, the presence of fibrosis was confirmed for two participants who had an infection that prevented re-implantation at the time of explantation and caused partial insertion of the CI array for one of them. Evidence suggests that the presence of pathology is a more important factor affecting performance than either aetiology or explantation-reimplantation on its own.

When the percentage of discriminable electrodes in each frequency range was considered as an independent potential predictor, the AAI was a significant predicting factor for CRM SRT, this is in line with previous findings (Waltzman et al.,1995; Gantz et al., 1993; Blamey et al., 2013; Chatelin et al., 2004; Friedland et al., 2010 and Lenarz et al., 2012) who found an AAI effect on CI performance. The presence of an AAI effect on CRM SRT only and not BKB scores could be due to the relative small number of participants and the nature of speech-on-speech masking in CRM. Speech-on-speech masking was reported to be more detrimental for older listeners (over 60 years) as compared to younger listeners making the effect for the AAI larger in CRM than BKB in quiet or in noise (e.g. Helfer et al., 2010 and Helfer and Freyman, 2008).

These findings indicated that having indiscriminable electrodes can affect speech perception with CIs. This in return provided further support to the potential importance of research actively searching for problematic electrodes in CIs with the goal of improving performance (e.g. Zwolan et al., 2007 and Zhou and Pfingst, 2012).

5.6 Conclusion

Results of this present study are in concordance with previous studies. CI recipients showed better performance in quiet than in noise. A relationship was found between PTED's results especially in the lower frequency range (≤ 2600 Hz) and the various measures of speech perception and the percentage of discriminable electrodes especially at lower frequencies (≤ 1000 Hz) was a significant predictor of speech perception. It also indicated that PTED -being a clinically viable test- potentially has a clinically relevant function to speech perception with CI.

5.7 Summary

- CI recipients showed better performance in quiet than noise.
- The majority of CI recipients had CRM SRTs at positive SNR.
- There was a positive association between percentage of discriminable electrode pairs as identified *via* PTED and all speech perception measures used (BKB in quiet and in noise and CRM).
- The strongest association between PTED and speech perception was found when speech testing took place in noise; test requirement for higher spectral resolution might be the reason.
- Having a larger proportion of discriminable electrodes at the lower frequency range (≤ 2600 Hz) was more important for speech perception than it was at the higher frequency range.
- Results provide further evidence validating the PTED as a clinical tool with functional potential that relates to speech perception with CI.

Chapter 6

The relationship between CI electrode array placement, electrode differentiation and speech perception

Abstract

This chapter describes a study that evaluates the association between scalar electrode array placement, the angular depth of array insertion, pure-tone electrode differentiation (PTED) results and speech perception. The outcome measures were BKB in quiet, BKB in noise and CRM. 16 individuals were evaluated for angular depth of insertion. Statistically significant correlations were found for BKB in quiet (Pearson’s r = 0.57*, $p < 0.05$) and BKB in noise (Pearson’s r = 0.71**, $p < 0.01$). No correlation was found with ED in the most apical electrodes. In addition the characteristic frequency of the most apical electrode was estimated and the “frequency shift” was calculated as the difference between the characteristic frequency and the centre frequency of the filter assigned to the corresponding electrode. Strong correlations were found for BKB in noise (Pearson’s r = -0.63*, $p < 0.05$) but not for BKB in quiet. These results indicate the positive effect of increased angular depth of insertion may at least be in part due to the frequency shift. Cone beam computed tomography (CBCT) provides high quality images that in this study allowed two highly experienced physicians to identify in-vivo scalar-placement of electrode arrays in nine implanted individuals. A significant correlation was not found between scalar placement in the scala tympani (ST) versus scala vestibuli (SV) with speech perception or between scalar-placement of each electrode with ED for the corresponding electrodes. However PTED results of electrodes at inter-scalar cross-over points between ST and SV showed pitch confusion. This indicated that PTED identified dead regions at points of inter-scalar cross-over. The lack of

correlation between PTED results and scalar-placement in this study population may also indicate the absence of trauma associated with SV placement.

6.1 Introduction

As discussed in the literature review in Chapter 2 (Section 2.2), the CI electrode design and the surgical insertion of the electrode array may affect post-implantation outcome (e.g. Aschendorff et al., 2007 and Finley and Skinner, 2008). Depth of insertion and scalar placement of the CI array might be factors that affect speech perception with CI. Although some researchers reported adverse effects of deeper insertions (Gani et al., 2007 and Finley and Skinner, 2008), it was also associated with poor ED of the apical electrode. Only two studies investigated the effect of scalar placement of the individual electrodes into the scala vestibuli (SV) versus the scala tympani (ST) (Aschendorff et al., 2007 and Finley and Skinner, 2008), but they did not investigate the relationship between scalar placement and ED. PTED results along with radiological imaging can shed some light on the effect of array placement (depth of insertion and scalar placement) on ED and speech perception with CI.

Deep insertion had been advocated by some researchers in order to widen the range of stimulated frequencies in the cochlea (e.g. Hochmair et al., 2003) and to match the stimulated frequency of the electrical signal and the normal tonotopic organisation of the cochlea (e.g. Baskent and Shannon, 2003 and 2005). However, associated with this is an increased possibility of insertion trauma (e.g. Finley and Skinner, 2008; Adunka et al., 2006 and Wardrop et al., 2005a) and the loss of frequency specificity due cross-turn stimulation as demonstrated by poor ED of the apical electrodes (Gani et al., 2007 and Finley and Skinner, 2008) may indicate the need to accomplish a balance between a sufficient depth of insertion and the avoidance of trauma. Another issue that has been evaluated was the scalar positioning of the array

(Skinner et al., 2007 and Finley and Skinner, 2008). Since the deliberate insertion into the SV in certain cases has been reported to produce comparable results to insertion into the ST (Barrettini et al., 2002; Kiefer et al., 2000 and Lin, 2009) it is stipulated that underlying mechanical damage to the spiral ganglion in cases of inter-scalar cross over (from ST to SV) may be the reason for the decreased performance reported by Finley and Skinner (2008) when the electrodes were placed in SV. Aschendorff et al., (2007) reported a significant difference in speech perception between intentional ST and unintentional SV array placement which they attributed to the difference not only in scalar placement but due to the trauma associated with insertion. Finley and Skinner (2008) also reported poor ED at the apical electrodes associated with positioning them in SV. Thus the evaluation of CI array positioning in the cochlea and its effect on performance may further inform surgical techniques and future CI electrode array design (e.g. Aschendorff et al., 2007). This is one of the drivers behind the development of imaging techniques that provide high quality images to allow adequate evaluation without artefacts while maintaining safety (relatively low radiation) and controlling for cost. CBCT has been suggested as an alternative to multiple slice CT (MSCT) in the field of otorhinolaryngology for the management of the hearing impaired (Gupta et al., 2004; Bartling et al., 2006; Rafferty et al., 2006; Faccioli et al., 2009; Hodez et al., 2011). It also has been evaluated for pre-cochlear implantation assessment (Barker et al., 2009) and for post-implantation assessment of the CI electrode array position in the cochlea (Gupta et al., 2004; Bartling et al., 2006; Ruivo et al., 2009; Trieger et al., 2010; Cushing et al., 2012 and Güldner et al., 2012).

This study examines the use of imaging to look at electrode placement and correlate this with the ED results obtained from PTED procedure in adults with CIs.

6.1.1 CBCT use with CI

CBCT is an “x-ray based volume acquisition method” (Hodez et al., 2011) that utilises a motorised rotating x-ray emitting tube and a parallel flat panel detector turning around the participant’s head. The computer then processes the images captured by the panel detector to construct a cylindrical volume, within this cylindrical volume each unit “voxel” is cubic and the cylindrical volume is considered “isotropic” which ensures constant spatial resolution regardless of slice orientation. Similar to MSCT it allows 3D multi-planar (axial, coronal, sagittal) reconstruction in addition to oblique reconstruction. It was initially intended for dental use but due to technological advances and improvement in imaging quality it has been suggested as a low-radiation alternative for MSCT to capture images of the bony structures especially in the head and neck region (e.g. Gupta et al., 2004; Bartling et al., 2006; Rafferty et al., 2006; Faccioli et al., 2009; Hodez et al., 2011; Ruivo et al., 2009; Cushing et al., 2012 and Güldner et al., 2012). The Advantages of using CBCT with CI include that it has:

(1) Lower-radiation exposure in comparison to MSCT; Ruivo et al., (2009) reported an effective dose of 80 μSv with the use of CBCT in comparison to an effective dose of 3,600 μSv for the 16-slice MSCT and 4,800 μSv for the 4-slice MSCT in an in vivo post-CI imaging.

(2) Reduced sensitivity to metallic artefacts in comparison to MSCT allowing for placement assessment for each individual CI electrode (Ruivo et al., 2009).

(3) Higher spatial resolution, which is determined by the “voxel” size, with smaller voxels the spatial resolution of bony structures can be as good as that of MSCT (Hodez et al., 2011). In addition to that, isotropicity ensures high resolution in all directions.

(4) Lower cost (e.g. Ruivo et al., 2009; Hodez et al., 2011 and Cushing et al., 2012), shorter testing time (Rafferty et al., 2006) and a more comfortable open testing environment than MSCT (Ruivo et al., 2009).

While CBCT has several advantages over MSCT, it has some disadvantages due to reduced radiation intensity; in addition to the increased noise levels, evaluation of fine soft tissue details cannot be conducted (e.g. Miracle and Mukherji, 2009; Hodez et al., 2011 and Cushing et al., 2012). Another disadvantage is the lack of unified terminology and settings across the different CBCT devices; this makes it difficult to draw generalised conclusions and comparisons in addition to the absence of standardised protocols to evaluate the CI array position for example. Despite these disadvantages, CI placement examination in temporal bones and cadaveric human heads (Bartling et al., 2006; Cushing et al., 2012 and Güldner et al., 2012) and in vivo studies such as (Ruivo et al., 2009 and Tieger et al., 2010) have demonstrated the potential of using CBCT for the evaluation of CI electrode placement within the cochlea.

It has been reported that CBCT can provide high quality images of CIs that allow the distinct identification of single CI electrodes (Gupta et al., 2004; Bartling et al., 2006; Ruivo et al., 2009; Tieger et al., 2010; Cushing et al., 2012 and Güldner et al., 2012). CBCT was also used to (1) measure precise in vivo anglular depth of insertion for 15 implanted individuals (Tieger et al., 2010), (2) detect kinking and number of intra-cochlear contacts (Ruivo et al., 2009 and Cushing et al., 2012) and (3) determine scalar position (Cushing et al., 2012). However Güldner et al. (2012) reported up to 51% artefact exist on the measurement of the electrode diameter particularly with the apical electrodes. This has raised doubts about CBCT for determining scalar position of electrodes in deep insertions beyond the basal medial turn of the cochlea. In Güldner et al.'s study (2012) 3 cadaveric human heads and one specific CT scanner was used. The authors did not attempt to evaluate scalar position of the individual electrodes. In contrast Cushing et al., (2012) used CBCT to evaluate the individual electrodes scalar position and showed similar results to those obtained *via* histopathological analyses with the use of 11 human temporal bones implanted with a straight research array (SRA) from Cochlear®.

CBCT application with regards to CI may potentially have surgical, clinical and research uses. Further evaluations of CBCT use with CI and future optimisation of CBCT testing protocol may be warranted.

6.1.2 Aims and hypotheses

This chapter describes a study that addresses the use of imaging with CI. The first part evaluates the effect of angular depth of insertion of the CI array -as measured *via* plain x-rays and/or CBCT- on CI performance and the relationship between the angular depth of insertion and PTED at the apical electrodes. The relationship between the frequency shift of the most apical electrode and speech perception was also evaluated to investigate the contribution of the frequency shift to speech perception with CI. The second part evaluated the use of CBCT to determine the scalar placement of each CI electrode and the relationship between scalar placement, speech perception and PTED results.

Main research hypotheses were that:

H_1: There is a correlation between depth of insertion of the CI electrode array and post CI speech perception.

H_2: There is a correlation between depth of insertion of the CI electrode array and the percentage of discriminable electrodes as identified by the PTED with particular reference to the apical electrodes.

H_3: There is a correlation between the frequency shift (of the most apical electrode) and post CI speech perception.

H_4: There is a correlation between scalar positioning of the CI electrodes in the cochlea (in ST versus SV) and post CI speech perception.

H_5: There is a correlation between scalar positioning of the CI electrodes in the cochlea and the ED.

H_6: There is a correlation between the number of interscalar cross-overs (between ST and SV) of the CI electrode array as identified with CBCT and post CI speech perception.

H_7: There is a relationship between the interscalar cross-overs (between ST and SV) of the CI electrode array as identified *via* CBCT and the ED in that region.

6.2 Method

6.2.1 Participants

Out of the 36 participants that were recruited for the study described in Chapter 5, participants from the RNTNEH who had their post-implantation plain x-ray films available were included in this study. Additionally 9 out of the 36 participants who were recruited had also undergone CBCT scanning. 17 adult CI recipients with acquired deafness in total were recruited for this study.

The same inclusion criteria described in 5.2.1 were used.

Participants' demographics:

(1) Duration of deafness was calculated for each participant from the date of diagnosis of a bilateral profound sensorineural hearing loss. (2) Age at testing ranged between 24 to 80 years with a mean of 58 years (±14.44). (3) The aetiology of the hearing loss was unknown in 6 out of the 17 participants. (4) CI experience was calculated from date of switch on of the currently used implant; it ranged from 8 to 172 months, with a mean of 47 months (±42) and a median of 45 months. (5) The hearing loss was progressive for all of the participants. (6) Among the participants there were 7 AB CI recipients, 5 MED-EI™ CI recipients and 5 Cochlea® CI recipients.

Three participants had a pre or peri-lingual onset (before 5 years old) hearing loss (participants 3, 4 and 8). Two participants (2) had a history of cochlear explantation and re-implantation and participant 5 had a rolled over electrode tip at insertion. Participant 17 was subsequently diagnosed with dementia which may have affected the speech perception assessments and the PTED procedure at the time of recruitment, thus her speech perception measures and PTED results were excluded from analysis. Table 6.1 details participants’ demographics.

Table 6.1 Participants demographic details, the duration of deafness was calculated from the date of diagnosis of a bilateral profound sensorineural hearing loss to time of receiving an implant.

Participant	**Aetiology**	**Progressive**	**Age in years**	**Age at implant in years**	**Duration of Deafness in years**	**Implant experience in months**	**Type of implant**
1	Post general anesthesia in 3rd decade	Yes	63	61	12	18	MED-EL™ SONATA$_{TI}^{100}$
2	Unknown	Yes	68	57	19	18	AB HiRes 90K
3	Meningitis at 8months	Yes	53	49	?	48	Nucleus® Freedom
4	Head injury, age 5 years	Yes	56	46	3	120	MED-EL™ PULSAR$_{CI}^{100}$ standard
5	Unknown	Yes	50	48	2	24	AB HiRes 90K
6	Unknown	Yes	65	61	?	48	AB HiRes 90K
7	Unknown	Yes	80	78	25	24	MED-EL™ SONATA$_{TI}^{100}$
8	Unknown at age 9mths?	Yes	41	40	15	17	Nucleus® CI 512
9	Endolymphatc Hydrops	Yes	48	47	6	8	Nucleus® CI 512
10	Sickle cell anemia	Yes	24	20	9	48	MED-EL™ PULSAR$_{CI}^{100}$ standard
11	Unknown	Yes	52	47	?	57	AB HiRes 90K
12	Meniers	Yes	71	70	5	13	MED-EL™ PULSAR$_{CI}^{100}$ standard
13	Unknown	Yes	64	52	6	172	Nucleus® 22
14	Hereditary	Yes	62	57	6	62	AB HiRes 90K
15	Hereditary	Yes	77	73	7	48	AB HiRes 90K
16	Endolymphatic Hydrops	Yes	42	39	1	34	Nucleus® Freedom (CA)
17	Genetic	Yes	71	67	10	45	AB HiRes 90K

6.2.2 Test battery

The PTED (described in Section 3.2.2.2) in addition to three speech perception measures were used in testing, the CRM (described in Section 4.2.2) and the BKB sentence test in quiet and in speech-spectrum shaped noise at a 10dB (described in Section 5.2.2).

6.2.2.1 Plain x-ray

Post CI plain x-rays of CI placement (a modified Stenver’s view) are undertaken routinely at the RNTNEH; these films were used in this study. A modified Stenver’s view provided a direct image of the intra-cochlear electrode array.

6.2.2.2 CBCT

The CBCT assessment of CI electrode array placement was performed with the use of 3D Accuitomo (J. Morita MFG. Corp., Kyoto, Japan) at Cavendish Imaging. Imaging protocol applied: tube current 6mA, tube voltage 90kV, acquisition time of 17.4sec, rotation of 360 ° tomography, field of view (FOV) was small cylindrical (6 x 6 X 6 cm) with 3D isotropic 0.125 x 0.125 x 0.125 mm voxels.

The images were analysed with bespoke software (idixel One Volume Viewer, V 1.6.0.20, J. Morita MFG. Corp., Kyoto, Japan) which enabled a 360-degree 3-D visualisation of the CI electrode array in the cochlea. Submillimeter multiplanar reconstructions with a slice thickness of 0.25 mm were undertaken.

6.2.3 Procedure

Testing for speech perception took place in a 3.7×3.25 m double-walled sound booth where the participant was seated 1 metre in front of an ear level loud speaker (Plus XS.2, Canton) from which the speech and noise were presented. The stimuli were stored (16 bits), sampling rate (44.1 KHz) presented digitally using the AB-York Crescent of Sound (Kitterick et al., 2011). Testing for PTED took place in a double-walled sound booth.

For CRM the participants used a touch screen monitor to respond and the software ran the test presentation and scoring in an automated fashion. During BKB testing, the tester recoded the participants' verbal response by selecting the correct key words in each sentence presented.

All participants underwent BKB and PTED testing, CRM SRTs were determined for 6 out of the 17 participants.

The angular depth of insertion of the CI electrode array was judged by a highly experienced consultant ENT and CI surgeon for all 17 participants. The angular insertion depth of the electrode array tip was estimated relative to rotation about the mid-modiolar axis starting at the cochlear canal basal end. (See Figure 6.1 for example demonstrating the angular depth of insertion).


[redacted]

Figure 6.1 Post CI plain X-ray (Stenvers view) showing a CI electrode array with an angular depth of insertion estimated at 540°. The X-ray shows the implanted transmitter, receiver and the electrode array. The X-ray is showing electrode array as it enters the basal turn and the angular depth of insertion of the tip of the electrode array was estimated at 540° from the round window (one and a half turn).

The CBCT images acquired for the 9 participants were examined to establish scalar positioning of the CI electrode array. Scalar position of each electrode was judged by two independent raters; a highly experienced consultant ENT and CI surgeon and a highly experienced consultant neuro-radiologist. Each electrode was assigned a value (- 4 for extra-cochlear, -3 kinked, -2 definitely in SV, -1 query in SV, 0 query, +1 query in ST, +2 definitely in ST).

6.3 Analyses

BKB scores were converted to rationalized arcsine-transform units (RAU) before conducting statistical analysis (Studebaker, 1985) to reduce the impact of floor and ceiling effects.

The same pass/fail criteria described in Chapter 3 (Section 3.2.3.2) was used to categorise all tested electrode pairs *via* the PTED for each participant. In addition to that an ED score was calculated for each electrode which was the mean ED for each electrode and the adjacent electrodes on either side (except for the most apical and most basal electrode where only the ED score with the adjacent electrode was used). These scores were also categorised according to the same pass/fail criteria.

The CI devices were categorised according to make (1 for AB, 2 for Cochlear and 3 for Med-El).

The two expert image reviewers analysed the CBCT images using a scale for establishing accuracy of placement. They were asked to estimate which scalar the electrodes fell within and the confidence with which they made the estimate, the categories used were: -2 definitely in SV, -1 possibly in SV, 0 not sure which scala, +1 possibly in ST, +2 definitely in ST).

For the final analyses the -2 and -1 responses were combined into one category (-1 for SV) and the +1 and +2 were grouped into one category (+1 for ST). For inter-rater agreement on scalar position, responses of 0 were removed to evaluate if the two raters agreed on assignment of electrodes to ST versus SV. In addition to that, the categories - 3 for extra-cochlear and -2 kinked were also used in analysis.

6.3.1 Angular depth of insertion

The frequency-position map of the spiral ganglion proposed by Sridhar et al. (2006) and Stakhovskaya et al. (2007) was used to estimate the characteristic frequency associated with the most apical active electrode for each participant based on the angular depth of insertion. The difference between the characteristic frequency and the centre frequency of the filter assigned to the corresponding (most apical) electrode was calculated, this difference will be called the “frequency shift” of the most apical electrode. Fu and Shannon (1999a) have indicated that the frequency shift at the apical electrodes had a greater effect on speech perception than the more basal electrodes. The estimated angular depth of insertion for the most apical active electrode was categorised into one of the three ranges (similar to Lazard et al., 2012): < 370°, 370°- 539° and > 540°. Both the estimated angular depth of insertion values and categories were used in analyses.

The statistical analysis was conducted to assess the following:

1. Whether there is a significant relationship between the angular depth of insertion in degrees and the percentage of discriminable electrode pairs at all frequencies and at the two and four most apical electrode-pairs.
2. Whether there is a significant relationship between angular depth of insertion in degrees and speech perception (BKB in quiet, BKB in noise and CRM).
3. Whether there is a significant relationship between angular depth of insertion (as categorical data) and PTED’s percentage of discriminable electrode pairs at all frequencies and at the two and four most apical electrode-pairs.
4. Whether there is a significant relationship between angular depth of insertion (as categorical data) and speech perception (BKB in quiet, BKB in noise and CRM).
5. Whether there is a CI manufacturer effect on the angular depth of insertion.

6. Whether there is a significant relationship between the frequency shift and speech perception (BKB in quiet, BKB in noise and CRM).
7. Whether there is a CI manufacturer effect on the frequency shift.

The Shapiro Wilk's test revealed that BKB (in quiet and in noise) in RAU, the angular depth of insertion (for the 16 participants) and the frequency shift were normally distributed. Hence Pearson's correlation coefficient was applied to establish the relationship between the angular depth of insertion and BKB and between the frequency shift and BKB. While Spearman's rho was applied to establish the relationship between the angular depth of insertion and (PTED and CRM) results and between the frequency shift and (PTED and CRM) results. Spearman's rho was also applied to establish the relationship between the angular depth of insertion (categorical ordinal data) and (PTED, BKB in quiet, BKB in noise and CRM) results. One way ANOVA was conducted to evaluate whether there is a difference in the angular depth of insertion between the different CI manufacturers (AB, MED-El, Cochlear) and to evaluate whether there was a difference in the frequency shift between the different manufacturers.

6.3.2 Scalar placement of the CI electrodes (CBCT results)

For scalar placement cases of discrepancy between raters or cases where an electrode was assigned the category (0) by both raters were excluded from analyses. The number of electrodes placed in the ST and SV were counted and proportions were calculated for each subject. Inter-scalar cross-overs of the CI electrode array were also identified. Inter-scalar cross-overs were defined as the point between two adjacent electrodes when one electrode was judged to be placed in ST and the other electrode in SV. Finley and Skinner (2008) defined the "scalar pattern" as the region "where the array first enters SV" and labelled them as Basal (B), Middle (M) and Apical (A). A scalar pattern was determined for each participant based on dividing the intra-cochlear portion of the array into three parts basal, middle and apical.

The statistical analysis was conducted to assess the following:

1. Whether there would be a significant inter-rater agreement on scalar positions of the CI electrodes.
2. Whether there would be a significant and positive relationship between the proportion of CI electrodes inserted in ST as identified using CBCT and speech perception (BKB in quiet, BKB in noise and CRM SRT).
3. Whether there would be a significant and positive relationship between the number of interscalar cross-overs (between ST and SV) of the CI electrode array as identified *via* CBCT and speech perception (BKB in quiet, BKB in noise and CRM).
4. Whether there would be a significant and positive relationship between the scalar positioning of the CI electrodes as identified using CBCT and ED of corresponding electrodes using PTED.

For CBCT results, percentage inter-rater agreement was calculated and Cohen's Kappa was also used to assess the inter-rater agreement on scalar positioning of the CI electrodes. The Shapiro Wilk's test revealed that only BKB (in quiet and in noise) in RAU and the angular depth of insertion were normally distributed. Hence Spearman's rho was applied to establish the relationship between the percent electrodes placed in ST and BKB (in quiet and in noise in RAU), the angular depth of insertion and PTED) results. Spearman's rho was also applied to establish the relationship between the scalar positions of each electrode (ST versus SV) and the ED for the corresponding electrode and between the number of number of inter-scalar cross-overs and (BKB (in quiet and in noise) and the angular depth of insertion).

Since the electrodes' ED scores were not normally distributed, the Mann-Whitney was used. It was applied to determine if scalar placement of the electrodes has an effect on ED scores (percentage) or ED score category (pass versus fail). The Lambda test was applied to evaluate whether there is a relationship between make and scalar pattern, since they were both categorical nominal variables.

At points of inter-scalar cross-overs the ED score for the electrode pairs in those regions was evaluated (pass versus fail) to establish whether inter-scalar cross-overs affected ED.

IBM SPSS STATISTICS 21 for windows was used to carry out the analyses except for Cohen's Kappa which was carried out with the use of STATA 12 because SPSS doesn't run Kappa if one rater used a category that was not used by the other rater. *p* values are two tailed and significance is reported when $p<0.05$.

6.4 Results

6.4.1 Angular depth of insertion

The angular depth of insertion ranged from 270°- 720° with a mean of 425° (± 125°). The MED-EL array with the deepest insertion ranging from 360°- 720°, AB ranging from 270°- 540° and Cochlear 270°- 450°. Table 6.2 details correlation results between angular depth of insertion and other variables (BKB in quiet, BKB in noise, CRM, the percentage of discriminable electrode-pairs and percentage discriminable electrode-pairs of the two most apical two and four most apical electrode-pairs). Table 6.3 details correlation results between angular depth of insertion (categorical data) and other variables (BKB in quiet, BKB in noise, CRM, the percentage of discriminable electrode-pairs and percentage discriminable electrode-pairs of the two most apical two and four most apical electrode-pairs). See Figures (6.2 and 6.3) for correlations between angular depth of insertion and BKB in quiet and in noise respectively. There was a significant positive moderate to strong correlation between the angular depth of insertion and BKB in quiet and in noise, thus the hypothesis H_1 was accepted. Considering that only six participants had CRM SRTs being underpowered might explain why such a correlation was not found between CRM SRT and the angular depth of insertion. There was not a statistically significant correlation between the angular depth of insertion and the percentage of discriminable electrodes (across the array and at the most apical electrode-pairs).

The one-way ANOVA with angular depth of insertion as the dependant and the make as the factor revealed a statistically significant difference between manufacturers (F (2, 13) = 4.58, *p* = 0.03). A Tukey post-hoc test revealed that the angular depth of insertion was statistically significantly higher for MED-EL implants (540°± 127°, *p* = .04) compared to AB implants (360°± 110°). There were no statistically significant differences between the MED-EL and Cochlear devices (360°± 75°, *p* = .98) or between the AB and Cochlear devices (*p* = .07). Although there was a significant difference between the angular depth of insertion across the CI manufacturers, a one-way ANOVA revealed no significant difference between BKB scores in quiet across the different manufacturers (F(2,13) = 0.41, *p* = 0.67) nor was there a significant difference between BKB scores in noise across the different manufacturers (F(2,13) = 2.03, *p* = 0.18).

Table 6.2 correlation results between the angular depth of insertion in degrees and the other variables (BKB in quiet (RAU), BKB in noise (RAU), CRM SRTs in dBA, percentage of discriminable electrode-pairs for all electrodes and percentage of discriminable electrode-pairs for the two most apical and four most apical electrode-pairs).

Variable	Correlation with the angular depth of insertion		
	Coefficient	*p*	N
BKB in quiet	Pearson's r = 0.57*	< 0.05	16
BKB in noise	Pearson's r = 0.71**	< 0.01	13
CRM	Spearman's r_s = -0.17	0.74	6
Percentage discriminable electrode-pairs	Spearman's r_s = 0.09	0.75	15
ED of the most apical four electrode-pairs	Spearman's r_s = -0.18	0.53	15
ED of the most apical two electrode-pairs	Spearman's r_s = -0.23	0.42	15

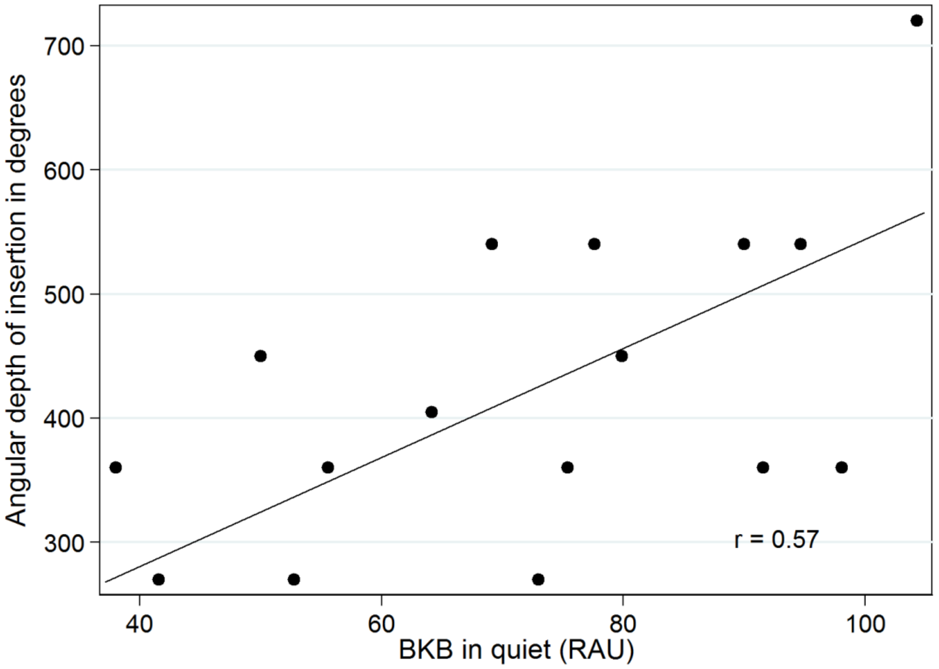


Figure 6.2 The relationship between BKB scores in quiet (RAU) and the angular depth of insertion. Angular depth of insertion on the y axis versus BKB scores in quiet (RAU) on the x axis showing a moderate positive relationship.

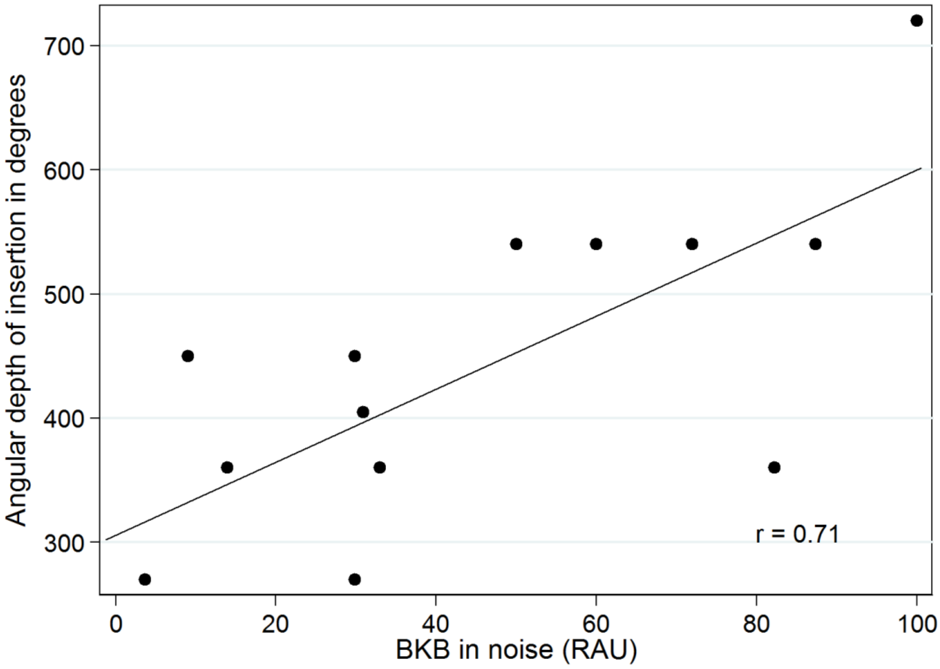


Figure 6.3 The relationship between BKB scores in noise (RAU) and the angular depth of insertion. Angular depth of insertion on the y axis versus arcsine transformed BKB scores in noise on the x axis showing a moderate positive relationship.

Table 6.3 correlation results between the angular depth of insertion category and the other variables (BKB in quiet, BKB in noise, CRM SRTs in dB, percentage of discriminable electrode-pairs for all electrodes and percentage of discriminable electrode-pairs for the two and four most apical electrode-pairs).

Variable	Correlation with the angular depth of insertion category		
	Coefficient	*p*	N
BKB in quiet	Spearman's r_s = -0.05	0.87	15
BKB in noise	Spearman's r_s = 0.73**	< 0.01	13
CRM	Spearman's r_s = -0.17	0.75	6
Percentage discriminable electrode-pairs	Spearman's r_s = 0.19	0.51	15
ED of the most apical four electrode-pairs	Spearman's r_s = -0.02	0.94	15
ED of the most apical two electrode-pairs	Spearman's r_s = -0.3	0.28	15

6.4.1.1 The frequency shift

The frequency shift ranged from -91 Hz – 1296 Hz with a mean of 524 Hz (± 116 Hz). Table 6.4 details correlation results between the frequency shift and other variables 'BKB in quiet', 'BKB in noise', CRM and the percentage of discriminable electrode-pairs. There was significant correlation between the frequency shift and 'BKB in noise' but not with 'BKB in quiet' and H_3 was accepted for 'BKB in noise' but not for 'BKB in quiet'. Again being underpowered might explain correlation was not found between CRM SRT and the frequency shift.

A one-way ANOVA revealed no significant difference between the frequency shift across the different CI manufacturers (F (2, 12) = 1.23, *p* = 0.33).

Table 6.4 correlation results between the frequency shift in Hz and the other variables (BKB in quiet, BKB in noise, CRM SRTs in dB and percentage of discriminable electrode-pairs for all electrodes).

Variable	Correlation with the frequency shift		
	Coefficient	*p*	N
BKB in quiet	Pearson's r = -0.5	0.06	15
BKB in noise	Pearson's r = 0.63*	< 0.05	12
CRM	Spearman's r_s = 0.09	0.87	6
Percentage discriminable electrode-pairs	Spearman's r_s = 0.24	0.42	14

6.4.2 Scalar placement of the CI electrodes (CBCT results)

CBCT images allowed judgment regarding the intra-cochlear placement of individual electrodes in ST versus SV and the identification of extra-cochlear electrodes without the interference of metallic artefacts. See Figures (6.4 and 6.5) for examples of CBCT images allowing placement judgment of individual electrodes with low metallic artefacts and an example of an MSCT image with metallic artefacts. Inter-rater agreement was 95.31 %, kappa revealed "almost perfect" inter-rater reliability for the raters (Landis & Koch, 1977), kappa = 0.83 (*p* <.0.001), 95% c.i. (0.66, 0.99).

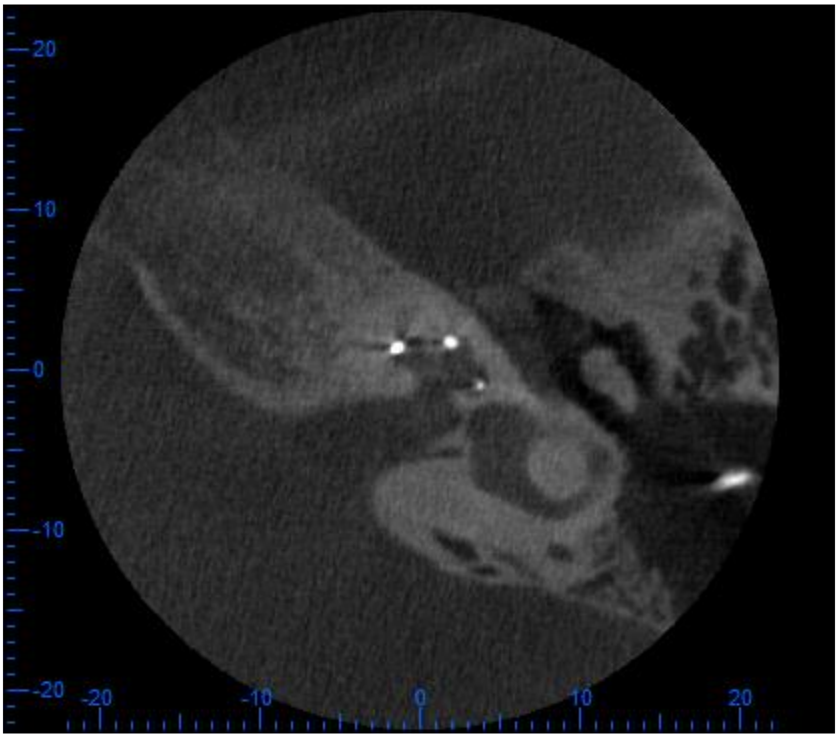


Figure 6.4 CBCT mid-modiolar reconstruction (axial-view) showing the position of MED-EL™ SONATA$_{TI}^{100}$ electrodes in scala tympani. Low metallic artefacts allow estimation of scalar placement of the individual electrodes.

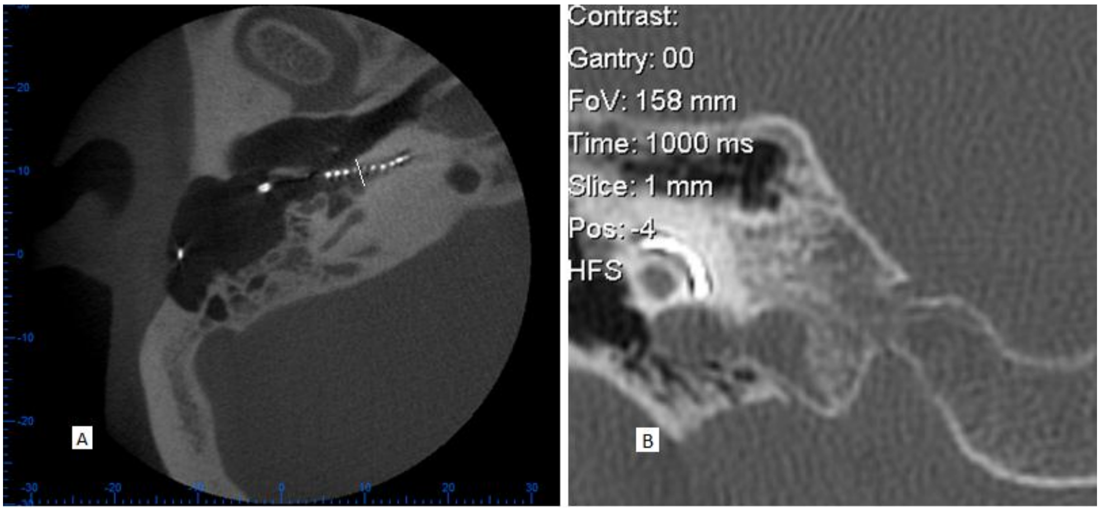


Figure 6.5 Examples of post CI CBCT and MSCT images. A) CBCT image of in an AB HiRes 90K implant electrode array which allowed the identification of individual electrode placement including the four extracochlear electrodes (as judged independently by both consultants and concurred later with the surgeon's report). B) MSCT image of a Nucleus® 22 electrode array intra-cochlear placement, individual electrode placement cannot be determined due to metallic artefacts.

For further statistical analyses, in cases of discrepancies between raters (ST versus SV), those electrodes (6 out of 130) were excluded from further analyses. Because of the substantial inter-rater agreement, it was decided that one rater’s judgement about scalar placement of an electrode is sufficient in case the other rater assigned it a (0). 11 electrodes were not assigned either ST or SV by any rater and were excluded; they were the six most apical electrodes for participant 3 who had a history of meningitis and five out of 22 electrodes in a participant that moved during testing. Table 6.5 details correlation results between proportion of electrodes placed in ST and other variables (BKB in quiet, BKB in noise, percentage discriminable electrode-pairs, ED of the most apical two and angular depth of insertion). There were no significant correlations between the proportion of electrodes placed in ST and any of the test variables.

Table 6.5 correlation results between the percentage of electrodes placed in ST and the other variables (BKB in quiet, BKB in noise, percentage of discriminable electrode-pairs for all electrodes, percentage of discriminable electrode-pairs for the two most apical and angular depth of insertion in degrees).

Variable	Correlation with the percentage of electrodes placed in ST		
	Coefficient	*p*	N
BKB in quiet	Spearman’s r_s = -0.07	0.86	8
BKB in noise	Spearman’s r_s = 0.46	0.43	5
Percentage discriminable electrode-pairs	Spearman’s r_s = -0.06	0.88	8
ED of the most apical two electrode-pairs	Spearman’s r_s = -0.25	0.58	8
Angular depth of insertion	Spearman’s r_s = 0.28	0.54	8

A Mann-Whitney test revealed that there was not a statistically significant difference between the scalar placement of the electrodes in ST versus SV median ED score (U = 1119, p = 0.77). No significant correlation was found between the number of inter-scalar cross-overs and CI performance nor with angular depth of insertion (see Table 6.6 for results). However a closer evaluation of PTED's results of the electrode-pairs in the region of inter-scalar cross-overs was warranted. Among the 9 participants there were 5 who had at least one inter-scalar cross-over. Participants 2, 3, 4 and 6 had one inter-scalar cross-over and participant 8 had two (the electrode array crossed from ST to SV then back again to ST). PTED results revealed that participants failed ED in those regions for all inter-scalar cross-over except for participant 2, who had fibrosis. The H_7 was accepted because a relationship was found between inter-scalar cross-overs and ED results.

Table 6.6 correlation results between the number of inter-scalar cross-overs and the other variables (BKB in quiet, BKB in noise and angular depth of insertion in degrees).

Variable	Correlation with the number of inter-scalar cross-overs		
	Coefficient	p	N
BKB in quiet	Spearman's r_s = -0.24	0.58	8
BKB in noise	Spearman's r_s = 0.05	0.93	5
Angular depth of insertion	Spearman's r_s = 0.53	0.18	8

6.4.2.1 Scalar-pattern of insertion

A one-way ANOVA revealed no significant difference between BKB scores in quiet across the different scalar-patterns of insertion (F (3, 4) = 1.53, p = 0.34) nor was there a significant difference between BKB scores in noise across the different scalar-patterns of insertion (F (2, 2) = 1.26, p = 0.44). However a Lambda test revealed a significant association between scalar-pattern of insertion and manufacturer, $\lambda = 0.73$, $p < 0.01$ (see Table 6.7 for number of devices demonstrating each scalar-pattern).

Table 6.7 The number of participants demonstrating each of the scalar-patterns per manufacturer

Scalar-pattern	Number of participants demonstrating the scalar-pattern		
	AB	Cochlear	MED-EL
Full insertion in ST	0	2	0
Apical scalar-pattern	3	0	0
Medial scalar-pattern	0	1	2
Basal scalar-pattern	1	0	0

6.5 Discussion

There was a significant positive strong and positive very strong relationship between the angular depth of insertion and BKB in quiet and BKB in noise respectively, which is in line with previous studies that advocate a deeper electrode array insertion (e.g. Fu and Shannon, 1999a; Skinner et al., 2002; Hochmair et al. 2003; Baskent and Shannon, 2003 and 2005; Yukawa et al., 2004 and Lazard et al., 2012). In addition the lack of correlation between the angular depth of insertion and ED of the most apical electrode-pairs may indicate that deep insertions for the participants in this study were achieved without causing insertion trauma in the apical region of the cochlea. This may explain why the negative effects of deep insertion on performance reported by Gani et al. (2007) and Finley and Skinner (2008) were not replicated in this study. Gani et al. (2007) and Finley and Skinner (2008) found that deep insertions were associated with increased pitch confusion of the apical electrodes. This most likely indicated insertion trauma (mechanical damage associated with surgical insertion of the CI array) at the apical region of the array rather than cross-turn stimulation. CRM SRTs were not correlated with the angular depth of insertion; this could be due to the small number of participants who had CRM SRTs (underpowered).

There was a manufacturers’ effect on angular depth of insertion, a significant difference was found between MED-EL and AB devices’ angular depth of insertion which could mainly be attributed to the longer MED-EL array and thicker AB array. However, there was no manufacturers’ effect on performance which concurred with previous findings (e.g. Friesen et al., 2001 and Green et al., 2007). A possible explanation for a manufacturers’ effect on angular depth of insertion but lack of a manufacturers’ effect on performance could be provided by the frequency shift results. There was a strong significant negative relationship between the frequency shift and BKB in noise which is in line with previous findings (e.g. Baskent and Shannon, 2003 and 2005). The absence of a statistically significant relationship between the frequency shift and BKB in quiet may indicate that other factors may contribute to CI performance (e.g. dead regions or ED). This pattern of results may reflect the BKB in noise requirement for better spectral representation than BKB in quiet and concurs with Whitford et al. (1993) who found an effect of better frequency alignment (between the characteristic and stimulated frequencies) on speech perception in noise but not in quiet.

There was no manufacturers’ effect on frequency shift, the lack of difference between the different manufacturers could be caused by the lower centre frequency stimulated by the most apical electrode in MED-EL (with the deepest angular depth of insertion) in comparison to the higher centre frequency stimulated in AB devices (with the most shallow angular depth of insertion in the study). This was supported by the lack of a manufacturers’ effect on the frequency shift.

The combined results of the angular depth of insertion and frequency shift indicated that the main effect of angular depth of insertion on performance could be at least partly contributed to the frequency shift in the absence of cochlear apical insertion trauma. In other words better frequency alignment between the cochlear normal tonotopic organization and the electrical stimulation of the CI without trauma at least partially contributed to better performance with CI.

There was no association between the frequency shift and the percentage of discriminable electrode-pairs which may indicate that the frequency shift doesn’t impact negatively on pitch ranking of the electrical stimulation.

The high inter-rater agreement on electrodes’ scalar-placement with the use of CBCT, provided further support to the functional potential of CBCT as an imaging tool for the evaluation of CI electrode placement. A finding which is supported by reports of high correlation between scalar placement judgements of CI electrodes made based on CBCT and histopathological evaluation of the corresponding electrodes (Saeed et al., personal communication). Additionally, only 11 out of a total of 130 electrodes scalar-placement could not be determined by either raters, five electrodes were for a participants that had movement artefact (moved during CBCT). The other six were the most apical electrodes of a Nucleus Freedom implant in a post-meningitic participant. Güldner et al. (2012) reported higher artefact with CBCT for the more apical electrodes in comparison to basal electrodes which was the case for this participant but it must be noted that the scalar position of the apical electrode (at an angular depth of 540°) for participant 1 was judged as definitely in ST by both raters. Meningitis may have caused pathological changes making it more difficult to identify scalar-placement of the apical electrodes for participant 3. In addition to that, electrodes of the Cochlear CI are larger in number and are closer to each other than other CI devices possibly increasing artefacts.

In contrast to Aschendorff et al.'s (2007) and Finley and Skinner's (2008) findings, the results of electrodes scalar-placement in this study indicated that placement in ST versus SV had no effect on CI performance. The lack of a relationship between scalar-placement and ED of the corresponding electrodes or the percentage of discriminable electrodes may shed some light on the matter. It may indicate that in the absence of mechanical damage secondary to SV electrode placement, scalar-placement in ST versus SV may not have a significant impact on performance which was observed in this study's population.

However when it came to inter-scalar cross-over of the array, close inspection revealed an association between inter-scalar cross-over and ED results of the corresponding electrodes. All seven observed inter-scalar cross-over points were associated with electrode pairs that failed ED in those regions except for participant 2 who had fibrosis which may have affected the reading of the CBCT regarding scalar placement. There are two possible explanations for failing ED in those regions of inter-scalar cross-over: one is that the electrode placed in the SV would be in closer proximity to the ganglion cells (SG) located adjacent to the next higher cochlear turn thus stimulating lower frequencies than ST placement and affecting ED. However, if this were the case it would mean that the direction of cross over from ST placement (of a more basal electrode) to SV placement (of a more apical electrode that stimulates SG in the higher cochlear turn) would not cause ED to fail. While crossover from SV placement (of a more basal electrode stimulating SG in the higher cochlear turn) to ST placement (of a more apical electrode stimulating SG in the implanted turn) would cause ED to fail. This was not observed and the direction of inter-scalar crossover did not have this effect on ED results. There were four points of crossover from ST to SV that failed ED. The second explanation for failing ED at regions of inter-scalar crossover is mechanical damage (insertion trauma) at those points which may affect SG survival (Finley and Skinner, 2008) or may affect current distribution of the CI stimulation at those points. In the absence of a difference between cross-over from ST to SV and cross-over from SV to ST, the direct mechanical damage caused by inter-scalar cross-over is the more plausible explanation for the failed ED. This indicates that ED can be used to identify points of mechanical damage due to insertion trauma, ED fails at those points.

Underlying neural survival could be associated with factors other than scalar-placement; this may explain the lack of general association between the number of inter-scalar cross-overs and CI performance. In addition to that numbers may have been too small to reach statistical significance.

In this study population, there was no association between the percentage of electrodes placed in ST and the angular depth of insertion or ED at the apical electrodes. Considering that ED identified points of mechanical damage due to insertion trauma, this may lend some support to the absence of trauma caused by forced insertion in cases where electrodes were placed in SV. However some indicator may be the results of insertion pattern which is indicative of where the inter-scalar cross-over occurred; insertion pattern was found to have a statistically significant association with the CI device manufacturers. Hence, the inter-scalar displacement that occurred within this study population could've been at least partially caused by mechanical attributes of the CI array, an argument proposed by Rebscher et al. (2008) and Finley and Skinner (2008) and seemed to hold true in this study. Only one out of nine participants exhibited a basal insertion pattern which may be associated with a cochleostomy that is too high on the lateral wall of the cochlea (Finley and Skinner, 2008).

6.6 Conclusion

In the absence of insertion trauma, increasing the angular depth of insertion of the CI array and decreasing the frequency shift had a positive impact on

CI performance. However in the absence of trauma, scalar placement in ST versus SV did not affect performance. ED was affected at inter-scalar cross-over indicating trauma and loss of spiral ganglion which was identified *via* PTED. There was no correlation between scalar placement in ST versus SV and ED, this may indicate that there might be dead regions or poorly differentiated electrodes that cannot be explained by surgical placement only, identifying those regions and addressing those regions in reprogramming might be beneficial. Given the considerably lower radiation exposure of CBCT in comparison to MSCT and the high definition of CBCT, it seems to be an imaging tool with great potential for clinical and research use.

6.7 Summary

- Evidence suggests that insertion trauma (mechanical damage associated with surgical insertion of the CI array) is a major factor with a negative impact on CI performance.
- In the absence of insertion trauma, increased angular depth of insertion has a positive effect on CI performance.
- In the absence of insertion trauma, there was no effect of scalar placement in ST versus SV.
- CBCT seems to be an imaging tool that provides high quality images with relatively low radiation exposure.
- PTED identified “dead” regions at inter-scalar cross-over; therefore PTED might be used to identify other dead regions across the CI electrode array which could further guide programming of the CI to enhance performance. A study evaluating the use of PTED to guide programming of CI is described in Chapter 7.

Chapter 7

Programming of CIs based on PTED results in unilaterally implanted recipients

Abstract

The effect of deactivating indiscriminable CI electrodes was evaluated using speech perception tests in quiet and noise for unilaterally implanted adults. The CI recipients underwent testing with PTED, BKB sentences test in quiet and in noise (whenever possible) and the adaptive CRM test. Each CI recipient who failed PTED in at least one electrode-pair received two research programs to try out in a cross-over study design. Research programs either employed discriminable electrodes only or the most discriminable two-thirds of the electrodes in the electrode array for CI recipients failing PTED for more than a third of the electrodes. The participants were also asked to subjectively report improvement of or decline in sound quality in everyday listening situations. There was significant improvement in CRM SRT, and BKB sentence scores in quiet and in noise after deactivating indiscriminable electrodes. Individually, 20 out of 25 participants who received the research programs reported and/or showed significant improvement with at least one research program. Only the five participants who had cochlear calcification or fibrosis or had placement issues showed no improvement, or reported no improvement, with the research programs. The findings show that the identification of discriminable electrodes in a clinically-viable procedure such as the PTED can potentially be used to enhance speech perception with CI.

7.1 Introduction

A priority for all CI manufacturers is to achieve maximal speech understanding for the CI recipients. One approach that manufacturers have adopted to attempt to enhance post-cochlear implantation performance is to increase the number of distinct pitch percepts (see Chapter 2), either by increasing the number of physical contacts, extending to 22 active electrodes, or by using “current steering” (described in Section 1.4.3.3) to focus stimulation and create a larger number of pitch percepts *via* virtual channels (Donaldson et al., 2005; Firszt et al., 2007; Koch et al., 2007; Bonham and Litvak, 2008; Wilson and Dorman, 2008). This approach may not always be effective if we consider that the number of perceptual channels is often less than the number of active CI channels (Blamey et al., 1992; Zwolan et al., 1997; Fu et al., 1998 and Friesen et al., 2001). Explanations for this discrepancy include the possibility that CI channels stimulate overlapping neuronal populations (Fu and Nogaki, 2004; Dorman and Spahr, 2006), which could be the result of neural “dead regions”, or due to electrodes being placed relatively far from the spiral ganglion neurons (Wilson and Dorman, 2008).

A second approach to producing distinct pitch percepts is the use of bipolar and tripolar CI stimulation (described in Section 1.2.5) to create more focused stimulation and reduce the spread of current (Bierer et al., 2005; Bonham et al., 2005; Litvak et al., 2007; Zhu et al., 2012). Because bipolar and tripolar coupling provides more focused stimulation, they could be more sensitive to the presence of dead regions (with little or no functioning spiral ganglion cells), making them useful stimulation modes for identifying such regions (Bierer and Faulkner, 2010 and Bierer et al., 2011). In Chapter 3, PTED a new, clinically-viable method for the identification of problematic electrodes was proposed, described and evaluated for reliability and validity. Further validation was offered to the PTED in Chapter 5, where a positive association was found between the percentage of discriminable electrodes as identified by PTED and three different speech perception measures. This finding is consistent with previous studies that have reported a positive relationship between the number of distinct perceptual channels and speech perception (Collins, et al., 1997; Henry, et al., 1997; Nelson, et al., 1995; Friesen et al., 2001). However, the question remains, “how might speech perception with CI be improved after identifying regions with poor spectral resolution or problematic electrodes?” Nelson et al. (1995) proposed the reduction of the number of the active CI electrodes in regions with poor spectral selectivity. This was confirmed by Zwolan et al.’s (1997) study that showed improvement among seven of nine CI recipients following the deactivation of indiscriminable electrodes. However the testing method that Zwolan et al. (1997) used was clinically non-viable, requiring a research interface and eight to ten testing trials that lasted between two to four hours each. The PTED may offer a clinically-viable alternative procedure due to the fact that it does not require a research interface, and takes less than an hour to complete. In addition, all the recruited CI recipients in Zwolan et al.’s study (1997) had the Cochlear Nucleus 22 device, and this thesis aims to investigate the effect of deactivating indiscriminable electrodes across different CI devices employing different strategies. The PTED procedure permits this.

In summary, evidence exists to demonstrate a positive relationship between the number of perceptually-distinct CI channels and speech perception. However, discrepancies between the number of CI channels and distinct pitch percepts are probably due to cochlear dead regions and placement issues. The identification of suspected dead regions with poor spectral selectivity or of channels that do not provide distinct pitch may be potentially used to improve the programming of the CI device.

This chapter describes a study that evaluated the impact of identifying (using PTED) and deactivating indiscriminable CI electrodes on speech perception of unilaterally implanted adults.

7.1.1 Aims and hypotheses

This study evaluated the use of CI recipients' ability to differentiate between the different CI electrodes in the identification of regions of poor ED by finding indiscriminable electrodes. The PTED procedure was used to assess ED and the effect of deactivating the indiscriminable electrodes was evaluated. A cross-over study design was used to compare speech perception with the everyday clinical program to speech perception with the two research CI programs.

In line with previous studies (Zwolan et al., 1997), it was predicted that deactivating indiscriminable electrodes (that stimulate suspected dead regions with poor spectral selectivity or of channels that do not provide distinct pitch) in the CI research program would improve speech perception with CIs. Delivery of information, that would otherwise be lost due to the distortions caused by dead regions, can improve speech perception with CIs as demonstrated in simulation studies (Smith and Faulkner, 2006). The clinical programme would be assessed at the beginning and end of the study to ensure that learning effects are accounted for. Main research hypotheses:

H_1: The CI recipients will have significantly different BKB scores (in quiet and in noise) with at least one research program (with deactivated indiscriminable electrodes) as compared to the clinical program (at the beginning and end of the study).

H_2: The CI recipients will have significantly different CRM SRTs with at least one research program (with deactivated indiscriminable electrodes) as compared to the clinical program (at the beginning and end of the study).

H_3: The CI recipients will report objective improvement in the sound quality delivered by the CI with at least one research program (with deactivated indiscriminable electrodes) as compared to the clinical program.

7.2 Method

7.2.1 Participants

Participants were recruited from the RNTNEH and through the NCIUA.

35 adult CI recipients with acquired deafness were recruited.

The inclusion criteria were that the participants had:

1. A minimum of six months CI experience.
2. An aural-oral mode of communication.
3. English as a first language.

Participants' demographics:

(1) Duration of deafness was calculated for each participant from the date of diagnosis of a bilateral profound sensorineural hearing loss, it ranged from 1 to 53 years. (2) Age at testing ranged between 19 to 83 years with a mean of 59 years (± 16). (3) The aetiology of the hearing loss was unknown in 15 out of the 35 participants. (4) CI experience was calculated from date of switch on of the present implant; it ranged from 8 to 204 months, with a mean of 68 months (± 48) and a median of 57 months. (5) The hearing loss was progressive for all of the participants. (6) Among the participants there were 10 AB CI recipients, 12 Med-El™ CI recipients and 13 Cochlear® CI recipients.

Five participants had a prelingual or perilingual onset (before 5 years old) hearing loss (participants 3, 4, 9, 26 and 31). Two participants (2 and 7) had a history of cochlear explantation and re-implantation and participant 5 had a folded over electrode tip at insertion. Table (7.1) details participants' demographics. Participant 34 was excluded due to being diagnosed with dementia and participant 15 retracted from the research because she had to travel after first session.

Table 7.1 Participants' demographics, duration of deafness was calculated from the date of diagnosis of a bilateral profound sensorineural hearing loss to time of receiving an implant.

Participant	Aetiology	Progressive	Age in years	Age at implant in years	Duration of Deafness in years	Implant experience in months	Type of implant
1	Post general anesthesia in 3rd decade	Yes	63	61	12	18	MED-EL™ SONATA$_{TI}^{100}$
2	Unknown	Yes	68	57	19	18	AB HiRes 90K
3	Meningitis at 8months	Yes	53	49	?	48	Nucleus® Freedom
4	Head injury, age 5 years	Yes	56	46	3	120	MED-EL™ PULSAR$_{CI}^{100}$ standard
5	Unknown	Yes	50	48	2	24	AB HiRes 90K
6	Unknown	Yes	65	61	?	48	AB HiRes 90K
7	Hereditary started at age 7 years	Yes	54	44	4	1st implant 24 2nd implant 104	MED-EL™ Tempo+
8	Unknown	Yes	80	78	25	24	MED-EL™ SONATA$_{TI}^{100}$
9	Unknown at age 9mths?	Yes	41	40	15	17	Nucleus® CI 512
10	Endolymphatc Hydrops	Yes	48	47	6	8	Nucleus® CI 512
11	Sickle cell anemia	Yes	24	20	9	48	MED-EL™ PULSAR$_{CI}^{100}$ standard
12	Typhoid and Otosclerosis	Yes	72	61	40+	132	MED-EL™ Combi 40+
13	Unknown	Yes	52	47	?	57	AB HiRes 90K
14	Meniers	Yes	71	70	5	13	MED-EL™ PULSAR$_{CI}^{100}$ standard
15	Unknown	Yes	31	22	15	100	Nucleus® CI 24R(CS)
16	Post general anesthesia in 3rd decade	Yes	64	52	6	172	Nucleus® 22
17	Measles, age 5 years	Yes	66	59	25	89	MED-EL™ Combi 40+

Table 7.1 (continued) Participants' demographics.

Participant	Aetiology	Progressive	Age in years	Age at implant in years	Duration of Deafness in years	Implant experience in months	Type of implant
18	Unknown	Yes	75	70	1	57	MED-EL™ PULSAR$_{CI}^{100}$ standard
19	Unknown	Yes	78	64	53	168	Nucleus® 22
20	Hereditary	Yes	62	57	6	62	AB HiRes 90K
21	Unknown	Yes	63	57	5	60	MED-EL™ PULSAR$_{CI}^{100}$ standard
22	Unknown	Yes	64	51	33	153	MED-EL™ Combi 40+
23	Unknown	Yes	71	69	9	25	MED-EL™ Combi 40+
24	Noise induced and otosclerosis	Yes	83	72	40+	123	Nucleus® CI 24M
25	Genetic started at age 20 years	Yes	77	73	7	48	AB HiRes 90K
26	Measles, age 5.5 years	Yes	62	57	6	62	Nucleus® CI 24R(CS)
27	Typhoid	Yes	27	15	5	144	AB CI
28	Unknown	Yes	67	66	?	12	Nucleus® CI 512
29	Genetic started at age 40 years	Yes	59	60	7	72	Nucleus® CI 24R(CS)
30	Endolymphatic Hydrops	Yes	42	39	1	34	Nucleus® Freedom (CA)
31	Genetic	Yes	19	2	1	204	Nucleus® 22
32	Unknown	Yes	60	56	?	42	AB HiRes 90K
33	Otosclerosis	Yes	69	63	7	71	Nucleus® Freedom
34	Genetic	Yes	71	67	10	45	AB HiRes 90K
35	Unknown	Yes	69	63	12	38	Nucleus® Freedom (CA)

7.2.2 Test battery

Three speech perception measures were used for testing, the BKB sentence test in quiet, BKB in speech-shaped noise at a 10dB SNR (described in Section 5.2.2), and the adaptive CRM test (described in Section 4.2.2).

7.2.2.1 PTED

As described in Section (3.2.2.2), each pair of adjacent electrodes was tested for a minimum of 5 consecutive trials. If the participant scored 80% or lower, the test trials were increased to ten successive trials. This cut off point will be referred to as an “adjacent electrode pair passing criterion”. Additional testing was also conducted with non-adjacent electrodes when two adjacent electrodes failed the 80% passing criterion level; this was referred to as the “non-adjacent electrode passing criterion”.

The following example will clarify the rules for non-adjacent electrode testing. If a participant scored less than 80% on an electrode-pair let us say electrode 1 (E1) and electrode 2 (E2) then testing continued between the electrode with the lower pitch in the first test-pair which is E1 in the example and the next electrode on the array which would be E3 in this case. See Figure (7.1) for a diagram of this example demonstrating the test hierarchy of non-adjacent electrode pairs.

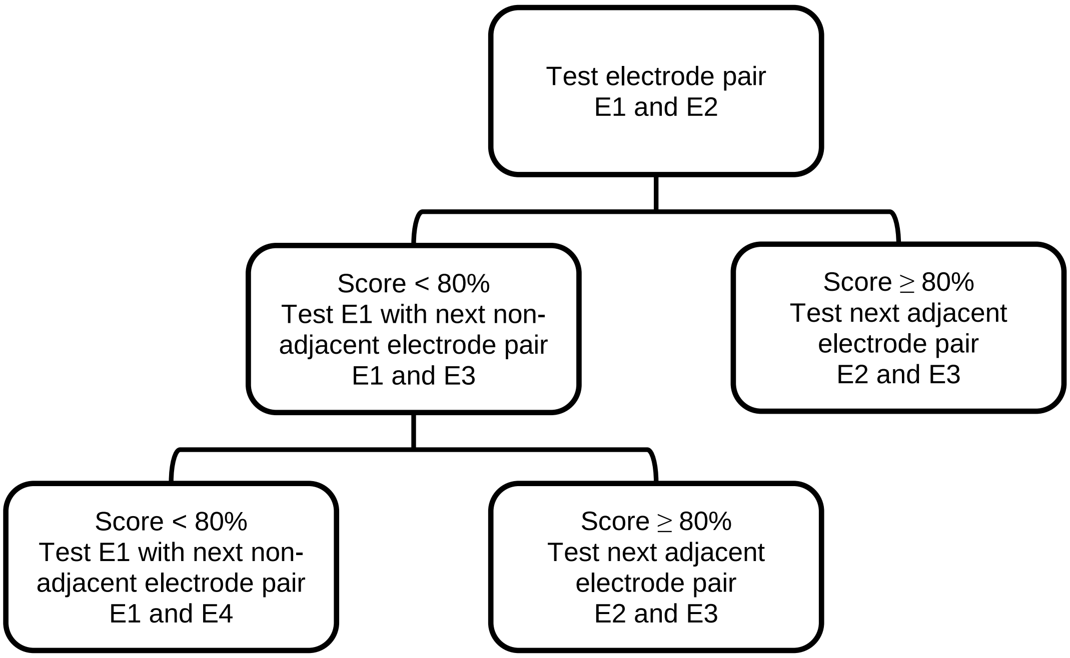


Figure 7.1 Example of rule hierarchy for testing electrode-pairs.

7.2.3 Procedure

Testing for PTED took place in a 2 x 2.5 m double-walled sound booth while testing for speech perception took place in a 3.7×3.25 m double-walled sound booth where the participant was seated 1 m in front of an ear level loud speaker (Plus XS.2, Canton) from which the speech and noise were presented. The stimuli were stored (16 bits), sampling rate (44.1 kHz) presented using the AB-York Crescent of Sound (Kitterick et al., 2011).

For CRM the participants used a touch screen monitor to respond and the software ran the test presentation and scoring in an automated fashion. During BKB testing, the tester recoded the participants' verbal response by selecting the correct key words in each sentence presented.

All participants underwent BKB and PTED testing, CRM SRTs were determined for 15 out of the 25 participants who received research programs. CRM was not used for participant testing at the beginning of the study but was introduced because some participants were performing at ceiling level of the BKB sentence test in quiet and in noise. Additionally, test-retest reliability had to be determined prior to initiating testing.

If a participant failed PTED for at least one electrode pair then they were included in the cross-over section of the study in which indiscriminable electrodes were deactivated. The rules for the deactivation of indiscriminable electrodes were:

1. If a participant failed pitch ranking for an electrode pair, scores of adjacent electrode pairs were reviewed. The more basal electrode or the electrode at the end of the electrode array (the most apical or most basal) in a single adjacent electrode pair was deactivated. If two adjacent pairs failed then the electrode common to both failed pairs was deactivated.
2. No more than one third of the total electrodes of the electrode array was deactivated for any participant at any time; this maintained a minimum of eight active electrodes for any participant which fits with the number of contacts required for good speech perception recommended by Friesen et al. (2001).
3. If a participant failed pitch ranking in electrode pairs that involved more than a third of the total number of electrodes then regions of failed pairs were identified. Then electrodes that failed ranking with a larger number of non-adjacent electrodes were deactivated in each region.

A cross-over study design was used (see Figure 7.2 for outline of the procedure). In the first session speech perception was assessed with the participant’s clinical program and the participant was provided with the first research program; either program A or program B (details given in Section 7.2.4) based on the PTED task. After one month trial use the participant returned for speech perception testing with the first research program; the participant was then provided with the second research program. The participant returned after a one month trial use for the final session. Speech perception testing was carried out with the original clinical program and the second research program. Final programming of the participant's speech processor was conducted, based on both performance and preference. The participant was also asked for feedback on each research program after each one-month trial; this provided valuable information on sound quality in different day-to-day listening situations. All participants were tested with BKB in quiet with the clinical program at the first and third sessions and once with each research program after the one month trial period. Participants who scored higher than 50% in their BKB test in quiet were tested for BKB in noise with the clinical program at the first and third sessions and once with each research program after the one month trial period. CRM SRTs were obtained twice in each session with the clinical program and with each research program at the end of the one-month trial period.

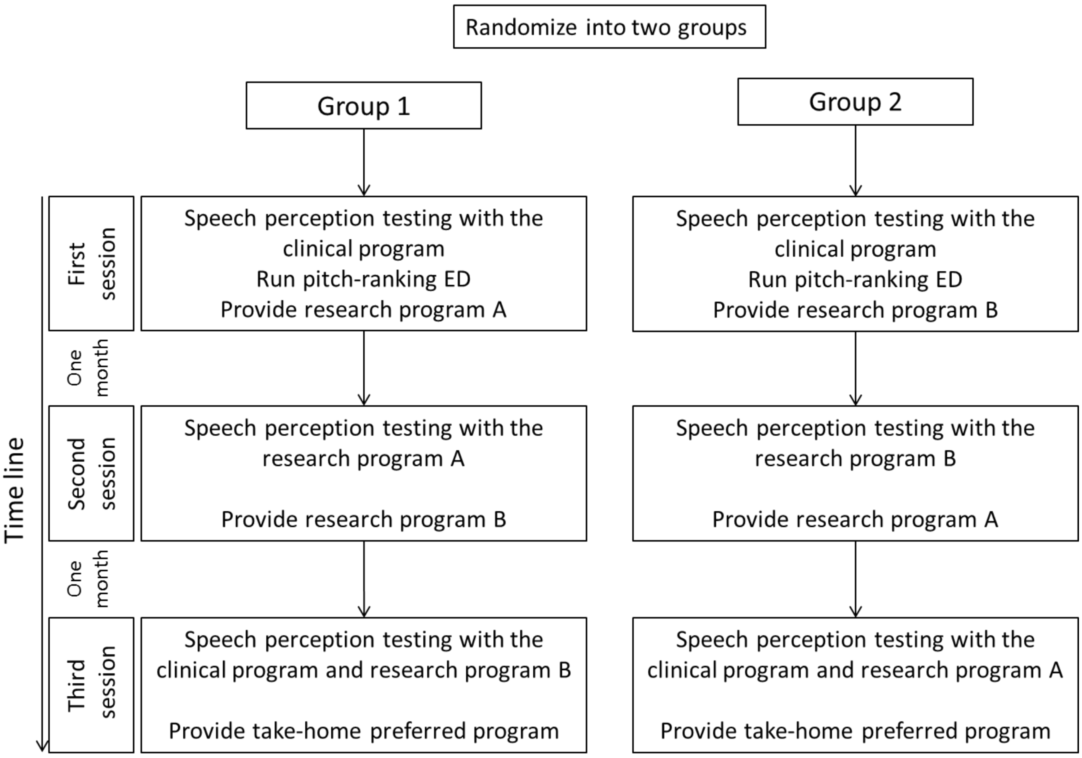


Figure 7.2 Outline of the cross-over study design, research program A with deactivated indiscriminable electrodes and increased rate per channel and research program B with deactivated indiscriminable electrodes while maintaining original rate per channel (original rate per channel is the rate of the original pre-research clinical program).

7.2.4 Research programs

Program options provided in the cross-over study were as follows:

Program (A) had the indiscriminable electrodes deactivated and an increase in stimulation rate per channel (RPC). For AB and Med-El devices, this rate increase occurred automatically once electrodes were deactivated. The rate per channel was manually increased in Cochlear participants to the maximum rate without M levels coming out of compliance for any of the electrodes.

Program (B) had the indiscriminable electrodes deactivated, but retained the original RPC, the same RPC as the pre-research clinical program. This meant the RPC was maintained on the original default settings for the

Cochlear devices and was manually decreased in AB and Med-El devices by increasing the pulse width.

7.2.4.1 Participants with different research programs

There were three participants with Cochlear® devices where program (A) had a lower Maxima (keeping same proportion of Maxima to number of active electrodes after deactivating indiscriminable electrodes) because we could not increase RPC due to technical reasons or because the participant refused to listen with an increased RPC.

7.3 Analyses

As mentioned, above, each participant was tested with the clinical program both at the beginning and end of the study to control for learning effects, and once with each research program following a one-month trial. The best speech perception results (BKB score in quiet and noise and CRM SRT average) achieved with the clinical program were compared with the speech perception results (BKB score in quiet and noise and CRM SRT average) obtained with the best research program for each participant.

Statistical analysis was conducted to assess the following:

1. Whether there was a significant change in BKB in quiet after deactivating indiscriminable electrodes.
2. Whether there was a significant change in BKB in noise after deactivating indiscriminable electrodes.
3. Whether there was significant change in CRM after deactivating indiscriminable electrodes.
4. Whether participants reported changes in sound quality after deactivating indiscriminable electrodes.

5. Whether there was a significant difference between research programs A and B.

7.3.1 Analyses of group results

BKB scores were converted to rationalized arcsine-transform units (RAU) before conducting statistical analysis (Studebaker, 1985) in order to include scores that were reaching ceiling. See Appendix D for raw BKB scores in quiet and in noise and figures.

All 25 participants who took part in the cross-over study received two research programs with the exception of participants 18 and 27. For these two participants it was not possible to apply any changes to pulse width, RPC or Maxima so they received program B only. Of those 25, participants 26, 29 and 30 received program A with the reduced Maxima. Group results were analysed for two sub-groups:

Group I included all 25 participants, group II was exclusively for the 20 participants who received both programs A (with increased RPC) and B.

According to the Shapiro Wilk's test, BKB scores in quiet and in noise were normally distributed for all three groups; hence *t*-tests were conducted to compare the clinical and research programs. While the Wilcoxon signed ranks test was used to analyse the CRM SRTs because they were not normally distributed.

7.3.2 Analyses of individual results

Each participant's results were analysed and comparisons were made on an individual basis comparing clinical and research programs to investigate any underlying patterns. Exploration of the frequency region of the deactivated electrodes was also evaluated.

7.3.2.1 Participant’s report

Each participant that received a research program was asked to report on the sound quality with the research programs in day-to-day listening situations. If the participant reported improvement in quality and reported better hearing/speech understanding in everyday listening situations that was considered as a positive report. If the participant either reported that they did not like the sound quality or reported a decline in hearing/speech understanding in everyday listening situations that was considered as a negative report. If the participant reported that there was no difference between the different programs they were recorded as equal.

7.3.2.2 CRM SRTs

Test-retest reliability of CRM SRTs was evaluated in Chapter 4 to calculate the minimum significant difference. As indicated in Chapter 4, the minimum significant change (at $p < 0.05$) in CRM SRTs among CI users is > 4dB.

7.3.2.3 BKB

For BKB scores, a 10% difference was considered significant. This value was based on calculations of the minimum significant difference (Skinner et al., 1995) which was >8.89% and an estimate of test-retest reliability of 7.6% (Sarant et al., 2001). In Sarant et al.’s study the estimate was based on (1) an inter-list variability of 10.1% across 126 pairs of BKB Sentences and (2) an inter-transcriber standard deviation across 160 lists of 5.7%. Based on the above, it was decided to consider a 10% difference as significantly different.

7.3.2.4 Risk of not showing benefit following deactivation of indiscriminable electrodes with and without cochlear pathological changes.

In order to calculate the risk of not showing benefit following the deactivation of indiscriminable-electrodes, all 26 participants who received a research program with deactivated indiscriminable-electrodes, were categorized according to change in performance. Those showing post-deactivation benefit in one category if they showed significant benefit in either, their subjective report, CRM SRTs or BKB in quiet or in noise in one category and those who did not show post-deactivation benefit in any of the above in another category. The presence of confirmed cochlear pathological changes secondary to aetiology (meningitis and otosclerosis) or confirmed radiological changes (e.g. fibrosis secondary to explantation) were considered as risk factors for showing no benefit following the deactivation of indiscriminable electrodes. STATA 12 was used in analysis with the absence of post-deactivation benefit as the “case variable” and the presence of cochlear-pathological changes as the “exposed variable” (risk factor).

7.3.3 Comparison between program A with increased RPC and program B with a maintained RPC

All 20 participants (group II) who received both programs A (with increased RPC) and B (with maintained RPC) underwent BKB testing in quiet. BKB scores in quiet were converted to rationalized arcsine-transform units (RAU) and used in analysis. In order to evaluate whether program A or B provided the best results, a mixed-design ANOVA was applied additionally the individuals’ preferred research program and the research program providing better speech perception was reported and grouped per CI manufacturer.

7.4 Results

7.4.1 Group results

The *t*-test was conducted on the BKB scores in quiet (RAU) for the two groups; group I with all participants, group II which exclusively included the participants who received both programs A (with increased RPC) and B. The *t* -tests showed significant improvements with the best research program compared to the best BKB score (RAU) with the clinical program for group I (t = -3.47, df = 24, $p < 0.005$ with $p = 0.002$). This was also significant for group II (t = -2.88, df = 19, $p < 0.05$ with $p = 0.01$) (See Figure 7.3 for results). Thus the hypothesis H_1 was accepted for all groups.

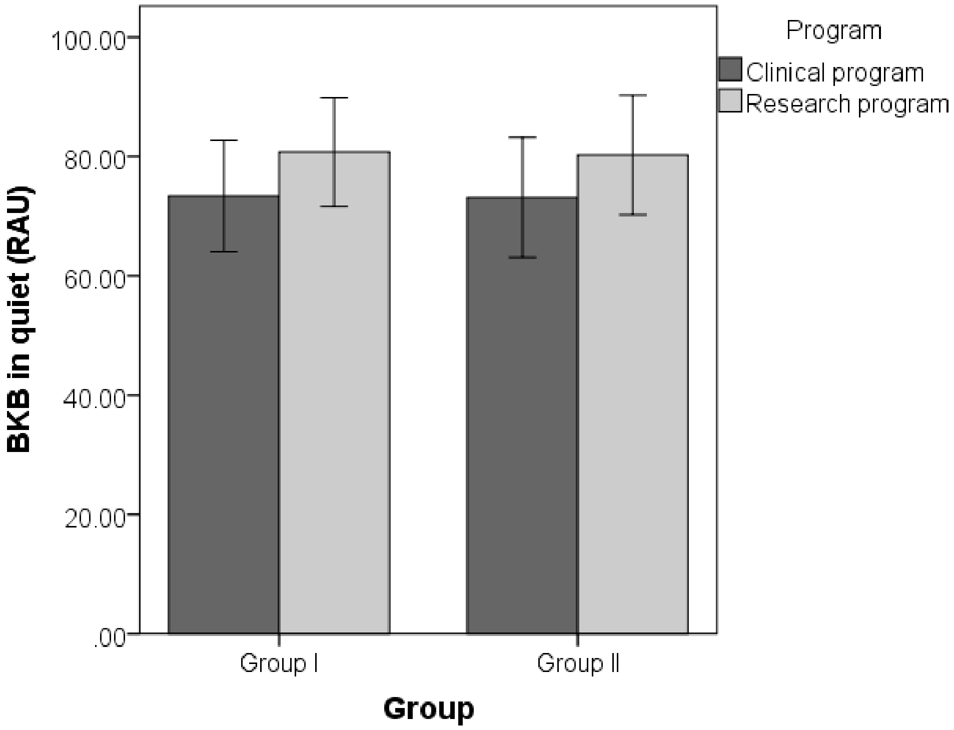


Figure 7.3 Mean BKB Sentence Test in quiet (RAU) for the two sub-groups with the use of the clinical program (dark grey bars) and the best research program (light grey bars).The bars show mean scores, error bars show ± 2SE.

The *t*-tests conducted on BKB scores in noise (RAU) revealed a significant improvement with the best research program compared to the best BKB score with the clinical program in group I (t = -2.91, df = 19, $p < 0.01$ with p =

0.009). This was also significant in group II (*t* = -2.64, df = 16, $p < 0.05$ with $p = 0.018$) (See Figure 7.4 for results). Thus the hypothesis H_2 was accepted for all groups.

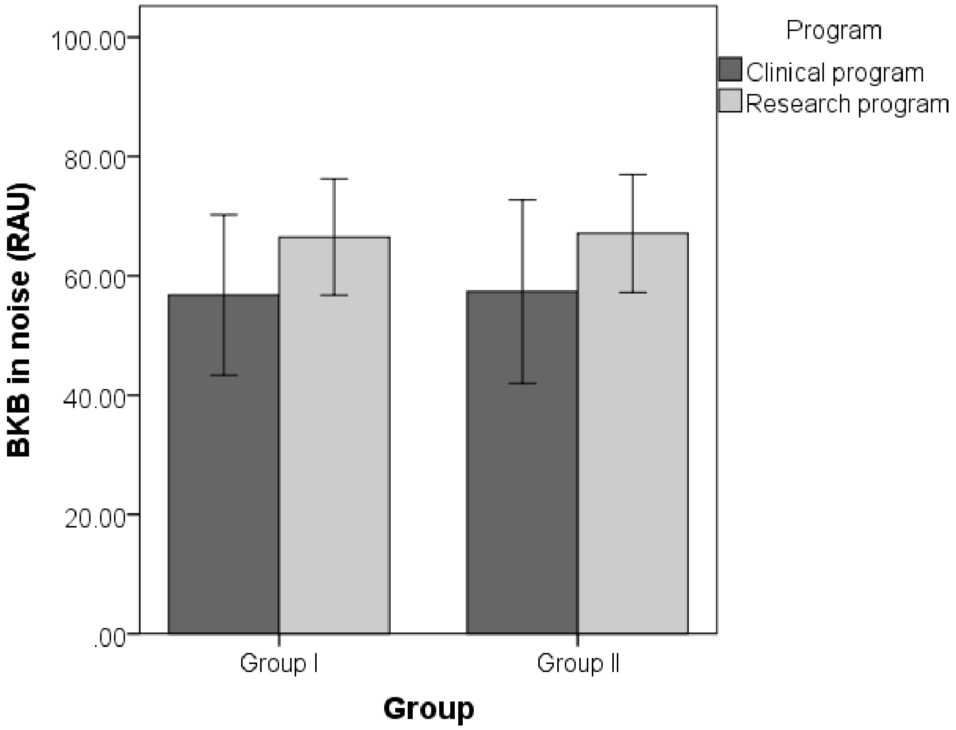


Figure 7.4 Mean BKB Sentence Test in noise (RAU) for the two sub-groups with the use of the clinical program (dark grey bars) and the best research program (light grey bars).The bars show mean scores, error bars show ± 2SE.

For CRM SRT results see Table (7.2). The Wilcoxon signed ranks test was used to analyse CRM SRTs and showed significant improvement with the best research program compared to the best CRM SRT with the clinical program in group I (Z = -3.17, N = 15, $p < 0.005$ with $p = 0.002$). This was also significant in group II (Z = -2.81, N = 10, $p < 0.01$ with $p = 0.005$) (See Figure 7.5 for results). Thus the hypothesis H_3 was accepted for all groups.

Table 7.2 Results of the best clinical and the best research CRM SRTs reported in dBA. Descriptive statistics: the 25th percentile (Q_1), the 50th percentile (median), the 75th percentile (Q_3) and the number of participants contributing the data (N). Results are reported for the different groups [group I for all participants and group II who received both research programs A (with increased RPC)].

Group	Clinical program			Research program			N
	Q1	Median	Q3	Q1	Median	Q3	
Group I	4.38	6.88	14.38	1.25	2.81	7.19	15
Group II	3.76	6.88	11.1	-.47	1.57	3.52	10

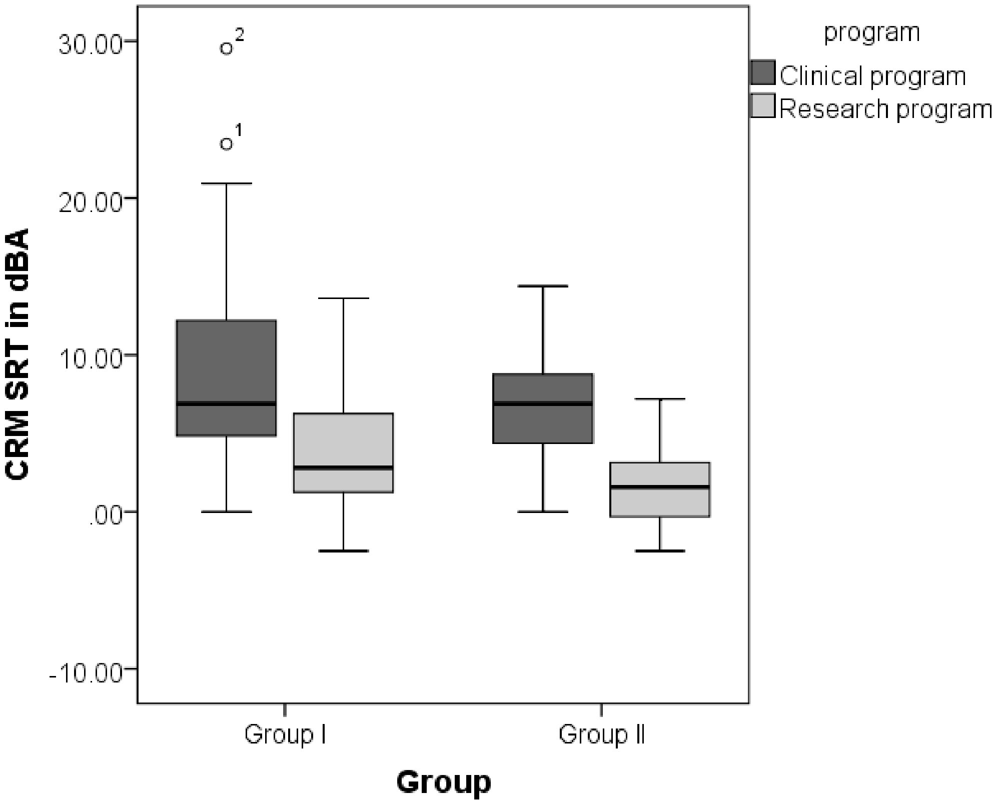


Figure 7.5 Results of the CRM SRTs in dBA for the two sub-groups with the clinical program (dark grey boxes) and the research program (light grey boxes), the boxes represent the range between the 25th and 75th percentiles and the line in the box represents the median. The whiskers show the 10th and the 90th percentiles.

7.4.2 Individual results

Participants were divided according to CI manufacturer to investigate patterns relating to electrode array design, such as the number of electrodes and the frequency to electrode assignment. Participants' data were organized according to change in performance, starting with participants showing the greatest benefit down to participants showing no benefit from the research program. Individual speech perception results and subjective reports (improvement versus decline versus no significant difference), the deactivated electrodes (DE) in the research programs, the number of DE at low frequencies < 2600Hz (DELF) and the number of DE at high frequencies

> 2600 Hz (DEHF) can be seen in Tables (7.3, 7.4 and 7.5) for Cochlear, MED-EL and AB respectively.

Eight out of the nine Cochlear participants either reported improvement, and/or showed significant improvement in at least one speech perception measure, and none showed significant decline. Five of those eight participants received significant benefit in speech perception. The two Cochlear participants who received significant benefit in both BKB tests in quiet and in noise had the majority of the indiscriminable electrodes in the frequency range below 2600 Hz and they both had adjacent electrodes deactivated at certain regions.

Table 7.3 Individual results for Cochlear® devices (BKB in quiet and noise, CRM SRTs and subjective report) and DE region, symbols used are: (=) for no significant difference, (+) for significant improvement which is a higher BKB score and a lower CRM SRT followed by change in score if any, (-) for significant decline, ceiling indicates BKB scores were at ceiling level for clinical and research programs and N/A indicates scores not available. Adjacent DE are shown in red to highlight when a region of electrodes were deactivated.

Participant	BKB in quiet	BKB in noise	CRM SRT in dBA	Report	DE	DELF	DEHF
10	(+) 20	(+) 26	N/A	(+)	1,2,5,11,16,17 & 20	4	3
9	(+)18	(+)12	N/A	(+)	1,6,10,14, 15 & 20	4	2
30	(+) 14	(=)	(+) 5.48	(+)	1,4 &9	1	2
28	(=)	(=)	(+) 5.31	(+)	1,2,6&17	1	3
29	(=)	N/A	(+) 15.93	(+)	7,14,16,17&19	1	4
26	Ceiling	(=)	(=)	(+)	4,8,19 & 21	2	2
35	Ceiling	Ceiling	(=)	(+)	2,6,8&16	2	2
16	(=)	(=)	(=)	(+)	1,14,17& 20	3	1
3	(=)	(=)	N/A	(=)	1,2,5,11,16, 17 & 20	3	4

Eight out of the ten MED-EL participants either reported improvement, and/or showed significant improvement in at least one speech perception measure, and only one participant showed significant decline. Seven of those eight participants received significant benefit in speech perception. The MED-EL participants who received significant benefit in both BKB tests in quiet and in noise either had all or at least half of the indiscriminable electrodes in the frequency range below 2600 Hz and the participant receiving most benefit had adjacent electrodes deactivated at a certain region.

Table 7.4 Individual results for MED-EL™ devices (BKB in quiet and noise, CRM SRTs and subjective report) and DE region, symbols used are: (=) for no significant difference, (+) for significant improvement which is a higher BKB score and a lower CRM SRT followed by change in score if any, (-) for significant decline followed by change in score if any, ceiling indicates BKB scores were at ceiling level for clinical and research programs and N/A indicates scores not available. Adjacent DE are shown in red to highlight when a region of electrodes were deactivated

Participant	BKB in quiet	BKB in noise	CRM SRT in dBA	Report	DE	DELF	DEHF
8	(+) 27	(+) 44	N/A	(+)	4&5	2	0
1	(+) 10	(+) 19	N/A	(+)	2&10	1	1
18	Ceiling	Ceiling	(+) 10	(+)	5&10	1	1
14	(+) 16	(=)	N/A	(+)	3,4,9 &11	2	2
17	Ceiling	Ceiling	(+) 5.32	(+)	9	0	1
23	(=)	(=)	(+) 5.6	(+)	10 (most basal)	0	1
22	Ceiling	Ceiling	(+) 5.63	(+)	12	0	1
11	Ceiling	Ceiling	(=)	(+)	10 & 12	0	2
7	(=)	(=)	N/A	(=)	1&2	2	0
12	(-)15	N/A	N/A	(=)	5&9	1	1

Six out of the eight AB participants reported improvement and showed significant improvement in at least one speech perception measure and only one participant reported a decline. The AB participant who received the largest benefit in both ‘BKB in quiet’ and in CRM SRT had the indiscriminable electrode in the frequency range below 2600 Hz.

Table 7.5 Individual results for Advanced Bionics devices (BKB in quiet and noise, CRM SRTs and subjective report) and DE region, symbols used are: (=) for no significant difference, (+) for significant improvement which is a higher BKB score and a lower CRM SRT followed by change in score if any, (-) for significant decline followed by change in score if any, ceiling indicates BKB scores were at ceiling level for clinical and research programs and N/A indicates scores not available.

Participant	BKB in quiet	BKB in noise	CRM SRT in dBA	Report	DE	DELF	DEHF
27	(+) 13	N/A	(+) 10.9	(+)	2	1	0
25	Ceiling	(+) 21	(+) 4.27	(+)	4, 14&16	1	2
13	Ceiling	Ceiling	(+) 11.57	(+)	1,2,13&15	2	2
6	(=)	(+) 10	N/A	(+)	13&16	0	2
2	(=)	(=)	N/A	(=)	7&8	2	0
5	(=)	(=)	N/A	(-)	4&16	1	1

7.4.2.4 Risk of not showing benefit following deactivation of indiscriminable electrodes with and without cochlear pathological changes.

In this population, with the use of STATA, the risk of not showing benefit following the deactivation of indiscriminable electrodes was calculated with and without the presence cochlear pathological changes. The presence of cochlear pathological changes was entered as a risk factor. Results indicated that the risk (probability) of not showing benefit if pathological changes are present is 1 (i.e. 100%) and is 0.047 (i.e. 4.7%) in the absence of pathological changes.

7.4.3 Comparison between program A (increased RPC) and program B (maintained RPC)

A mixed-design ANOVA with the research program (program A- with increased RPC- and program B) as a within-participants factor and order (program A first or program B first) as a between-subjects factor was applied on BKB scores in quiet. It revealed no main effect of research program, F (1, 18) = 0.025, *p* = 0.88 and no significant order effect F (1, 18) = 3.08, *p* = 0.09. This indicated that there was no general pattern indicating that one research program was consistently better than the other. Therefore, individual results of the research program that provided the better outcome for participants who have received benefit were grouped by manufacturer. Table (7.5) summarizes each participant’s manufacturer, the preferred research program and the program that provided better speech perception in at least one measure (only significant differences are reported) for the 15 participants that received benefit and received program A (increased RPC ranging from 1653 to 4000 pps) the preferred program also gave better speech perception, except for participants 1 and 23 who both chose programs with RPC around 2000 pps. Individual results and results per manufacturer will be discussed later.

Table 7.6 Summary of RPC and participants' preferred research program and the program that provided better speech perception (only significant differences are reported) for the 15 participants that showed benefit and received both programs A and B. The preferred program is the program that the participant requested to take home, for some participants they took both programs A and B. When A and B are indicated under the program with better performance; it means that both programs had equally good speech perception measures. RPC is reported in pulse per second (pps).

Participant	**RPC for program A**	**RPC for program B**	**Research program with better performance**	**Preferred research program**	**Manufacturer**
9	1800	900	A&B	B	Cochlear®
10	1800	900	A	A	Cochlear®
28	2400	900	A&B	A&B	Cochlear®
29	1800	1200	A&B	A&B	Cochlear®
35	1800	900	A&B	A&B	Cochlear®
8	2281	2013	A	A	MED-EL™
1	2564	1961	A	B	MED-EL™
14	2198	1531	B	B	MED-EL™
22	1653	1515	A	A	MED-EL™
17	2020	1818	A&B	B	MED-EL™
23	2034	1770	B	A	MED-EL™
11	1326	1170	A&B	B	MED-EL™
25	1947	1586	A&B	B	AB
13	2109	1513	A&B	B	AB
6	4000	2566	B	B	AB

7.5 Discussion

This study showed statistically-significant improvements for the group as a whole in all speech perception measures (BKB in quiet, BKB in speech-shaped noise and CRM SRTs) when indiscriminable electrodes were deactivated (H_1, H_2 and H_3 were accepted).

These results indicated that ED assessment might be a useful aide to guide programming of CIs in order to maximize performance.

Group results for the 25 participants who received at least one research program with indiscriminable electrodes deactivated showed a significant improvement with the best research program compared to the best score with a clinical program. This improvement was reflected in both BKB scores in quiet and in speech-shaped noise and for CRM SRTs, this was consistent with findings reported by Zwolan et al. (1997) when they deactivated indiscriminable electrodes.

A closer evaluation of each individual participant's results provided more information. In our study 20 out of the 25 participants receiving research programs reported improvement in hearing or improved sound quality perception when indiscriminable electrodes were deactivated. Sixteen of the 25 (64%) showed significant improvements in at least one speech perception measure (BKB in quiet, BKB in noise and/or CRM). Four of the participants who did not show a statistically-significant change in performance reported better sound quality that included (1) reduced noise, (2) improved environmental sounds perception, (3) less reliance on their induction loop system, (4) better speech understanding in noisy environments or public places such as church or (5) more refined hearing e.g. one participant reported hearing the hoarseness in their own voice for the first time. Three out of those four participants (participants 11, 26 and 35) had at least one BKB score at ceiling and two of them (participants 11 and 35) had BKB scores at ceiling with their clinical programs in both quiet and noise. This may have indicated that the speech perception tests were not sensitive enough to detect the differences between the clinical and research programs or that some of the incorrectly ranked electrodes may have affected sound quality without significantly affecting speech perception. For one of these four participants (participant 11) the indiscriminable electrodes fell in the frequency range higher than 2600Hz and for two of these participants (26 and 35) half of the indiscriminable electrodes fell in the region above

2600Hz. This frequency region was reported to be of less importance to speech perception than the lower frequency range (Shannon et al., 2001; McKay and Henshall, 2001) and thus is less likely to have an impact on speech compared with the lower frequency region. For the fourth participant (16), it might have been that the speech perception tests used were not sufficiently sensitive to highlight differences, this participant also suffered from a strange change in the quality of sound after continuous CI use for several hours which might have influenced her speech perception results.

A closer inspection of the individual participant’s frequency region for indiscriminable (deactivated) electrodes and the associated speech perception scores in Tables (7.3, 7.4 and 7.5) revealed consistent patterns. The eight participants who showed BKB scores at ceiling with their clinical programs (participants 11, 17, 18, 22, 23, 25, 26 and 35) had at least half of their indiscriminable electrodes in the frequency range higher than 2600Hz. Three out of those eight participants (11, 17 and 22) showed indiscriminable electrodes only in the high frequency range (>2600Hz), and no participant showed more than two indiscriminable electrodes for frequencies lower than 2600Hz. On the other hand, participants who had indiscriminable electrodes in the low frequency range only (< 2600 Hz), or who had the majority of the indiscriminable electrodes involving the low frequency range, were poorer performers and none of them reached ceiling BKB scores with their clinical programs. The biggest improvements in speech perception scores were observed after deactivating indiscriminable electrodes either only in the low frequency range (participant 27 with AB and participant 8 with Med-El) or when more than half of the deactivated electrodes were in the low frequency range (participants 9 and 10 with Cochlear® and participant 2 with Med-El). This again is consistent with previous research highlighting the importance of the low frequency range (< 2600 Hz) for speech perception (Shannon et al., 2001; McKay and Henshall, 2001).

In order to evaluate the difference between the higher RPC and the lower RPC a closer evaluation of the 15 participants who showed a significant improvement in at least one speech perception measure and have received both programs (A and B) with program A having a higher RPC was warranted. A closer inspection of the preferred program and the better program in terms of performance on the speech perception measures with each of the different manufacturers might shed some light on the matter. Three out of the seven participants implanted with MED-EL™ devices (participants 1, 8 and 22) performed better with program A where the default increase in RPC that occurred when the indiscriminable electrodes were deactivated was allowed. While two out of seven (participants 14 and 23) performed better with program B where RPC was maintained and two participants (participants 11 and 17) did just as well with either program. Out of those seven, four (participants 1, 11, 14 and 17) preferred program B (maintaining the original clinical RPC) even when the participant did better with program A as seen in participant (1) or equally as well with program B (participant 17). Three participants preferred program A (participants 8, 22 and 23), two of them did better with program A (participants 8 and 22) and one (participant 23) did better with program B. So out of the seven Med-El participants, only two of them selected the program that was not necessarily the best program (participant 1 and 23) in terms of speech perception. This highlights two issues (1) the implanted individual preference may not always be reflected in speech perception measures and that sound quality should be considered as well (participant 1 thought program A with higher rate was squeaky), (2) the RPC that both of these participants preferred was around 2000 pps, participant 1 preferred the original RPC of 1961 pps over the faster rate of 2564 pps and participant 23 preferred the faster rate of 2094 pps over the original rate of 1770 pps. For the other participants (8, 11, 14, 17 and 22) their choice concurred with the speech perception measure, none of them chose an RPC >2300 and the participant who did equally well with programs A and B (participant 17) chose program B with RPC of 1531 over program A with RPC 2198. For participant 17 it could have been an adaptation issue but it must be noted that she thought program A was squeaky; the same remark that participant 1 had about program A with the faster RPC, again this highlighted the importance of quality and may have indicated that the preferred RPC could be subject-dependent; each participant has an upper limit for what is an acceptable RPC. However, no adjustments were applied to T or MCL levels to following the deactivation of the indiscriminable electrodes to ensure that other factors were not confounding the results. It is possible that adjusting these levels may have improved sound quality.

There was not any clear pattern of results observed with Cochlear® participants however it must be noted that RPC never exceeded 1800 pps except for participant 28. In participants with AB participants always preferred program B (6, 13 and 25) with the lower RPC over program A with the faster RPC, however we must point out (1) that we cannot generalize results on such a small number, (2) that their preferred program was either the program that they performed best with or did just as equally as well with; there was no disagreement between the preferred research program and the better program in terms of speech performance and (3) better performers may benefit from higher rates.

Out of the twenty five participants who have received at least one research program only five did not report or show significant improvement in the speech perception measure. Four out of the five participants who did not show improvement after deactivating indiscriminable electrodes reported no difference between the research programs and the clinical program and one participant showed significant decline in at least one speech perception measure. Among those five; participant 3 had a history of meningitis, participant 12 had otosclerosis, participants 2 and 7 had a history of explantation and re-implantation with radiologically confirmed fibrosis in participant 2 and participant 5 had radiologically confirmed CI placement issues including a fold over electrode array tip. In participants (3, 12, 2 and 7) etiology, history and in some cases radiology suggested the possibility for the presence of fibrosis or calcification in the cochlea. Calcification, fibrosis or cochlear pathology in those cases may have altered the electrical current flow in the cochlea (e.g. Rotteveel et al., 2010) rendering ED an ineffective tool to identify problematic or dead regions in the cochlea. This highlights the importance of checking the etiology and medical history when assessing electrode differentiation. These results also demonstrate that there are different types of indiscriminable electrodes, and deactivating each electrode might produce different results.

The risk of not showing benefit after deactivating indiscriminable-electrodes based on PTED in the presence and absence of cochlear pathological changes indicates that the presence of pathological changes is a contraindication for the use of PTED. However the risk (probability) of not showing benefit after deactivating indiscriminable-electrodes is very small (4.7%) in the absence of cochlear pathological changes and it reflects the post deactivation lack of improvement in participant 5 with placement issues. This minimum risk of not showing improvement, provides further support to the identification of indiscriminable-electrodes *via* PTED as a procedure with potential to be used to enhance CI programming. In other words the deactivation of indiscriminable electrodes identified *via* PTED will most likely (95.6% probability) cause improvement in performance with CI.

The improvement in sound quality and speech perception observed in this research was not dependent on a certain device or a particular strategy. Hence it indicated that testing for indiscriminable electrodes uncovered an underlying cause or pathology that affected pitch perception for those electrodes. Dead regions or holes in hearing may have been a plausible explanation, some support could be provided by examining results of implanted participants with the Cochlear device since it had the largest number of electrodes which are closer in proximity to one another. An examination of the results revealed that the two participants who received the greatest benefit with the greatest improvement in BKB scores (in quiet and in noise) after deactivating indiscriminable electrodes had adjacent electrodes deactivated. Deactivating electrodes that stimulated dead regions might have improved performance because the information would have been lost when they were active and deactivating them redirected the information around those dead regions. This is consistent with the findings of Smith and Faulkner (2006) where redirecting information around a simulated dead region improved speech perception. Those two participants might have had larger dead regions than other participants and the information that was lost when electrodes falling in the dead region were activated affected their speech perception. Hence a large improvement was observed when those electrodes were switched off and the information was redirected around that relatively large dead region. More support to this explanation was provided by the patterns that were discussed above (1) three out of the eight participants who had pre-study BKB scores at ceiling had all their indiscriminable electrodes in the basal region and at least half of the indiscriminable electrodes were basal electrodes in the remaining five, (2) None of the participants with all or the majority of the indiscriminable electrodes in the apical region had ceiling pre-research BKB scores. These two findings were consistent with Shannon et al.’s (2001) study where holes in the apical region of the cochlea were more devastating to speech perception than holes in the basal region.

For those showing benefit, PTED might have uncovered underlying dead regions and deactivating the indiscriminable electrodes in those regions redirected the information around the dead region which could have been the cause of improvement seen. When there was cochlear pathology such as fibrosis or calcification it may have affected the effectiveness of the electrode differentiation test in identifying those dead regions. This in return could have been the cause of lack of improvement in participants suffering from those cochlear pathologies. As discussed earlier in Section 2.3.2.3.1 the presence of dead regions can affect ED, the presence of such dead region not only drops information delivered to those regions. But it also can cause distortion because of the need for higher stimulation levels for electrodes stimulating those regions in order to reach T and M levels thus stimulating surrounding spiral ganglion. Overlapping neural populations would be stimulated by different electrodes negatively affecting speech perception.

Based on this, indiscriminable electrodes identified by PTED can be broadly categorised into 1) indiscriminable electrodes stimulating dead regions (with little or no functioning spiral ganglion) and 2) indiscriminable electrodes stimulating regions with viable spiral ganglion. The second type of indiscriminable electrodes would include cases of cochlear pathology (ossification, calcification and fibrosis) and surgical placement issues.

7.6 Conclusion

PTED can be used to identify regions of poor ED and deactivating indiscriminable electrodes can potentially lead to improvements in speech perception. Greater improvement was observed when the deactivated indiscriminable electrodes fell in the region representing frequencies below 2600 Hz which is more important for speech perception. No improvement was observed in cases of cochlear pathology most likely due to the abnormal spread of current in those cases due to pathology. Sound quality improvement was not always reflected in performance on speech perception measures highlighting the importance of subjective reports and possibly indicating the insensitivity of the speech perception tests.

The electrode differentiation pitch ranking task alone in its current format took between 20 minutes to one hour, depending on how many electrode pairs fail and the number of electrodes on the array. This is still too long for clinical practice but the results would suggest that sufficient information can be obtained by testing adjacent electrodes only (similar to the protocol used in Chapter 3) and not moving to non-adjacent electrodes when an electrode-pair fails (as was used in the protocol in Chapter 7).

7.7 Summary

- Deactivating indiscriminable electrodes can lead to improvements in speech perception
- Indiscriminable electrodes in the apical region were more detrimental to speech perception than those in the basal region.
- Deactivating indiscriminable electrodes improved speech perception to a greater extent when all or the majority of deactivated electrodes (more than 50%) fell in the frequency range lower than 2600 Hz, i.e. mostly apical electrodes.
- Deactivating indiscriminable electrodes can sometimes improve perceived sound quality even if it was not reflected in the speech perception scores, possibly due to the region of deactivation being higher than 2600 Hz. Even though the higher frequency region is less critical for speech it does have importance for sound quality and also music perception, which we did not test here. It may also be an indication that the speech perception measures that we used were not sufficiently sensitive to demonstrate changes.
- Aetiology, medical history and electrode placement could be contributing factors in the success of deactivating indiscriminable electrodes (e.g. calcification and fibrosis can affect the spread of electrical current).
- The improvements seen after deactivating indiscriminable electrodes were not device or strategy related which may have indicated a common underlying cause for the indiscriminable electrodes; dead regions might be a plausible explanation. The difference between indiscriminable electrodes falling in the apical versus the basal region provided further support to this explanation.
- The PTED test has the potential to become a clinically viable tool to improve performance with CIs.

Chapter 8

Comparison of pitch ranking ability between different electrodes in discriminable and indiscriminable electrode regions

Abstract

The ability to utilise pitch information and rank pitch correctly in regions of discriminable electrodes (electrode-pair A) was compared to regions of indiscriminable electrodes (electrode-pair B). Additionally, to evaluate the effect of deactivating indiscriminable electrodes, the ability to pitch rank before and after deactivation of indiscriminable electrodes (electrode-pairs B and C respectively) was evaluated. The change in performance following the deactivation of indiscriminable electrodes was evaluated, and a "performance score" was assigned to each CI recipient. Additionally, the CI recipients were divided into three groups: those showing benefit following the deactivation of indiscriminable electrodes, recipients showing post-deactivation decline in performance and those showing limited post-deactivation benefit. Each group showed different patterns of pitch ranking ability when tested in the three different electrode-pairs, participants showing post deactivation benefit had a lower ability to rank pitch in electrode-pairs B and C than in electrode-pair A, while those showing limited benefit or decline did not. The performance score was also found to be significantly associated with the difference between electrode-pairs A and B ($\gamma = 0.59$, N = 18, $p < .05$) and with the difference between electrode-pairs C and B ($\gamma = 0.95$, N = 13, $p < .001$).

8.1 Introduction

In Chapter 7, following deactivation of indiscriminable electrodes, the CI participants showed different patterns of results with respect to those gaining or not gaining benefit from de-activation. Some participants achieved big improvements in performance while others, such as those with pathological changes secondary to meningitis or otosclerosis received no benefit. A possible explanation for those obtaining benefit was that the identification of indiscriminable electrodes helped identify underlying dead regions (Moore, 2004). Reprogramming by deactivating those electrodes allowed the speech information to be redirected to functional neural regions, giving rise to improvement in speech performance. This is in line with studies that simulated "dead regions" and found that redirecting the information that would have been otherwise dropped (lost) around those spectral holes (dead regions) provided better performance (Smith and Faulkner, 2006 and Faulkner, 2006). To explore this hypothesis it was predicted that CI participants showing benefit from deactivating indiscriminable electrodes would be poorer at discriminating pitch information delivered in between electrodes identified as indiscriminable with the PTED procedure compared to regions of discriminable electrodes. Additionally, those recipients should be better able to process pitch information when indiscriminable electrodes are deactivated in contrast to when those electrodes are active, while CI recipients showing no benefit or a decline in performance from deactivating indiscriminable electrodes would be equally able to discriminate pitch information delivered to regions of electrode-pairs identified as indiscriminable with the PTED procedure compared to regions of discriminable electrode-pairs. It was also predicted that those recipients (showing no benefit or a decline) would not be able to process pitch information when indiscriminable electrodes are deactivated, in contrast to when those electrodes are active.

There is a body of evidence to suggest that for all implant systems intermediate pitch percepts should be perceived between the physical contacts of the CI. For the AB system, intermediate pitches should be perceived due to current steering, but it has also been demonstrated that stimulation of electrode pairs produced perceptions of intermediate pitches for the Cochlear and MEDEL CIs (McDermott and McKay, 1994; Donaldson et al., 2005; Kwon and van den Honert, 2006 and Nobbe et al., 2007). These intermediate pitches were produced with simultaneous stimulation of electrode-pairs (Donaldson et al., 2005 and Nobbe et al., 2007) and with sequential stimulation of electrode-pairs as well (McDermott and McKay, 1994; Kwon and van den Honert, 2006 and Nobbe et al., 2007). There was no significant difference between simultaneous and sequential stimulation of electrode-pairs in terms of the frequency difference limen or the number of intermediate pitch percepts elicited (Donaldson et al., 2005 and Nobbe et al., 2007). The difference limen and number of intermediate pitch percepts varied between CI recipients and, within participants, between the different electrode-pairs at different points on the array (McDermott and McKay, 1994; Donaldson et al., 2005; Kwon and van den Honert, 2006 and Nobbe et al., 2007). Hence, the CI recipient ability to utilise pitch information at specific regions of specific electrode-pairs could be evaluated by testing for discriminable intermediate frequencies.

This chapter describes two studies; the first study compared the ability to rank pitch in regions of indiscriminable electrodes versus regions of discriminable electrodes for CI users with different patterns of post-deactivation results (showing benefit versus showing little or no benefit). The second study evaluated the difference between the CI recipients' ability to utilise pitch information delivered to regions of indiscriminable electrodes both before and after electrode deactivation for CI users with different patterns of post-deactivation results (showing benefit versus showing little or no benefit).

8.2 Experiment I: Comparison between discriminable and indiscriminable electrode-pair regions (A and B)

8.2.1 Introduction aims and hypotheses

This study evaluated the CI recipients' ability to utilise pitch information in regions of both discriminable and indiscriminable electrode-pairs in a pitch ranking (direction) task of pure-tone presentations, using the PTED procedure described in Chapter 3. The change in performance and sound quality for those participants following the deactivation of indiscriminable electrodes was categorised according to the type of change (positive versus negative) and degree of change. The first objective of this study was to compare between the CI recipients' ability to utilise pitch information in regions of discriminable versus indiscriminable electrode-pairs. This was evaluated with the use of a pitch ranking task of pure-tones presented at the centre frequencies of the tested electrode-pair and three frequencies intermediate to them. The second objective was to categorise the change in CI performance of participants following the deactivation of indiscriminable electrodes (in Chapter 7). Then evaluate if the change in performance (degree of benefit; ranging from deterioration in more than one measure to achieving significant improvement in more than one measure) was associated with the difference between their ability to rank pitch in regions of discriminable versus regions of indiscriminable electrode-pairs. The third objective was to evaluate whether pitch ranking of intermediate frequencies (IF) can potentially be used to improve CI programming, especially in cases of discrepancy between indications of the PTED and the IF testing. It was hypothesised that participants showing benefit following the deactivation of indiscriminable electrodes would not be able to rank intermediate frequencies in regions of indiscriminable electrodes in comparison to regions of discriminable electrodes because indiscriminable electrodes uncovered dead regions. While participants showing no or little benefit will be able to rank intermediate frequencies equally well in both regions because indiscriminable electrodes did not uncover dead regions.

Main research hypothesis:

H_1: There will be significant correlation between change in performance following the deactivation of indiscriminable electrodes and the difference in number of IF in regions of discriminable electrodes versus those of indiscriminable electrodes.

Different participants were hypothesised to demonstrate different patterns in terms of their pitch ranking abilities in regions of discriminable versus indiscriminable electrode-pairs. See Figure 8.1 for a diagram demonstrating the hypothesised difference between participants showing benefit following deactivation of indiscriminable electrodes and participants showing little or no post deactivation benefit.

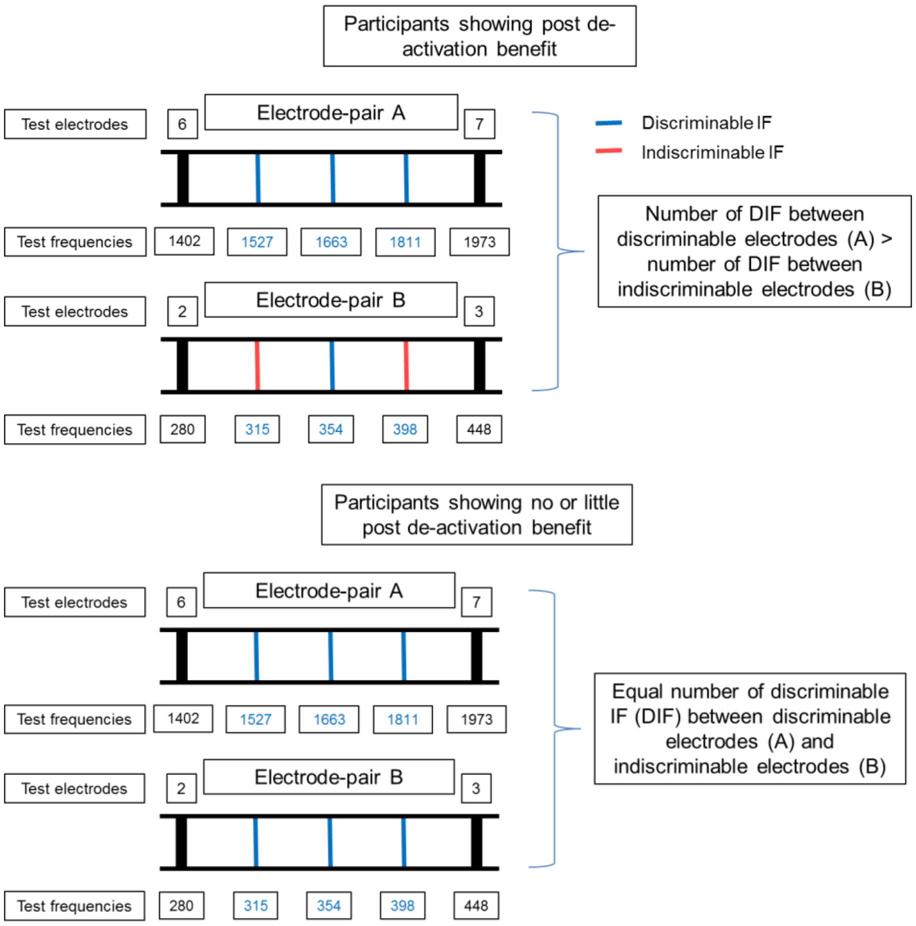


Figure 8.1 Example demonstrating the hypothesis. The number of discriminable IF for electrode-pairs (A and B) for participants showing post deactivation benefit versus those showing no post deactivation benefit; the centre-frequencies of the electrode pair are shown in black and the three IF in blue. Discriminable IFs are shown with blue lines and indiscriminable IFs are shown with red lines.

8.2.2 Method

8.2.2.1 Participants

The participants for this study were recruited for the study described in Chapter 7, in addition to two additional participants that were recruited from the RNTNEH and through the NCIUA. Participants 9 and 13 could not come for the two follow up appointments (required for the study described in Chapter 7) but were particularly recruited for this study because they had otosclerosis and meningitis, respectively, as their aetiology of deafness; these aetiologies of deafness were associated with limited benefit following the deactivation of indiscriminable electrodes (Chapter 7) and were of special interest.

22 adult CI recipients with acquired deafness were recruited. The same inclusion criteria for participants in the studies reported in Chapters 5 and 7 were used, with the addition of having a clear concept of pitch without the need for training and/or are musically trained. To ensure that all participants had a clear understanding of pitch, the three participants (5, 7 and 19) who had a prelingual or perilingual onset of hearing loss were recruited because they were previously musically trained. Participants 1-18 received at least one research program with the indiscriminable electrodes deactivated, and participants 19-22 were star performers who passed PTED for all electrode-pairs and had BKB scores in noise approaching ceiling at a SNR of 10dB and 5dB one. The star performers had CI devices from the three different CI manufacturers, one had an AB device, one had a MED-EI™ device and two had Cochlear® devices. The participants for this study were recruited for the study described in Chapter 7, in addition to two additional participants. Participants 9 and 13 could not come for the two follow up appointments (required for the study described in Chapter 7) but were particularly recruited for this study because they had otosclerosis and meningitis, respectively, as their aetiology of deafness; these aetiologies of deafness were associated

with limited benefit, following the deactivation of indiscriminable electrodes (Chapter 7) and were of special interest.

Participants’ demographics:

(1) Duration of deafness was calculated for each participant from the date of diagnosis of a bilateral profound sensorineural hearing loss; it ranged from 2 to 53 years. (2) Age at testing ranged between 19 to 77 years, with a mean of 59.5 years (± 15) and a median of 63.5 years. (3) The aetiology of the hearing loss was unknown in 9 out of the 22 participants. (4) CI experience was calculated from date of switch on of the present implant; it ranged from 12 to 204 months, with a mean of 63 months (± 48) and a median of 52.5 months. (5) The hearing loss was progressive for all of the participants except participant 13. (6) Among the participants, there were 5 AB CI recipients, 9 MED-EL™ CI recipients and 8 Cochlear® CI recipients. Table (8.1) details participants’ demographics.

Table 8.1 Participants' demographics; duration of deafness was calculated from the date of diagnosis of a bilateral profound sensorineural hearing loss to time of receiving an implant.

Participant	**Aetiology**	**Progressive**	**Age in years**	**Age at implant in years**	**Duration of Deafness in years**	**Implant experience in months**	**Type of implant**
1	Unknown	Yes	75	70	1	57	MED-EL™ Pulsar ci 100 standard
2	Unknown	Yes	67	66	?	12	Nucleus® CI 512
3	Sickle cell anemia	Yes	24	20	9	48	MED-EL™ Pulsar ci 100 standard
4	Unknown	Yes	64	51	33	153	MED-EL™ Combi 40+
5	Measles, age 5.5 years	Yes	62	57	6	62	Nucleus® CI 24R(CS)
6	Unknown	Yes	50	48	2	24	AB HiRes 90K
7	Measles, age 5 years	Yes	66	59	25	89	MED-EL™ Combi 40+
8	Unknown	Yes	71	69	9	25	MED-EL™ Combi 40+
9	Otosclerosis	Yes	67	58	2	106	AB HiRes 90K?
10	Unknown	Yes	69	63	12	38	Nucleus® Freedom (CA)
11	Endolymphatic Hydrops	Yes	42	39	1	34	Nucleus® Freedom (CA)
12	Hereditary started at age 40 years	Yes	59	60	7	72	Nucleus® CI 24R(CS)
13	Meningitis	No	47	44	3/12	27	Nucleus® 22
14	Unknown	Yes	52	47	?	57	AB HiRes 90K
15	Genetic started at age 20 years	Yes	77	73	7	48	AB HiRes 90K
16	Typhoid and Otosclerosis	Yes	72	61	40+	132	MED-EL™ Combi 40+
17	Post general anesthesia in 3rd decade	Yes	63	61	12	18	MED-EL™ Sonata
18	Meniers	Yes	71	70	5	13	MED-EL™ Pulsar ci 100standard

Table 8.1 (continued) Participants' demographics; duration of deafness was calculated from the date of diagnosis of a bilateral profound sensorineural hearing loss to time of receiving an implant.

19	Unknown	Yes	63	57	5	60	MED-EL™ Pulsar ci 100standard
20	Genetic	Yes	19	2	1	204	Nucleus® 22
21	Unknown	Yes	60	56	?	42	AB HiRes 90K
22	Otosclerosis	Yes	69	63	7	71	Nucleus® Freedom

8.2.2.2 Test battery

The PTED test (described in Section 3.2.2.2) was used to detect indiscriminable electrodes and speech perception tests (BKB test in quiet and in noise (described in Section 5.2.2) and the CRM test (described in Section 4.2.2) were delivered to determine the change in performance following deactivation of indiscriminable electrodes. The pure-tone IF testing was administered (described in the following section).

8.2.2.2.1 Pure-tone Intermediate Frequency (PTIF) testing

The intention was that the PTIF testing protocol would have potential future clinical use and could be used with devices from the different manufacturers without the use of a research interface. In line with the PTED testing protocol, the same setup, instructions and software were used. The PTIF testing protocol including the number of IF and scoring of discriminable versus indiscriminable frequencies was based on a pilot study.

Pilot study

The pilot study involved the four star performers (participants 19-22) and two good performers (BKB in quiet > 85) who had at least one indiscriminable electrode-pair. In the pilot phase the participants underwent pitch ranking of three and of seven IF between the centre frequencies of two active electrodes. Testing was conducted at loudness balanced levels for all test frequencies and was applied with electrode-pairs in the apical, mid and basal regions of the electrode array. An IF which was correctly ranked with at least two other test frequencies (PTIF ≥ 80%) and did not show reversal (PTIF ≤ 20%) with any IF was considered discriminable. The four star performers (with no indiscriminable electrodes) had up to 7 discriminable IF (DIF) in each of the three regions except for participant 19 (a telephone user) who had 3 DIF only in the basal region. The two good performers (with at least one indiscriminable electrode) did not have more than three DIF at any region (average of 2 DIFs) and found testing with seven IF very difficult. Based on these findings it was determined that three IF will be sufficient for testing, especially since a star performer who was a telephone user had three DIFs only at one of the tested regions and none of the good performers had more than three DIFs.

PTIF testing protocol

Pure tones that corresponded to the centre frequencies of the processing filters of the test electrode-pair and three frequencies intermediate to those two centre frequencies were presented through the same STAR software and sound box used in Chapters 5-7 (Medical Research Council Institute of Hearing Research (MRC IHR), Nottingham – 'STAR box'). The three intermediate frequencies were determined by equally dividing the frequency range between the centre-frequencies of the test electrode-pair by calculating the geometric mean, giving a total of five test-frequencies, the two centre-frequencies of the test electrode-pair and three IF (see Figure 8.2 for example).

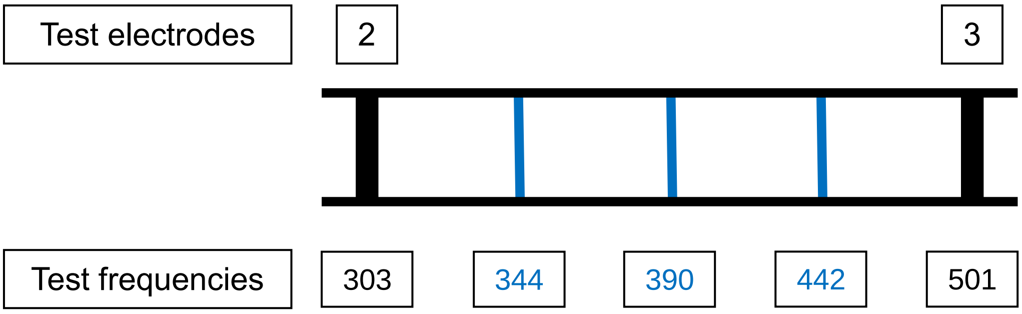


Figure 8.2 Example demonstrating the test-frequencies for an electrode-pair; the centre-frequencies of the electrode pair are shown in black and the three IF in blue. Frequencies are in Hz, and 390 Hz is the mid IF.

Similar to the PTED, the duration of the pure tones was 400 ms, with 50 ms onset and offset cosine ramps and an inter-stimulus interval of 500 ms. The stimuli were presented directly to the speech processor as an auxiliary audio input with a 2 -dB- level rove (ranging from -1 to +1dB with a 1 dB step resolution) in order to remove the impact of loudness cues. Stimuli were delivered at a comfortable level from a desktop PC *via* the IHR soundbox to the patient's CI 'auxiliary' input lead. Comfort level was established for one frequency representing the mid (2nd) IF. Loudness matching was then conducted at both increasing and decreasing test-frequencies to ensure that stimuli were all equally loud. An 'adjacent reference method' for loudness balance (Throckmorton and Collins, 2001) was used where each test-frequency was sequentially balanced to its adjacent, previously balanced test-frequency in a procedure similar to that used in PTED testing (see Section 3.2.2.2).

The pitch-ranking task employed a 2I-2AFC paradigm in which the listener responded to the statement "which sound has the higher pitch?" All possible test-frequency pairs were tested (i.e., each frequency is tested with the four other frequencies) for a minimum of 5 consecutive trials. If the participant scored 80% or lower, a further five trials were carried out giving ten successive trials in total. As mentioned earlier, this was based on binomial distribution calculation of minimum correct responses required to achieve significance at the $p<0.05$ level (Skellam, 1948). The STAR software provided automated delivery and scoring (percent correct and pass or fail categorization) for each test-frequency pair, thus avoiding bias.

8.2.2.3 Procedure

The testing protocol for PTED, BKB (in quiet and in noise) and CRM testing described in Section (7.2.3) was applied, and the same rules for deactivating indiscriminable electrodes were used in the research program. Data previously collected in Chapter 7 was used with the addition of PTED, BKB (in quiet and in noise) and CRM pre and post-deactivation results for participants 9 and 13 who weren’t participants in the study described in Chapter 7. Participants 9 and 13 were each provided with one research program with deactivated indiscriminable electrodes while maintaining the clinical rate of stimulation (similar to program B described in Section 7.2.4) and were tested for speech perception (BKB in quiet and in noise and CRM), following a one-month trial period to evaluate post-deactivation change in CI performance.

Testing for PTIF took place in a 2 metre by 2.5 metre double-walled sound booth. Certain adjustments to the speech processor’s programming (see Section (8.2.2.3.1) below for speech processor programming) had to be applied before administering the PTIF test. For each participant PTIF was conducted for:

(1) For at least one control discriminable electrode-pair (electrode-pair A), which was in the mid-section of the electrode array to avoid placement issues. In this control electrode-pair, both electrodes must have passed PTED with the adjacent electrodes on both sides at a level > 90%.

(2) For at least one indiscriminable electrode-pair (electrode-pair B).

8.2.2.3.1 Research program based on PTIF results in electrode-pair B

Participants who had some indiscriminable electrode-pairs with a number of IF equal to the number of IF for the discriminable electrode-pairs received a new research program where those indiscriminable electrodes were re-activated. In the extra research program based on PTIF results not all indiscriminable electrodes in the PTED were deactivated; i.e. only indiscriminable electrode-pairs with a number of DIF < number of DIF in electrode-pair A were deactivated. The participants were tested for speech perception (BKB in quiet and in noise and CRM) after a one month trial period. Testing was conducted in noise if BKB in quiet > 50.

8.2.2.3.1 Adjusting the speech processor for testing PTIF

The program used when running the PTIF tasks was the participant's original clinical program. Testing program settings were similar to those used for PTED testing (see Section 3.2.3.1) except for maxima settings in Cochlear® implantees. For participants with Cochlear® devices, the number of maxima (see Section1.3.2.3) was adjusted and set to the value of 2 to ensure that the two test electrodes were successively stimulated/stimulation cycle to produce the IF (McDermott and McKay (1994) and Kwon and van den Honert (2006) found that intermediate pitch percepts can be elicited by successive stimulation of two adjacent electrodes in Cochlear® devices).

8.2.3 Analyses

All participants with at least one indiscriminable electrode-pair and have received at least one research program with deactivated indiscriminable electrodes (participants 1-18) were scored for post-deactivation change in CI performance. Each electrode-pair tested for PTIF in electrode-pairs A and B was assigned a score. Statistical analysis was conducted to assess whether there is a significant relationship between post-deactivation change in performance and the difference between number of IF in electrode-pairs A and B.

The post-deactivation change in performance score and the number of IF in the different electrode-pairs were used in group and individual analyses.

8.2.3.1 Post-deactivation change in performance scores

To establish the scoring system of post-deactivation change in CI performance, the change in performance for the 25 participants who received a research program (in Chapter 7) was analysed.

Based on results of those 25 CI participants following the deactivation of indiscriminable electrodes and according to the protocol described in Section (7.3.2) for analysis of individual results, it was found that participants could be categorised into one of the following:

Reported improvement and (a) showed significant improvement in all measures of speech perception or (b) showed significant improvement in two speech perception measures or (c) showed significant improvement in one speech perception measure or (d) did not show significant improvement in any measure of speech perception.

Reported that they did not like the research program’s sound quality and (a) did not show significant difference in any measure of speech perception or (b) showed significant decrement in at least one measure of speech perception or (c) showed significant decrement in two measures of speech perception or (d) showed significant decrement in all measures of speech perception.

A positive point was given for each of the following: (a) reporting improvement, (b) significant improvement in BKB in quiet, (c) significant improvement in BKB in quiet and noise (>10%) and (d) significant improvement in CRM (decreased) threshold (<4dBA). And a negative point was given for each of the following: (a) reporting dislike or decreased performance, (b) significant decrement in BKB in quiet, (c) significant decrement in BKB in noise and (d) significant decrement in CRM (increased) threshold. This would give rise to a “performance score” ranging from -4 up to +4.

8.2.3.2 IF score

The number of IF for each tested electrode-pair was obtained according to the following criteria:

An IF which was correctly ranked with at least two other test frequencies, and did not show reversal (PTIF ≤ 20%) with any IF, was considered discriminable (DIF) and was given a positive point.
An IF that showed reversal with at least two IFs and was not correctly ranked with any other IF (PTIF ≥ 80%) was considered a reversal and was given a negative point. In line with Nelson et al. (1995) who reported that they found pitch-reversals and because all participants had and demonstrated a clear understanding of pitch, it was decided to assign a negative point to reversals. The points are added, giving a score “number of IF” ranging between -3 and +3 IF for each electrode-pair.

For analysis purposes the median number of IFs in electrode-pairs B was subtracted from the median number of IFs in electrode-pair(s) A to obtain the difference between both electrode-pairs for each participant (A - B). The median was used in case more than one electrode-pair was tested in any electrode-pair.

8.2.3.3 Analyses of group results: relationship between post-deactivation change in performance and difference between electrode-pairs A and B

Both the post-deactivation change in performance score and the difference between electrode-pairs A and B (A – B) are categorical ordinal data, so Goodman-Kruskal Gamma was used (Agresti & Finlay, 1997).

8.2.3.4 Analyses of individual results

Individual results were further analysed for:

Participants who showed post-deactivation decline (performance score < 0). IF in electrode-pairs A, B and (A – B) were reported for each participant.

Participants who showed significant post-deactivation benefit in at least one speech perception measure and reported improvement (performance score > 1). IF in electrode-pairs A, B and (A – B) was reported for each participant.

Participants who showed discrepancy between ED and IF indications and received a program based on PTIF results in electrode-pair B. IF for each indiscriminable electrode-pair was reported, and comparisons between speech reception measures with the research programs based on PTED and PTIF were evaluated for significance (see criteria of significant change described in Section 7.3.2).

8.2.4 Results

8.2.3.1 Group results

The Goodman-Kruskal Gamma revealed a significant moderate correlation between the post-deactivation change in performance and the number of IF in (A - B) ($\gamma = 0.59$, $N = 18$, $p < .05$). Thus, the H_1 was accepted and a significant moderate positive correlation was found between the post-deactivation change in performance and the difference between the number of IF in regions of discriminable electrode-pairs and the number of IF in regions of indiscriminable electrode-pairs.

Based on change in performance scores three subgroups were identified: (1) participants showing significant benefit (performance score ≥ 2), (2) participants showing limited benefit (performance score = 1) and (3) participants showing decline (performance score < 0). See Figure (8.3) for IF results for electrode-pairs A, B and (A – B) for the different subgroups.

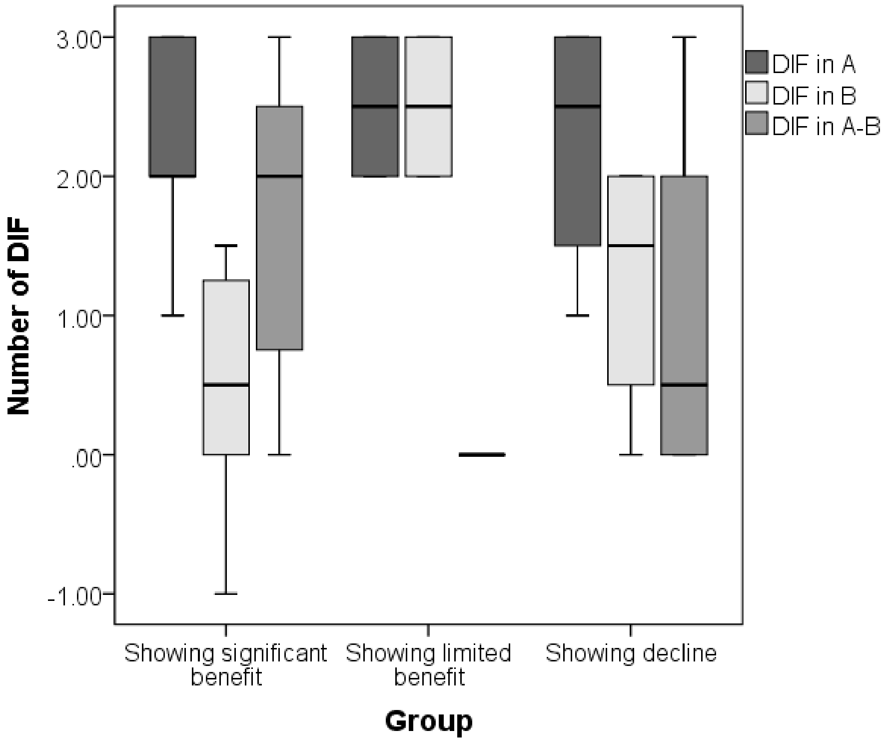


Figure 8.3 IF results for electrode-pairs A (very dark grey boxes), B (light grey boxes) and (A – B) (grey boxes) in number of IF for the three sub-groups. The boxes represent the range between the 25th and 75th percentiles and the lines in the boxes represent the median and whiskers show the 10th and 90th percentiles.

8.2.3.2 Individual results

8.2.3.2.1 Participants who showed post-deactivation decline

Participants who had a change in performance score < 0 were cases of (a) ossification (participants 9 and 16 due to otosclerosis) and (participant 13 due to meningitis) (b) placement issues (participant 6). Post-deactivation change in performance and detailed IF results are shown in Table (8.2).

Table 8.2 Performance scores and detailed IF results in number of IF of electrode-pairs A, B and A – B for all participants who have shown decline after deactivation of indiscriminable electrodes. The median IF score is shown in addition to IF scores for all failed electrode-pairs for participants (6, 9 and 16).

Participant	Performance score	IF in A	IF in B	IF in (A – B)
6	-1	1	1 (1 and 1)	0
9	-2	3	0	3
13	-2	2	2	0
16	-2	3	2 (1 and 3)	1

8.2.3.2.2 Participants who showed significant post-deactivation benefit

Participants were considered to show post-deactivation significant benefit if they both reported benefit and showed significant improvement in at least one speech perception measure; they all had a change in performance score ≥ 2. Performance scores and IF results are shown in Table (8.3).

Table 8.3 Performance scores and IF results in number of IF of electrode-pairs A, B and A – B for all participants who have shown significant benefit after deactivation of indiscriminable electrodes

Participant	Performance score	IF in A	IF in B	IF in (A – B)
1	2	3	1.5 (0 and 3)	1.5
2	2	3	1	2
4	2	3	1	2
5	2	1	-1	2
7	2	3	0	3
10	2	3	1.5	1.5
11	3	2	1	1
12	2	2	1.5	.5
14	2	2	0	2
15	3	2	-1	3
17	2	2	1	1
18	2	2	0	2

8.2.3.2.3 Participants who showed discrepancy between PTED and PTIF indications and received a program based on PTIF in electrode-pair B

Three participants (1, 16 and 18) were provided with a program based on PTIF results in electrode-pair(s) B. They received the extra program because discrepancy was found between PTED and PTIF indications for problematic regions; i.e., the electrode-pair failed PTED but it had a number of IF = IF in a passing electrode-pair (electrode-pair A). Table (8.4) shows the indiscriminable electrode pairs as identified by PTED, the number of IF for each pair and speech perception results with a program based on PTED and a program based on PTIF.

Table 8.4 Summary of results for participants who showed discrepancy between PTED and PTIF indications and received a program based on PTIF in electrode-pair(s) B. PTED's indiscriminable electrode-pairs, IF results in number of IF for each indiscriminable electrode-pair and for electrode-pair A (discriminable electrode-pair), the deactivated electrodes in the program based on PTIF and speech perception results with the use of the programs based on PTED and PTIF. Significant improvement indicated by *. CRM SRT is reported in dBA and percent correct scores are reported for BKB.

Subject	Electrode pairs failing (PTED)	IF in corresponding electrode pair	IF in A	Deactivated electrodes based on PTIF	Speech perception with PTED program	Speech perception with PTIF program
1	5 and 6	3 IF	3 IF	10	BKB in quiet and noise ceiling CRM 11.56	BKB in quiet and noise ceiling CRM 7.5*
	10 and 11	0 IF				
16	4 and 5	3 IF	3 IF	9	BKB in quiet 34	BKB in quiet 55*
	9 and 10	1 IF				
18	2 and 3	0 IF	2 IF	3	BKB in quiet 86 BKB in noise 66	BKB in quiet 91 BKB in noise 80*
	3 and 4	0 IF				
	4 and 5	2 IF				
	8 and 9	2 IF				
	11 and 12	2 IF				

8.2.5 Summary of experiment I

There was a significant association between the change in performance after deactivating indiscriminable electrodes and the difference between IF in regions of discriminable electrodes versus those of indiscriminable electrodes (IF in A – B). The individuals who showed significant improvement had a median IF in (A – B) of 2, while those showing limited benefit or declined benefit had a median IF in (A – B) of 0. Three participants received research programs based on PTIF; they performed significantly better with that program than they did with the best PTED program. Participant 9 did not follow the same pattern and experiment II may help explain why.

8.2.6 Discussion of experiment I

8.2.6.1 Group results

In line with previous studies, intermediate pitches were elicited by the stimulation of electrode-pairs which varied across the participants and across the different electrode pairs (McDermott and McKay, 1994; Donaldson et al., 2005; Kwon and van den Honert, 2006 and Nobbe et al., 2007). As hypothesised there was a statistically significant relationship between post-deactivation change in CI performance and the difference between the number of IF in regions of discriminable versus indiscriminable electrode-pairs regions. Subjects showing benefit following deactivation of indiscriminable electrodes had a larger number of IF in areas of discriminable electrode-pairs in comparison to areas of indiscriminable electrode-pairs. When the CI recipient cannot make use of spectral information delivered to a certain region in the cochlea, that is consistent with the presence of “holes in hearing” (Shannon et al., 2001) or dead regions. Dead regions are “regions in the cochlea with no (or very few) functioning inner hair cells and/or neurons are called dead region” (Moore, 2004). For participants showing benefit, PTED’s indiscriminable electrodes may have identified dead regions and the information delivered to those areas when those electrodes were active may have been lost or at least not fully utilised by the CI recipient. Hence, deactivating those indiscriminable electrodes allowed redirection of an otherwise lost information, which is line with findings of Faulkner (2006) and Smith and Faulkner (2006). While those showing decline did not show signs of dead regions, so deactivating electrodes in regions of good spectral selectivity for those participants may have decreased the CI signal's spectral resolution and negatively affected their performance. This is in concordance with studies indicating reduced performance with decreased spectral resolution (e.g. Shannon et al., 2001; Henry et al., 2000 and McKay and Henshall, 2002). There was a lack of difference between the participant's ability to utilise pitch in areas of discriminable versus indiscriminable electrode-pairs for cases suffering from cochlear pathological changes secondary to their cause of deafness, including meningitis and otosclerosis (participants 13 and 16) or electrode placement problems (participant 6). This provides further support to findings in Chapter 7 where PTED's indiscriminable electrodes most likely have identified underlying dead regions but not when the spread of current may have been compromised, e.g., due to ossification (Rotteveel et al., 2010).

8.2.6.2 Individual results

For those showing post-deactivation significant benefit, there was a difference between the participant's ability to utilise pitch information delivered to regions identified as indiscriminable and those identified as discriminable by the PTED. Individual results were consistent with group results and in line with previous findings as well of studies investigating dead regions (e.g., Shannon et al., 2001). This was not the case for those who weren't showing benefit, with the exception of participant (9) who showed the pattern demonstrated by those who were showing benefit; this may warrant further investigation. Besides, a closer inspection of individual IF results showed that participants (1, 16 and 18) had electrode-pairs that were deemed indiscriminable by the PTED but had an IF equal to electrode-pairs deemed discriminable. Reactivating those electrodes produced significant benefit in comparison to when they were deactivated. It must be noted that this meant additional benefit for participants (1 and 18). The finding again is consistent with enhanced spectral resolution when electrodes that stimulated non-dead regions were reactivated and only electrodes normally stimulating dead regions were deactivated (e.g. Shannon et al., 2001; Henry et al., 2000 and McKay and Henshall, 2002). Participants (1 and 18) have previously shown significant benefit in at least one speech perception measure following the deactivation of all indiscriminable electrodes based on PTED. This meant that gain in performance due to the deactivation of indiscriminable electrodes according to PTED (including those with IF = IF in A and those with IF < IF in A) outweighed the possible decline due to the deactivation of electrodes in regions with good spectral selectivity (IF = IF in A). In other words, stopping stimulation delivered to dead regions for those two participants produced benefit that outweighed the spectral loss due to stopping stimulation to regions that were not dead regions. Based on studies associating improved performance with better spectral resolution (Shannon et al., 2001; Henry et al., 2000 and McKay and Henshall, 2002), it might be assumed that deactivation of electrodes otherwise stimulated dead regions enhanced spectral representation of the signal.

For participant 16 there was not any added gain; the benefit shown in speech perception did not exceed his performance with the original clinical program, but in his case it again highlighted that PTED did not identify regions with poor spectral selectivity in cases of cochlear pathology (fibrosis, calcification or ossification). Results of those participants (1, 16 and 18) most likely indicated that testing for IF has identified dead regions (Shannon et al., 2001) with possibly greater specificity than the PTED. Participant (9)’s IF pattern highlighted the need to investigate the effect of deactivating the indiscriminable electrodes.

8.3 Comparison between discriminable and indiscriminable electrode-pair regions before and after deactivation (A, B and C)

8.3.1 Introduction: aim and hypothesis

This study not only evaluated the CI recipients' ability to utilise pitch information in regions of discriminable and indiscriminable electrodes, it also evaluated their ability to utilise pitch information in regions of indiscriminable electrodes before and after deactivation of indiscriminable electrodes. The same task and scoring system of IF and post-deactivation change in performance described in experiment I (Section 8.2) was used. The first objective of this study was to compare the CI recipients' ability to utilise pitch information in regions of indiscriminable electrode-pairs before and after deactivation. The second objective was to evaluate if the change in performance following the deactivation of indiscriminable electrodes (level of benefit/change ranging from showing decline in more than one measure to gaining significant benefit in more than one measure) was associated with the difference between their ability to rank pitch in regions of indiscriminable electrode-pairs before and after deactivation. The third objective was to evaluate whether post-deactivation pitch ranking of intermediate frequencies (IF) can potentially be used to improve CI programming especially in cases of discrepancy between indications of the PTED and the IF testing. It was hypothesised that participants showing benefit following the deactivation of indiscriminable electrodes would be better able to rank intermediate frequencies in regions of indiscriminable electrodes following deactivation as compared to when these electrodes were active because indiscriminable electrodes uncovered dead regions. While participants showing no or little benefit will be able to rank intermediate frequencies equally well in regions of indiscriminable electrodes before and after deactivation because indiscriminable electrodes did not uncover dead regions. Redirecting information around dead regions would improve performance.

Main research hypothesis:

H_1: There will be a significant correlation between change in performance following the deactivation of indiscriminable electrodes and the difference in number of IF in regions of indiscriminable electrodes before deactivation as compared to post-deactivation.

It was hypothesised that different participants would demonstrate different patterns in terms of their pitch ranking abilities in regions of indiscriminable electrode-pairs before and after deactivation. See Figure 8.4 for a diagram demonstrating the hypothesised difference between participants showing benefit following deactivation of indiscriminable electrodes and participants showing little or no post deactivation benefit.

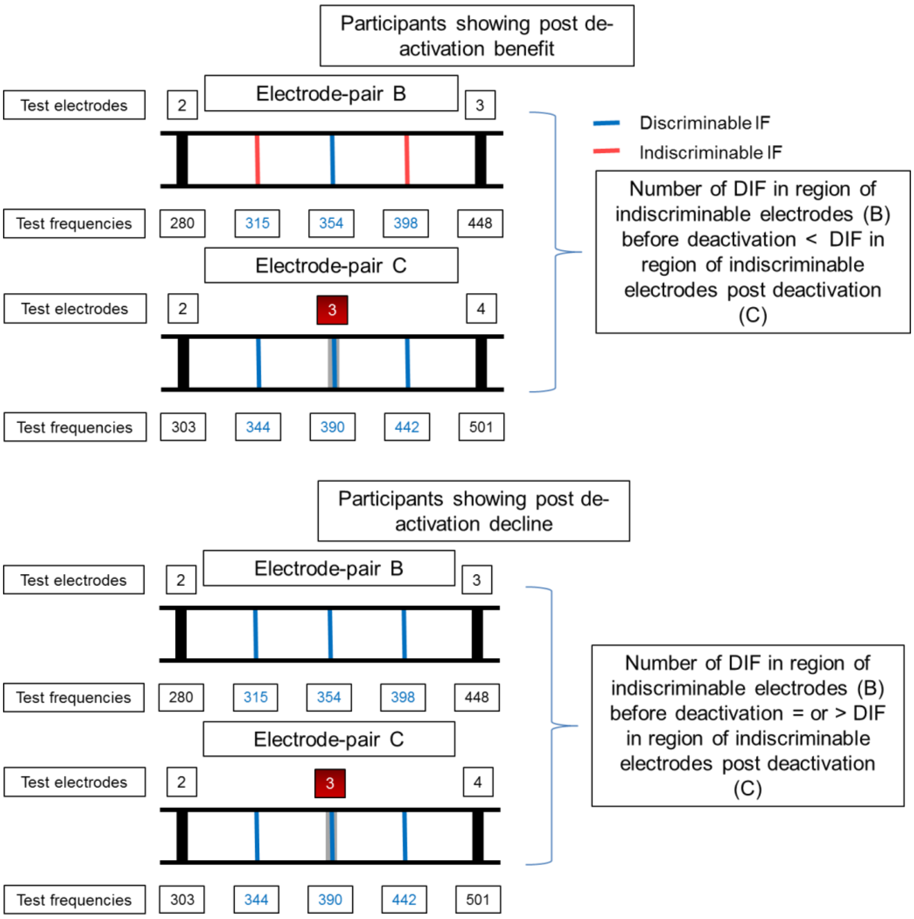


Figure 8.4 Example demonstrating the hypothesis. The difference in number of discriminable IF for electrode-pairs (A and C) for participants showing post deactivation benefit versus those showing no post deactivation benefit; the centre-frequencies of the electrode pair are shown in black and the three IF in blue. Discriminable IFs are shown with blue lines and indiscriminable IFs are shown with red lines. Electrode 3 is the deactivated electrode when testing electrode-pair C in these examples.

8.3.2 Methods

8.3.2.1 Participants

In order to test for post-deactivation IF in the indiscriminable electrode-pair region, the deactivated electrode cannot be located at either the apical or basal end of the array. Hence the same recruitment criteria used in experiment I (described in Section 8.1.2.1) was used with the addition of having deactivated indiscriminable electrodes that weren't at either ends of the electrode array. 13 participants from experiment I who fit these criteria and agreed to continue testing were recruited for experiment II. See Table (8.5) for participants' detailed demographics.

Table 8.5 Participants' demographics for experiment II

Participant	**Aetiology**	**Progressive**	**Age in years**	**Age at implant in years**	**Duration of Deafness in years**	**Implant experience in months**	**Type of implant**
1	Unknown	Yes	75	70	1	57	MED-EL™ Pulsar ci 100 standard
2	Unknown	Yes	67	66	?	12	Nucleus® CI 512
5	Measles, age 5.5 years	Yes	62	57	6	62	Nucleus® CI 24R(CS)

Table 8.5 (continued) Participants’ demographics

7	Measles, age 5 years	Yes	66	59	25	89	MED-EL™ Combi 40+
9	Otosclerosis	Yes	67	58	2	106	AB HiRes 90K?
10	Unknown	Yes	69	63	12	38	Nucleus® Freedom (CA)
11	Endolymphatic Hydrops	Yes	42	39	1	34	Nucleus® Freedom (CA)
12	Genetic started at age 40 years	Yes	59	60	7	72	Nucleus® CI 24R(CS)
13	Meningitis	No	47	44	3/12	27	Nucleus® 22
14	Unknown	Yes	52	47	?	57	AB HiRes 90K
15	Genetic started at age 20 years	Yes	77	73	7	48	AB HiRes 90K
16	Typhoid and Otosclerosis	Yes	72	61	40+	132	MED-EL™ Combi 40+
17	Post general anesthesia in 3rd decade	Yes	63	61	12	18	MED-EL™ Sonata

8.3.2.2 Test battery

The same test battery used in experiment I was used.

8.3.2.3 Procedure

Data used and collected in experiment I for the participants of experiments II was used, which included change in performance scores and IF of discriminable and indiscriminable electrode-pair regions (electrode-pairs A and B). Additionally, PTIF was applied to test the region of indiscriminable electrode-pairs following deactivation, which was called electrode-pair(s) C (see Figure (8.5) for diagram demonstrating electrode-pairs B and C). IF testing for electrode-pair(s) C was applied with research programs based on PTED (in Chapter 7) and PTIF (in experiment I). Testing for PTIF took place in a 2×2.5 m double-walled sound booth with the use of adjustments to the speech processor's programming described in Section (8.2.2.3).

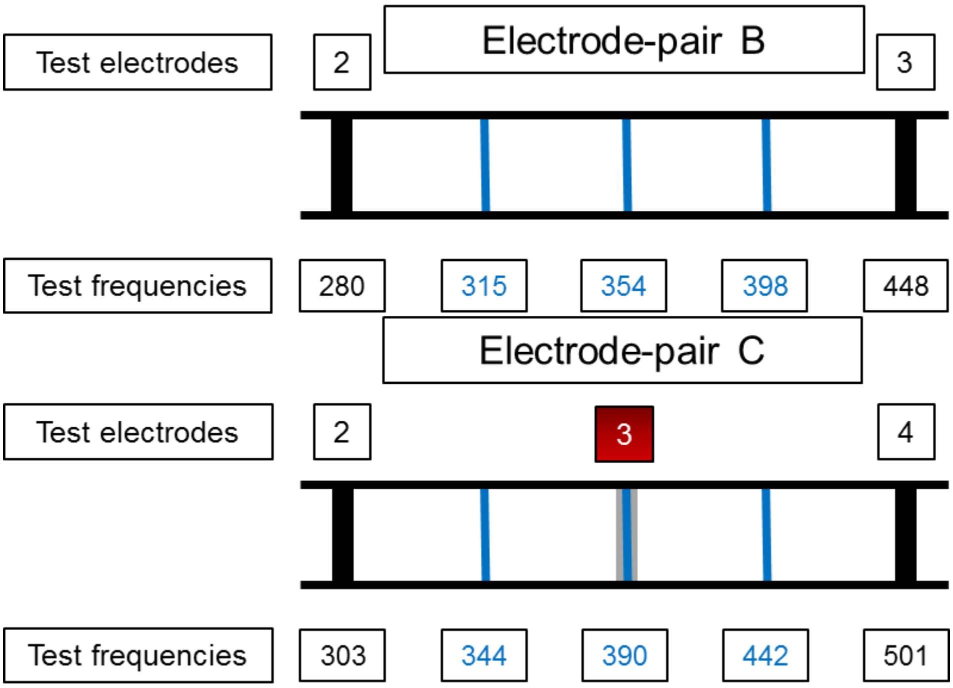


Figure 8.5 Example demonstrating the test-frequencies for an indiscriminable electrode-pair in electrode-pair B and for the corresponding electrode pair in electrode-pair C. The electrode pair is electrodes 2 and 3 in electrode-pair B with electrode 3 active and the electrode pair in electrode-pair C with electrode 3 deactivated (shown in red), the centre-frequencies of the electrode pair are shown in black and the three intermediate frequencies in blue.

8.3.2.3.1 Research program based on PTIF results in electrode-pair C

One participant (12) who had IF = 0 in electrode-pair type C for one post-deactivation electrode-pair (electrodes 6 and 8), but not the other three electrode-pairs tested for electrode-pair type C, was provided with an additional research program. In line with Nelson et al.'s (1995) recommendation regarding regions of poor electrode-pitch-ranking, the extra research program increased the spatial separation in that region (electrodes 6 and 8); an additional electrode (6) was deactivated. The participant was tested for IF (electrode-pair type C between electrodes 5 and 8) and speech perception (BKB in quiet which was lower than 50 and CRM) after a one month trial period.

8.3.3 Analyses

Scores for post-deactivation change in CI performance (described in 8.2.3.1) and IF scores (described in 8.2.3.2) for each electrode-pair tested for PTIF in electrode-pairs B and C were obtained. Statistical analysis was conducted to assess whether there is a significant relationship between post-deactivation change in performance and the difference between number of IF in electrode-pairs B and C.

The post-deactivation change in performance score and the number of IF in the different electrode-pairs were used in group and individual analyses. For analysis purposes the median number of IF in electrode-pair(s) B was subtracted from the median number of IF in electrode-pair(s) C to obtain the difference between both types of electrode-pairs for each participant (C - B). The median was used in case more than one electrode-pair was tested in any electrode-pair.

8.3.3.1 Analyses of group results: relationship between post-deactivation change in performance and difference between electrode-pairs B and C

Both the post-deactivation change in performance score and the difference between electrode-pairs C and B (C – B) are categorical ordinal data, so Goodman-Kruskal Gamma was used (Agresti & Finlay, 1997).

8.2.3.2 Analyses of individual results

Individual results were further analysed for:

Participants who showed post-deactivation decline (performance score < 0). IF in electrode-pairs B, C and (C – B) were reported for each participant.

Participants who showed significant post-deactivation benefit in at least one speech perception measure and reported improvement (performance score > 1). IF in electrode-pairs B, C and (C – B) were reported for each participant.

Participants who showed discrepancy between PTED and PTIF indications and received a program based on PTIF in electrode-pair B (provided in experiment I). IF in electrode-pairs B, C and (C – B) were reported for each participant if applicable.

Participants who showed discrepancy between PTED and PTIF indications and received a program based on PTIF in electrode-pair C.

8.3.4 Results

8.3.4.1 Group results: relationship between post-deactivation change in performance and difference between electrode-pairs B and C

The Goodman-Kruskal Gamma revealed a significant strong association between the post-deactivation change in performance and the number of IF in (C - B) ($\gamma = 0.95$, $N = 13$, $p < .001$). Thus the H_1 was accepted and a significant strong positive correlation was found between the post-deactivation change in performance and the difference between the number of IF in regions of indiscriminable electrode-pairs before and after deactivation.

Based on change in performance scores, two subgroups were identified: (1) participants showing significant benefit (performance score ≥ 2) and (2) participants showing decline (performance score < 0). See Figure (8.6) for IF results for electrode-pairs B, C and (C – B) for the different subgroups.

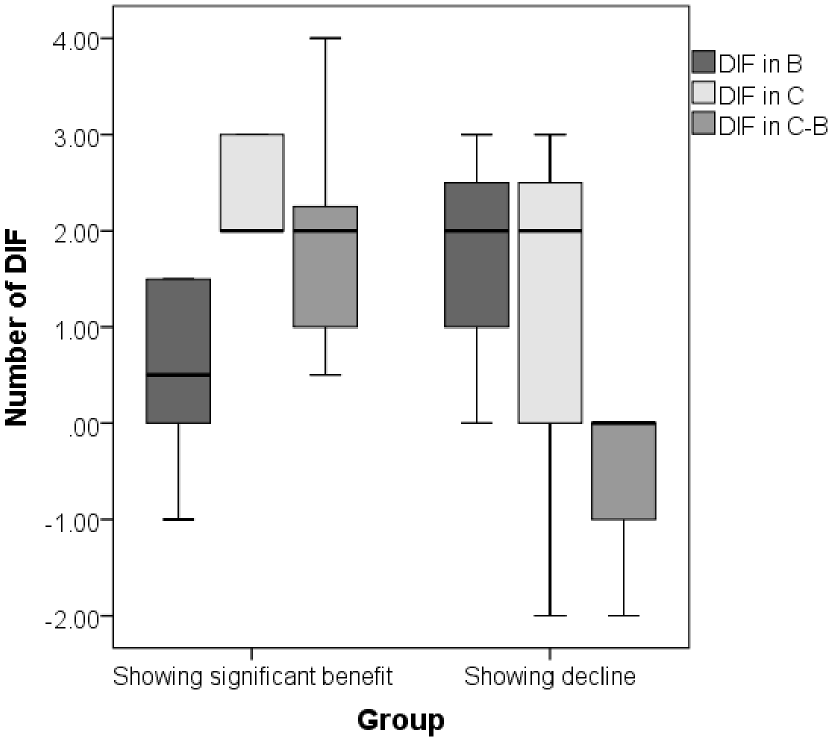


Figure 8.6 IF results for electrode-pairs B (very dark grey boxes), C (light grey boxes) and (C – B) (grey boxes) in number of IF for the three sub-groups. The boxes represent the range between the 25th and 75th percentiles and the lines in the boxes represent the median and whiskers show the 10th and 90th percentiles.

8.2.3.2 Individual results

8.2.3.2.1 Participants who showed post-deactivation decline

As previously reported, some participants who had a change in performance score < 0 were cases of ossification due to Otosclerosis (participants 9 and 16) or secondary to meningitis (participant 13). Only these participants had indiscriminable electrodes in the middle of the array allowing testing for IF in electrode-pair C. Since participant (16) received an additional research program based on PTIF in experiment I, results reported here are with the PTED research program only. Change in performance and IF results are shown in Table (8.6).

Table 8.6 Performance scores and detailed IF results in number of IF of electrode-pairs A, B, C and (C – B) for participants who have shown decline after deactivation of indiscriminable electrodes. The median IF score is shown in addition to IF scores for all failed electrode-pairs for participant (16). The median number of IF is reported, in cases where electrode-pairs in one electrode-pair were not homogenous in term of the number of IF all IF values are reported within brackets.

Participant	Performance score	IF in A	IF in B	IF in C	IF in (C – B)
9	-2	3	0	-2	-2
13	-2	2	2	2	0
16	-2	3	2 (1 and 3)	3 (3 and 3)	1 (2 and 0)

8.3.3.2.2 Participants who showed significant post-deactivation benefit

Participants were considered to show post-deactivation significant benefit if they all had a change in performance score ≥ 2. Performance scores and IF results are shown in Table (8.7).

Table 8.7 Performance scores and IF results in number of IF of electrode-pairs A, B, C and (C – B) for all participants who have shown significant benefit after deactivation of indiscriminable electrodes. The median number of IF is reported, in cases where electrode-pairs in one electrode-pair were not homogenous in term of the number of IF all IF values are reported within brackets.

Participant	Performance score	IF in A	IF in B	IF in C	IF in (C – B)
1	2	3	1.5 (0 and 3)	3 (3 and 3)	2.25 (1.5 and 3)
2	2	3	1	2	1
5	2	1	-1	2	4
7	2	3	0	2	2
10	2	3	1.5	3	1.5
11	3	2	1	2	1
12	2	2	1.5	2 (2,2,3 and 0)	.5
14	2	2	0	2	2
15	3	2	-1	2	3
17	2	2	1	3	2

8.3.3.2.4 Participants who showed discrepancy between PTED and PTIF indications and received a program based on PTIF in electrode-pair B

The speech perception and IF (in electrode-pair B and C) results for the three participants (1, 16 and 18) who received research programs based on PTIF in experiment I are shown in Table (8.8).

Table 8.8 Results of Participants who showed discrepancy between PTED and PTIF indications and received a program based on PTIF in electrode-pair B. IF results for participants (1, 16 and 18) who received a program in experiment 1 based on IF in electrode-pair B, IF results in number of IF for each indiscriminable electrode-pair (electrode-pair B) involving a deactivated electrode and for electrode-pair C (corresponding region for each electrode-pair B), and speech perception results with the use of the programs based on PTED and PTIF. Ceiling scores were not reported and significant improvement is indicated by *. CRM SRT is reported in dBA and percent correct scores are reported for BKB.

Subject	PTED program				PTIF program			
	IF in B	IF in C	IF in (C – B)	Speech testing	IF in B	IF in C	IF in (C – B)	Speech testing
1	3	3	0	CRM 11.6dBA	0	2	2	CRM 7.5*dBA
	0	2	2					
16	3	3	0	BKB in quiet 34	1	3	2	BKB in quiet 55*dBA
	1	3	2					
18	0	2	2	BKB in quiet 86 BKB in noise 66	0	2	2	BKB in quiet 91 BKB in noise 80*
	2	2	0					
	2	2	0					
	2	2	0					

8.3.3.2.4 Participants who showed a peculiar pattern in performance and received an extra program based on results of IF in electrode-pair C

As mentioned in Section (8.3.2.3) only participant (12) showed a peculiar pattern in performance after deactivating the indiscriminable electrodes provided in the study described in Chapter 7. She showed significant improvement with CRM and reported improvement in understanding men's voices but not as much with women’s voices. IF results showed a somewhat corresponding pattern, a greater number of IF in electrode-pair C at the lower frequency range (240 Hz- 1520 Hz) but 0 IF in electrode-pair C at the higher frequency range (3249 Hz- 4288 Hz). She subsequently received an extra program based on results of IF in C but did not show improvement in speech perception measures. See Table (8.9) for results.

Table 8.9 Deactivated electrodes and IF results of the corresponding electrode-pair C for participant (12) (corresponding region for each deactivated electrodes) in number of IF with the programs based on PTED and PTIF (based on electrode-pair C).

Program based on PTED		Program based on PTIF	
Deactivated electrodes	IF in corresponding electrode-pair C	Deactivated electrodes	IF in corresponding electrode-pair C
7	0	6 and 7	0
14	2	14	2
16 and 17	3	16 and 17	3
19	2	19	2

8.3.4 Summary of experiment II

There was a significant and strong correlation between the change in performance after deactivating indiscriminable electrodes and the difference between IF in regions of indiscriminable electrodes before and after deactivation (IF in C – B). The individuals who showed significant improvement had a median IF in (C – B) of 2 while those showing decline benefit had a median IF in (C – B) of 0. IF in electrode-pair C (-2) for participant 9 may explain the decline in performance despite displaying the pattern observed in participants showing improvement (IF in A > IF in B). IF in electrode-pair C for participants who have received a program based on IF in electrode-pair B were also consistent with the observed improvement.

8.3.5 Discussion of experiment II

8.3.5.1 Group results

As hypothesised there was a statistically significant positive relationship between post-deactivation change in CI performance and the difference between the number of IF in regions of indiscriminable electrode-pairs regions before and after deactivation. The participants who showed significant benefit following deactivation of indiscriminable electrodes (in the study described in Chapter 7) had a larger number of IF in areas of indiscriminable electrode-pairs post-deactivation in comparison to IF in regions of indiscriminable electrode-pairs when they were active. These findings were consistent with improved spectral representation following the deactivation of indiscriminable electrodes (Shannon et al., 2001; Henry et al., 2000 and McKay and Henshall, 2002). This pattern also supported Nelson's (1995) proposal to increase spatial separation in areas of spectral resolution in order to enhance performance. This is also in line with studies that improved performance by deactivating problematic electrode/ sites (Zwolan et al., 1997 and Zhou and Pfingst, 2012). While participants showing decline did not have a larger number of IF in areas of indiscriminable electrode-pairs post-deactivation in comparison to IF in the pre-deactivation regions of indiscriminable electrode-pairs, consistent with decreased spectral resolution (e.g. Shannon et al., 2001). This again provides further support to the presence of underlying dead regions “holes in hearing” that were detected by PTED's indiscriminable electrodes in participants showing benefit. And redirecting information around those regions by deactivating those electrodes provided the observed benefit. An explanation which is in line with findings by Faulkner (2006) and Smith and Faulkner (2006) where they reported that redirecting information around a simulated spectral hole improved speech perception in comparison to dropping that information.

8.3.5.2 Individual results

Participants' showing post-deactivation significant benefit, were better able to utilise pitch information delivered to regions of indiscriminable electrodes post-deactivation, in comparison to pre-deactivation (as proposed by Nelson et al., 1995). Participants who received programs based on PTIF in experiment I and received benefit showed the same pattern. Examining IF in electrode-pair C helped shed light on why participant (9) demonstrated the IF (in A and B) pattern of participants showing post-deactivation improvement but suffered from a decline in post-deactivation performance. The participant's IF testing in electrode-pair C showed that he suffered from reversals after deactivating the indiscriminable electrode, so his ability to utilise pitch information did not improve, which is probably why he did not like the sound quality. Reversals could be due to several reasons, including cross-turn stimulation, or calcification negatively affecting the spread of current (Rotteveel et al., 2010). However, since the participant did not show reversals in electrode-pair B and considering that the deactivated electrode is in a more basal position, cross-turn stimulation is an unlikely reason. A more likely reason would be a combination of an underlying dead region and calcification affecting the spread of current, which became worse with increased spatial separation between the active electrodes (post-deactivation of the electrode). In such cases of calcification deactivating electrodes in most likely dead regions may not be ideal; filter frequency-range manipulation to limit the information delivered to that region might provide a solution. Another solution could be the use of a more focussed stimulation such as partial-tripolar (Bierer et al., 2005; Bonham et al., 2005; Litvak et al., 2007; Zhu et al., 2012) (described in Section 1.2.5) in combination with filter-frequency-range adjustment to minimise the negative effect of abnormal spread of current. Participant (12) IF results in electrode-pair C for the different regions of deactivated electrodes reflected to an extent post-deactivation change in performance. She showed limited ability to utilise pitch information in the region of the deactivated indiscriminable-electrode at high frequencies as opposed to better pitch perception in the region of the deactivated indiscriminable-electrode at lows frequencies. These IF results corresponded with the participant’s report of better perception of men’s voices but not that of women, which is in concordance with men’s voices having lower fundamental frequencies (e.g. Saxman and Burk, 1967). Increasing spatial separation between active electrodes in the high frequency range did not improve her speech perception nor did it increase the number of IF in that region. Again, performance reflected the pattern observed in IF testing. This lack of improvement may reflect poor neuronal survival (dead regions as shown by Shannon et al., 2001) in that frequency range or placement issues (e.g. relative distance from spiral ganglion as proposed by Wilson and Dorman, 2008) so no matter how much spatial separation there is between active electrodes it did not enhance her ability to rank pitch in that range. The deactivation of indiscriminable electrodes in that region for such a case may not be the best option, limiting information presented to that region by manipulating the filter-frequency-range and/or by using focussed stimulation might be better options and may be explored in future research.

8.4 Discussion for experiments I and II

In line with previous findings, the stimulation of electrode-pairs produced intermediate pitches and the number of discriminable IF varied both within and between subjects (McDermott and McKay, 1994; Donaldson et al., 2005; Kwon and van den Honert, 2006 and Nobbe et al., 2007). The studies reported in this chapter showed that the number of IF in the different regions and electrode-pairs (A, B and C) can reflect the change in performance observed, following the deactivation of indiscriminable electrodes as identified *via* PTED. These results may shed some light on results of the study described in Chapter 7. Deactivation of indiscriminable electrodes as identified by PTED provided benefit when those electrodes uncovered underlying dead regions (Shannon et al., 2001). Redirecting information around those regions gave rise to improvement, which is in concurrence with findings of simulation studies (Faulkner, 2006 and Smith and Faulkner, 2006). PTIF also sheds some light on the lack of post-deactivation improvement in performance in some participants (cases of Otosclerosis or meningitis). PTIF also identified some indiscriminable electrodes that did not stimulate dead regions either due to placement issues or in the absence of pathological changes (e.g. fibrosis or calcification) or placement problems. Deactivating electrodes for those participants did not improve their ability to utilise pitch information in regions of deactivated electrodes, and deactivation may have caused decreased spectral resolution (Henry et al., 2000 and McKay and Henshall, 2002). PTIF may potentially be used to further guide programming of CI to improve performance or identify dead regions, and results from these two studies provide some validation to the PTIF test. Further research in this area could be fruitful.

These results further support the presence of different types of indiscriminable electrodes (1) those stimulating dead regions, (2) those stimulating regions with functioning spiral ganglion cells (non-dead regions) due to cochlear pathological changes such as fibrosis, calcification or ossification, (3) those stimulating regions with functioning spiral ganglion cells (non-dead regions) due to surgical placement issues and (4) those stimulating regions with functioning spiral ganglion cells (non-dead regions) in the absence of cochlear pathological changes such as fibrosis, calcification or ossification. In contrast to the latter three types (2, 3 and 4) the deactivation of the first type provides improvement in speech perception.

8.5 Conclusion

This Chapter provided an explanation of change in CI performance following the deactivation of CI electrodes, including the patterns observed in Chapter 7. Participants showing benefit post deactivation (of indiscriminable electrodes) had a larger number of discriminable IF in regions of discriminable electrodes, compared to regions of indiscriminable electrodes; however, those showing limited benefit or decline post deactivation did not. Furthermore, those showing post deactivation benefit had a larger number of

DIF in regions of indiscriminable electrodes post deactivation of indiscriminable electrodes, compared to those regions when those electrodes were active, but those showing limited benefit or decline post deactivation did not. It also demonstrated the potential of using the PTED and PTIF tests as possibly clinically applicable tools to help guide optimise programming, with the additional potential for PTIF to be used to identify dead regions and possibly predict the effect of deactivating electrodes; however, further research is required. This chapter also highlighted the need to explore other options besides deactivating electrodes deemed indiscriminable or have possible underlying dead regions.

8.6 Summary

- PTIF demonstrated that electrodes identified as indiscriminable *via* the PTED have most likely uncovered underlying dead regions and the benefit observed reflects the redirection of information that would have otherwise been lost.
- In cases where cochlear pathological changes are suspected the PTIF may provide a test for underlying dead regions.
- PTIF can potentially be used as a clinical tool to guide programming of CI.

Chapter 9

Electrode differentiation with bilateral cochlear implants

Abstract

This study examined the efficacy of two different CI research programs based on matching pitch and loudness across the two CI devices for six bilaterally-implanted adults. One research program was based on direct-stimulation (DS) matching with the use of two clinical programming interfaces, and the other research program based on pure-tone (PT) auditory matching. Evaluation measures included spatial release from masking (SRM) with the use of BKB sentences in speech-spectrum shaped noise, with speech presented from the front (at 0°azimuth) and noise presented to the right (at +90°) or to the left (at -90°), a localisation test (for 30° and 15° of separation) and, finally, an across-ears pitch comparison test . Statistically significant improvements were found in localisation at 30° of separation with the research program based on DS only (t = -3.03*, df = 5, $p < 0.05$) and in localisation at 15° of separation with the use of DS and PT respectively (t = -2.62*, df = 5, $p < 0.05$ and t = -6.95**, df = 5, $p < 0.005$). Statistically significant improvements were also observed for the ‘BKB in noise’ with the use of the best research program, compared to the best clinical BKB score with speech-spectrum shaped noise presented on the right and on the left, respectively (t = -3.179*, df = 4, $p < 0.05$ and t = -3.22*, df = 4, $p < 0.05$) after the exclusion of the participant with unilateral, severe cochlear ossification in the weaker side. Although three out of six participants showed statistically significant improvements in ‘BKB in noise’ with speech presented from the front (at 0°azimuth), no overall statistically significant improvement was observed as a group. A ‘pitch comparison test’ was applied across-ears (to evaluate how well matched the two bilateral implants are in terms of

frequency) and revealed statistically significant improvement with the use of DS (t = -5.22**, df = 5, $p < 0.005$).

9.1 Introduction

Bilateral implantation has been considered one of the advances that produced significant improvement in performance with CI (Wilson and Dorman, 2008). Having both ears implanted ensures that the better ear will be implanted and provides the hearing impaired with a “back-up” device if one should fail (e.g. Verschuur et al., 2005). It is essential in cases of meningitis urgently to provide bilateral implants due to the speed at which ossification can occur, leading to a poorer hearing and speech perception outcome following implantation. In addition to allowing listeners to detect and locate potential sources of danger (e.g. traffic) bilateral implantation has the potential to improve localisation performance the perception of speech in noise, leading to improved communication abilities. Many researchers have demonstrated improvements in localisation with bilateral, compared to unilateral, implantation (Schleich et al., 2004; Seeber et al., 2004 ; Laszig et al., 2004; Verschuur et al., 2005; Tyler et al., 2007; Neuman et al., 2007; Mosnier et al., 2009; Kerger and Seeber, 2012) and also improved speech perception in noise, especially when speech and noise are spatially separated (Laszig et al., 2004; Schleich et al.,2004; Eapen et al., 2009; Litovsky et al., 2006 and Ricketts et al., 2006). However, some studies that evaluated bilateral CI benefit in speech perception in quiet and in noise when both speech and noise were presented only from in front of the listener (at 0°azimuth) report conflicting results. Some found a bilateral advantage for speech perception in quiet (e.g. Mosnier et al., 2009; Tyler et al., 2007; Eapen et al., 2009; Dunn et al., 2010 and Litovsky et al., 2006), whilst others did not (Ramsden et al., 2005 and Laszig et al., 2004). For speech in noise at 0° azimuth, some report an improvement (Schleich et al.,2004; Ramsden et al., 2005; Eapen et al., 2009 and Wackym et al., 2007) but others do not (Laszig et al.,2004; Litovsky et al., 2006). One potential reason for this discrepancy could be that the observed benefits stem predominantly from the head-shadow effect, which cannot be utilised when signal and noise are both presented from the front. Different degrees of performance might arise as a result of the variable amount of bilateral summation between subjects, possible due to the degree of mismatch in frequencies between ears. Supporting evidence for the mismatch effect was shown in a simulation study (Siciliano et al., 2010), in which six-channel noise vocoders were used with normally-hearing adults, three out of six channels were binaurally mismatched with an upward frequency shift in one ear only. These authors demonstrated that participants did not show any speech perception benefit from the three mismatched channels when performance was compared to a condition which used three binaurally matched channels only. They also found that program frequency mismatch between ears could not be accommodated for by training. In line with these findings, Zhou and Pfingst (2012) found that dichotic programs employing the best stimulation sites (electrodes) only, as identified by the modulation detection threshold, provided better speech perception than programs employing the same electrodes but with frequency redistribution permitted. In dichotic programs, the program in each device contained ‘spectral holes’ that were complemented by the corresponding contralateral site, thus avoiding pitch-mismatches between ears. However, localisation performance was not evaluated with any of their programs. Considering that Dunn et al. (2004) found that splitting frequencies between ears significantly reduced localisation, localisation could have been affected in the dichotic programs.

In Chapter 7, deactivating indiscriminable electrodes based on a pitch ranking task (were non-tonotopic) provided benefit for 20 out of 25 unilaterally implanted recipients. In this chapter a study that evaluates the effect of deactivating electrodes which are indiscriminable or non-tonotopic in relation to the contralateral ear by providing programs which matches the two implants for pitch.

9.1.1 Interaural differences

The ability to exploit information arriving at both ears underlies binaural hearing. This entails the perception of interaural differences in time of arrival (to each ear) and sound level when entering each ear (e.g. McAlpine, 2005). When a sound source lies to the front of a listener (at 0°azimuth), it arrives at both ears at the same time and at an equal loudness level. However moving the sound even slightly to the left, for example, has two consequences. (1) The sound will arrive at the left ear first creating an interaural time difference (ITD) between the ears and (2) the sound will enter the left ear at higher loudness level than the right ear giving rise to an interaural level difference (ILD).

The duplex theory of binaural hearing (Rayleigh, 1907) stipulates that ITD cues mainly operate at frequencies lower than about 1500 Hz whilst ILD cues operate at higher frequencies, where the wavelength of sound relative to the source generates sufficient ‘shadowing’ by the head. This was also supported by findings of Stevens and Newman (1936) where the ability to localise pure-tones varied according to frequency; localisation of frequencies lower than 1000 Hz was based on ITD and localisation of frequencies above 4000 Hz was based on ILD.

9.1.2 Spatial release from masking (SRM)

Spatial release from masking (SRM) refers to improved speech perception in noise when the speech and noise are spatially separated (Plomp and Mimpen, 1981; Bronkhorst and Plomp, 1992; Nilsson et al., 1994; Koehnke and Besing, 1996; Peissig and Kollmeier, 1997; Hawley et al., 1999; Shinn-Cunningham et al., 2001; Litovsky et al., 2002). It is usually assessed by comparing speech perception in noise (either the speech perception threshold in an adaptive test or the percentage correct response in a fixed level test) at two different conditions, with both speech and noise presented from the front (at 0°azimuth) and with speech presented from the front (at

0°azimuth) and noise presented to the right (at +90°) or to the left (at -90°) - see Figure (9.1). Speech perception is usually better (lower thresholds or higher percentage correct scores) when noise is presented to the side (either at +90°or at -90°). This occurs because of two underlying reasons (Durlach, 1963; Zurek, 1992; Bronkhorst, 2000): (1) one ear is shielded by the head when the noise is presented at the contralateral side of the head (head shadow), providing an improved SNR at frequencies greater than 500-1000 Hz and (2) the difference in ITD between the speech and the noise. SRM provides a measure of binaural benefit in speech perception that does not require the deactivation of either of the two CI devices during testing.

9.1.3 Aims and hypotheses

This chapter describes a study aimed at improving frequency matching between the two implants in bilaterally-implanted individuals *via* DS and *via* PT auditory stimulation. The implanted participants were evaluated with the use of SRM, BKB in speech-spectrum shaped noise, a “number localisation” task and CRM. To evaluate how well matched the two devices were, a test applying an across-ears pitch-comparison task with a fixed set of nine frequencies was administered with each program. It was hypothesised that matching the bilateral CIs for pitch will binaural hearing and consequentially will affect speech perception [CRM and BKB in noise when speech is presented from the front (at 0°azimuth) and noise is presented from one of the front (at 0°azimuth), right (at +90°) or left (at -90°)]. It was also hypothesised that it will therefore affect SRM, localisation and performance on the across-ears pitch-comparison test. If the degree of pitch matching between the two implants (as measured by performance on the across-ears pitch comparison test) is correlated to localisation and/or speech perception then this could be indicative of better/degree of matching between the two implants affecting localisation and use of binaural hearing.

Main research hypotheses:

H_1: Matching electrodes’ pitch and frequency tables (see Section 1.3.2) between the bilateral CI devices based on pitch perception *via* direct stimulation will affect CI performance.

H_2: Matching electrodes’ pitch and frequency tables (see Section 1.3.2) between the bilateral CI devices based on pitch perception *via* pure-tone auditory stimulation will affect CI performance.

H_3: There will be a significant correlation between localisation with the use of five speakers at 30° and 15° of separation and performance on the across-ears pitch-comparison test.

H_4: There will be a significant correlation between speech perception and performance on the across-ears pitch-comparison test.

Sub-hypotheses are:

1- Matching electrodes’ pitch and frequency tables between the bilateral CI devices based on pitch perception either *via* direct stimulation or *via* pure-tone auditory stimulation will affect speech perception [CRM and BKB in noise when speech is presented from the front (at 0°azimuth) and noise is presented from one of the front (at 0°azimuth), right (at +90°) or left (at -90°)].

2- Matching electrodes’ pitch and frequency tables between the bilateral CI devices based on pitch perception either *via* direct stimulation or *via* pure-tone auditory stimulation will affect SRM.

3- Matching electrodes’ pitch and frequency tables between the bilateral CI devices *via* DS will affect localisation in a number-localisation task with the use of five speakers at 30° and 15° of separation.

4- Matching electrodes’ pitch and frequency tables between the bilateral CI devices *via* PT auditory stimulation will affect localisation in a number localisation task with the use of five speakers at 30° and 15° of separation.

5- Matching electrodes’ pitch and frequency tables between the bilateral CI devices *via* DS will affect performance on the across-ears pitch-ranking screening test.
6- Matching electrodes’ pitch and frequency tables between the bilateral CI devices *via* PT auditory stimulation will affect performance on the across-ears pitch-ranking screening test.
7- There will be a significant correlation between performance on the across-ears pitch-comparison test and localisation in a number-localisation task with the use of five speakers at 30° and at 15° of separation.

8- There will be a significant correlation between performance on the across-ears pitch-comparison test and speech perception [CRM and BKB in noise when speech is presented from the front (at 0°azimuth) and noise is presented from one of the front (at 0°azimuth), right (at +90°) or left (at -90°)].

9.2 Methods

9.2.1 Participants

Participants were recruited from the Royal National Throat Nose and Ear Hospital (RNTNEH) and through the National Cochlear Implant Users Association (NCIUA).

Six adults with bilateral CIs and acquired deafness were recruited.

The inclusion criteria were:

1- A minimum of six months bilateral CI experience.

2- An aural-oral mode of communication.

3- Have English as a first language.

Participants’ demographics:

(1) Duration of deafness was calculated for each participant from the date of diagnosis of a bilateral profound sensorineural hearing loss - it ranged from 3 months to 20 years. (2) Age at testing ranged from 42 to 70 years, with a mean of 60 years (± 12.77). (3) The aetiology of hearing loss was unknown in 2 of the 6 participants. (4) Cochlear implant experience was calculated from date of switch-on of the present implant; it ranged from 8 to 168 months, with a mean of 46.83 months (± 51) and a median of 27.5 months. (5) The hearing loss was progressive for five of the participants. (6) Among the participants were two bilateral Advanced Bionics (AB) CI recipients, one bilateral Med-El™ CI recipients and three Cochlear® CI recipients. Participant 3 had a prelingual onset of hearing loss. Table (9.1) details participants’ demographics.

Table 9.1 Participants' demographics, duration of deafness was calculated from the date of diagnosis of a bilateral profound sensorineural hearing loss to time of receiving an implant, age at implant and duration of deafness are in years and implant experience is in months.

Participant	Age	Aetiology		Age at implant		Duration of deafness		Implant experience		Type of implant	
		Right (R)	Left (L)	R	L	R	L	R	L	R	L
1	67	Unknown progressive	Unknown progressive	63	63	20	20	39	39	MED-EL™ Sonata	MED-EL™ Sonata
2	69	Usher's syndrome	Usher's syndrome	68	66	4	2	8	33	Advanced Bionics HiRes 90K	Advanced Bionics HiRes 90K
3	42	Progressive genetic	Progressive genetic	41	40	15+	15+	8	24	Advanced Bionics HiRes 90K	Advanced Bionics HiRes 90K
4	66	Meniers	Meniers	63	50	16	3	28	36	Nucleus® CI 512	Nucleus® 22
5	45	Meningitis	Meningitis	42	42	3/12	3/12	27	27	Nucleus® CI 512	Nucleus® CI 512
6	70	Unknown progressive	Unknown progressive	57	59	8	1	168	138	Nucleus® CI24M	Nucleus® CI24M

9.2.2 Test battery

Two speech perception tests were used, the BKB sentence test in noise at a 10dB SNR or 5 dB SNR if the participant reached ceiling at a 10dB SNR (described in Section 5.2.2) and the CRM (described in Section 4.2.2).

9.2.2.1 SRM

BKB in speech-spectrum shaped noise was conducted with speech presented from the front (at 0°azimuth) and noise presented from the front (at 0°azimuth), from the right (at +90°) and from the left (at -90°). Percentage correct responses scores were used rather than thresholds because sentences are not equally difficult, and because pilot testing revealed that test-retest difference in thresholds with the use of BKB in noise was equal to, or greater than, the estimated SRM.

9.2.2.2 Number “digit” Localisation test

Two number localization tests were administered, with the use of five audio-visual stands (a speaker and a monitor beneath it) separated by 30° (at 0°, ± 30°, and ± 60°) and five audio-visual stands separated by 15° (at 0°, ± 15°, and ± 30°). In each stand, the monitor displayed a number between 1 and 5, and the touch screen monitor which the participant used to respond displayed five rectangles, each with a digit from 1 to 5. The speech stimulus “Hello, what’s this?” was presented at 70dBA by a female talker with a random, roving level of ±5 dB at 1dB steps from a randomly-selected speaker at each of the 30 trials. The task of the participant was to localize the source of the stimulus and choose the number displayed on that stand with the use of the touch screen in a five alternative-forced choice task. The output score was the percentage of correct responses excluding the responses of the five training trials administered before testing. See Figure (9.1) for schematic representation of the testing setup.

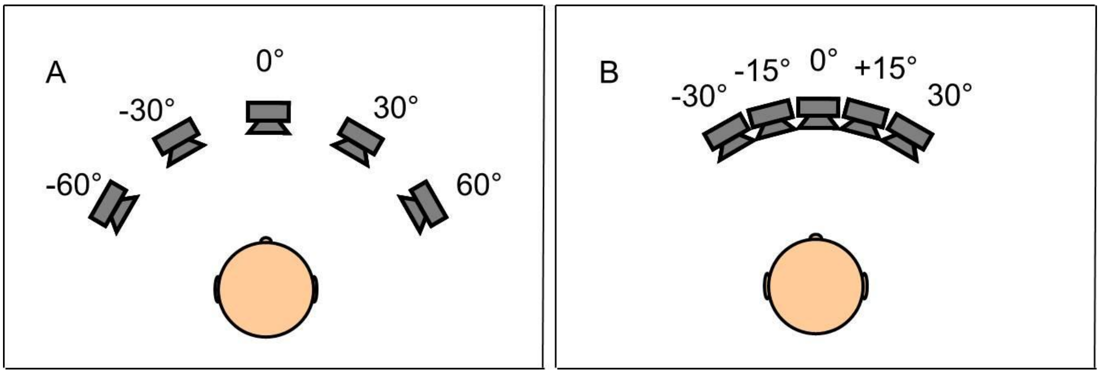


Figure 9.1 The location of the active audio-visual stands (speaker and a monitor below it) for the two conditions of the Number Localisation test. A) 30° separation between five alternative locations. B) 15° separation between five alternative locations.

9.2.2.3 Bilateral matching

Reiss et al. (2011) applied a pitch comparison task between electrodes across ears to find electrodes that matched in pitch. In each trial they presented stimuli from an electrode-pair and the participant had to respond by stating if the second presentation “electrode” had a higher (H), a lower (L) or a similar (S) pitch. A pitch comparison task similar to that of Reiss et al. (2011) was administered between two electrodes across-ears; i.e. an electrode from one implant was tested with an electrode (E) from the contralateral implant in each trial. According to participants’ remarks in the pilot phase, the number of presentations was modified to two presentations per electrode in each trial. The number of trials and the classification of each electrode-pair were statistically calculated in order to reach a 95% significance level. The criteria of choosing the tonotopic electrodes which are matched between the two ears and used in the research programs were designed by the author for this study.

Randomly-selected electrode-pairs were presented at loudness-balanced levels and each trial consisted of two presentations (e.g. E1 -silence - E2 - silence- E1- silence - E2) before a response was made. The apical and the basal electrodes were each tested against at least three contralateral electrodes, and other electrodes were each tested against at least five contralateral electrodes. Each electrode pair was tested for a minimum of three trials and if the response was the same for each (either “similar”, “higher” or “lower”) then testing was terminated, otherwise the trials increased to five. If by five trials responses did not reach significance level, then the number of trials was increased to ten and if responses did not reach significance (8 out of 10) by this point in at least one classification type then the electrode-pairs were classified as having confused pitch (see Table 9.2 for response patterns required to classify the second electrode’s pitch).

Table 9.2 The classification of responses used in matching between ears with the corresponding *p* values calculated based on the number of test trials per test electrode-pair.

Classification	Number of trials	Outcome required	*P* value
Higher	3	3 higher	0.037
	5	4 higher	0.04
	10	7 higher	0.016
Lower	3	3 lower	0.037
	5	4 lower	0.04
	10	7 lower	0.016
Similar	3	3 similar	0.037
	5	4 similar	0.04
	10	7 similar	0.016
	10	5 higher and 5 lower	0.03

Non-apical and non-basal electrodes were tested with up to six contralateral electrodes until tonotopicity in relation to the contralateral implant was established or negated. Electrodes were classified into tonotopic versus non-tonotopic based on results. Non-apical and non-basal tonotopic electrodes exhibited a pattern with at a turning point from L to H and least 2 L and 2 H in a tonotopic order (e.g. L, L, S, H, H or L, L, L, H, H, H). Non-tonotopic electrodes showed confused pitch with more than one electrode, or reversed tonotopicity, or were judged similar to more than one electrode.

Only tonotopic electrodes were included in the matching process. In cases where some tonotopic electrodes were not judged as similar to any contralateral electrode the best match was determined between the two electrodes around the turning point (from L to H). The two electrode-pairs representing the two possible matches were presented at loudness-balanced levels (test E- silence - E1 -silence - test E - silence - E2) and the participant was asked to choose the pair that sounded the closest in pitch. The order of presenting E1 and E2 was alternated in a minimum of six trials. The best matches were established between equal numbers of electrodes in each implant. This matching process was administered *via* direct stimulation using a clinical fitting station and software, and *via* pure-tone presentations.

For loudness balancing, a two interval alternative-forced-choice task was applied, whereby the participant was presented with two pure-tones representing the two test electrodes and had to respond as to whether the second tone had a higher, quieter or the same loudness level as the first tone. A simple up-down staircase adaptive procedure was followed. Step size started at 5 dB for PT auditory testing and at 2 clinical units for DS testing. The step size was halved after the second reversal, and testing was terminated after the participant indicated that the second tone has same loudness level as the first tone on three occasions. The average loudness level of the three responses judged as having the same loudness was considered to be the loudness-balanced level.

9.2.2.3.1 Bilateral direct-stimulation matching

In the bilateral direct-stimulation matching, a standard fitting station with two programming interfaces (see Appendix A) was used to deliver the stimuli. The default settings used in programming the AB and MEDEL CI devices were used in the direct stimulation matching process because not all CI programming software allows for manipulation of the pulse duration, and because participants reported that default setting provided stimuli sufficient for them to make judgments concerning pitch comparisons. However, for Cochlear devices during pilot testing, participants (5 and 6) reported that the pulse duration had to be increased to 500 ms before the participant was able to make pitch comparison judgments. Hence 500 ms pulse duration was used with Cochlear participants. For each tested electrode-pair the presentation order of test electrodes alternated between trials.

9.2.2.3.1 Bilateral pure-tone auditory matching

In the bilateral pure-tone matching, pure tone presentations at the centre frequencies (either provided in the frequency table or calculated as the geometric mean) of the tested electrodes were used after applying adjustments to the speech processor see Section (9.2.3.1).

To conduct matching between the bilateral CIs without direct stimulation, pure tones that corresponded to the centre frequencies of the processing filters within a participant's individual CI program were presented through a Creative Labs Sound Blaster X-Fi Surround 5.1 PRO sound card. The purpose of this USB-connected sound card was to present high-fidelity sounds that bypassed the host computer's sound card. All filter centre frequencies associated with switched-on electrodes were used. The audio presentation was controlled through bespoke software that was developed by Dr Ray Glover for testing under conditions of 'bimodal' stimulation, further modifications were incorporated (to allow more manipulation of intensity, duration of stimuli, ISI and frequency settings of presentations) to allow matching between both CIs in this study. Verification of the accuracy of frequency, duration of stimulation and level of presentation was determined with an oscilloscope. Pure-tones were presented to participants at a comfortable level from a laptop PC *via* the Sound Blaster X-Fi Surround 5.1 PRO Sound Card, using high-fidelity headphones (Sennheiser 580). Stimuli consisted of 600-ms tones and an inter-stimulus-interval (ISI) of 400 ms. The stimuli and ISI settings were reached after pilot testing with three bilaterally-implanted individuals (with different devices) who reported that these settings provided the minimum durations required for them to make accurate judgments about pitch comparison.

9.2.2.4 The screening across-ears pitch comparison test

To evaluate how well the ears were matched after the matching process, a screening pitch comparison test was administered. This consisted of a fixed list of nine frequencies that were chosen based on a musical scale with six-semitone separation between them (see Table 9.3 for set of frequencies). A pitch-comparison task was administered with the presentation of the same frequency across-ears at loudness-balanced levels by using the same set up employed for PT auditory-stimulation matching (Section 9.2.2.3). Participants were presented with the same tone in both ears at loudness-matched levels and were required to respond by stating if the second presentation had a higher (H), a lower (L) or a similar (S) pitch. The order of frequency presentations was randomly selected and each trial consisted of two presentations (E1 -silence - E2 - silence- E1- silence - E2) before a response was made. The number of trials and scoring used was similar to that used in the matching process (described in Section 9.2.2.3).

Table 9.3 The list of frequencies used in the across-ears pitch comparison test and the corresponding musical notes based on a scale created using A_4 = 440 Hz.

Note	Frequency
F4	349 Hz
B4	494 Hz
F5	698 Hz
B5	988 Hz
F6	1397 Hz
B6	1976 Hz
F7	2794 Hz
B7	3951 Hz
F8	5588 Hz

9.2.3 Procedures

Bilateral matching took place in a 2×2.5 m double-walled sound booth while testing for speech perception took place in a 3.7×3.25 m double-walled sound booth where the participant was seated 1 m in front of an ear-level loud speaker (Plus XS.2, Canton) from which the speech and noise were presented. The stimuli were stored (16 bits), using the AB-York Crescent of Sound (Kitterick et al., 2011).

As previously described, for CRM, the participants used a touch screen monitor to respond, and the software ran the test presentation and scoring in an automated fashion. During BKB testing, the tester recoded the participants' verbal response by selecting the correct key words in each sentence presented.

A cross-over study design was used. (See Figure 9.3 for outline of the procedure.) In the first session, speech perception was assessed with the participant's clinical program and the participant was provided with the first research program, either program A or program B (details provided in Section 9.2.4) based on the bilateral-matching task. After one month trial use, the participant returned and speech perception was assessed with the first research program; the participant was then provided with the second research program. The participant returned once more, following one month's trial use, for a final session. Speech perception and localisation testing was performed with the original clinical program and the second research program. Final programming of the participant's speech processor was provided, based on both performance and preference. The participant was also asked to provide feedback on each research program after each one-month trial; this provided valuable information on sound quality in different day-to-day listening situations. All participants were tested for 'BKB in noise' with the clinical program at the first and third sessions, and once with each research program after the one-month trial period. 'BKB in noise' was conducted with speech presented from the front (at 0°azimuth) and noise presented from the front (at 0°azimuth), to the right (at +90°) or to the left (at -90°). CRM SRTs were obtained twice (to obtain an average) in each session with the clinical program at all visits, and with each research program at the end of the one-month trial period. Both number localisation tests (at 30° and 15° separation) were administered with the clinical program at all sessions and once with each research program after the one month trial period.

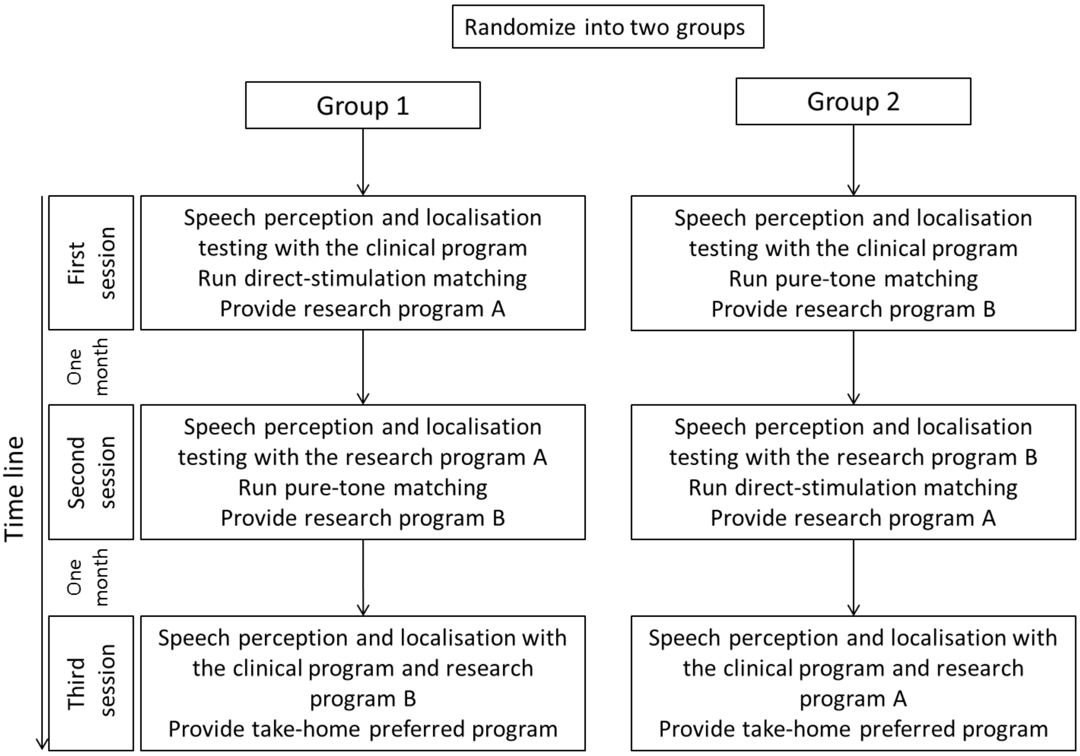


Figure 9.2 Outline of the cross-over study design, research program A based on bilateral direct-stimulation matching and program B based on bilateral pure-tone matching.

9.2.3.1 Adjusting the speech processor for pure-tone matching

The program used when running the pure-tone matching was the participant's preferred clinical program. For participants with Cochlear® devices, the number of maxima (see Section 1.3.2.3) was adjusted and set to the value of 1 to ensure that only one electrode, the test electrode, was stimulated. Both the threshold and highest comfort level were increased with this maxima setting by 15% in the participant's testing program. Care was taken that levels did not cause non-auditory stimulation and were comfortable before conducting loudness balancing and pitch comparison. Adaptive Dynamic Range Optimization (ADRO) was deactivated.

9.2.4 Research programs

Research programming options were as follows:

Program (A) Based on direct-stimulation matching, non-tonotopic electrodes were deactivated and only the matched electrodes were active. The same frequency table (see Section 1.3.3) was used in both CIs to ensure that each electrode in the matched electrode-pair was allocated the same frequency range and centre frequency. No changes were applied to the rate of stimulation, processing strategy or T levels (see Section 1.3.3). However, because the matching process used loudness-balanced levels, the M/C levels (see Section 1.3.3) were balanced across ears. Both devices were activated to make sure they were at a comfortable level of loudness and did not result in any discomfort or non-auditory stimulation.

Program (B) Based on pure-tone matching, non-tonotopic electrodes were deactivated and only the matched electrodes were active. The same frequency table (see Section 1.3.2) was used in both CIs to ensure that each electrode in the matched electrode-pair was allocated the same frequency range and centre frequency. No changes were applied to the rate of stimulation, processing strategy or T levels (see Section 1.3). However because the matching process used loudness balanced levels in the direct-stimulation matching process, the M/C levels (see Section 1.3) were balanced across ears for the pure-tone matched programs as well. Both devices were activated to make sure they were at a comfortable level of loudness and did not cause any discomfort or non-auditory stimulation.

9.3 Analyses

As described above, each participant was tested with the clinical program both at the beginning and end of the study, and once with each research program following a one-month trial. Group analysis compared the best speech perception results acquired for each participant with the clinical program, with the speech perception results acquired with the better of the two research programs. Group analysis was also performed to compare the best BKB score in noise for each condition [noise presented from the front (at 0°azimuth), right (at +90°) and left (at -90°)] with the best research program for each participant, with the best BKB score in noise for each condition with the clinical program. The best CRM SRT average with the clinical program and the CRM SRT average with each research program were assessed in the analyses. The best localisation score with the clinical program in each condition (at 30° and 15° separation) was compared with the best research program (at 30° and 15° separation) and with each research program (at 30° and 15° separation).

SRM was calculated by subtracting the BKB score in noise when both speech and noise were presented from the front, from the BKB score in noise when the noise was presented from one or other of the sides. SRM was calculated for each research program and with the use of the best clinical BKB scores (acquired in one session).

The responses of the across-ears pitch-comparison test were categorised into ‘same’ or ‘different’ for each test frequency. The percentage of frequencies judged as the same was calculated for each program for all frequencies, and separately for frequencies below 1500 Hz and frequencies above 1500 Hz.

Similar to the study described in Chapter 7, participants were also asked to provide subjective feedback and report the sound quality, in addition to the localisation task performed with each program. For purposes of analysis, the same criteria for improvement described in Section (7.3.2.1) were used.

Statistical analysis was conducted to assess the existence of:

1) a significant change in ‘BKB in noise’ in any condition [noise presented from the front (at 0°azimuth), right (at +90°) and left (at -90°)] with the best research program.
2) a significant change in ‘CRM’ with the best research program.
3) Whether there is significant change in SRM with the best research program.
4) a significant change in the across-ears pitch comparison test with either research programs (based on DS matching and PT auditory matching).
5) a significant relationship between the across-ears pitch comparison AEPC test results and localization (at 30° and 15° separation).
6) a significant relationship between AEPC test results and ‘BKB in noise’ at any condition [noise presented from the front (at 0°azimuth), right (at +90°) and left (at -90°)].
7) a significant difference between research programs A and B.

9.3.1 Analyses of group results

Similar to Chapters 4-7, for statistical purposes BKB scores were transformed to arcsine distribution (Studebaker, 1985), in order to include scores that reached either the test floor or the ceiling. Since it has been observed with cochlear pathology such as ossification affected participants’ performance on ED tasks (see Chapter 7), it was decided to conduct speech perception analyses both including and excluding participant (5), who had a history of meningitis and severe ossification in the left ear.

The Shapiro Wilk’s test was applied on all variables. Statistical tests were determined accordingly.

The *t*-test with was applied to compare performance between the clinical program and each research program for all localization tests and the across-ears pitch comparison test results, and between the clinical program and the research program with the best results, ‘BKB in noise’ scores (for all conditions), ‘SRM’ and ‘CRM’. Bonferroni corrections were applied.

In order to evaluate whether the difference between BKB in noise when noise was presented on either side (± 90° left or right) is significantly better than BKB in noise when both speech and noise were presented from the front (as expected with binaural hearing), a paired *t*-test was applied to the date for noise at each side and with each program.

According to the outcome of the Shapiro Wilk’s test, either Pearson’s correlation coefficient or Spearman’s *rho* were applied to establish the relationship between the ‘AEPC’ results and ‘BKB in noise’ at any condition [noise presented from the front (at 0°azimuth), right (at +90°) and left (at -90°)] and between AEPC results and localisation (at 30° and 15° separation). This was applied with the percentage of frequencies judged as the same for all frequencies and for frequencies below 1500 Hz and frequencies above 1500 Hz, with all three programs (clinical and the two research programs). Group results from all programs were pooled for correlation analyses.

9.3.2 Analyses of individual results

Each participant’s data were further analysed, and comparisons were made between the clinical program and each research program for all tested variables, to investigate any underlying patterns. In order to evaluate participants’ subjective report, CRM and BKB (at each condition) the same criteria and minimum significant difference used and described in Sections (9.3.2.1, 9.3.2.2 and 9.3.2.3), respectively, were applied in reporting the data.

In the absence of data relating to the minimum significant difference on the localisation tasks and AEPC test, all changes in performance were reported. The percentage of frequencies judged as similar was calculated for the full range of frequencies range, and separately for frequencies above, and frequencies below, 1500 Hz.

9.4 Results

9.4.1 Group results

Group results (BKB scores in noise at all conditions, localisation and CRM) are provided in Table (9.4). For group AEPC results, see Table (9.5).

t-test and Bonferroni corrections were applied to group data to compare the speech perception scores (BKB scores in noise at all conditions and CRM) for the best research program with those for the best clinical program/ Comparisons were made for data from all participants, and with the exclusion of participant (5) (see Table 9.6 for results). With the exclusion of participant (5 who has unilateral severe calcification of the cochlea) there was a significant difference between the best ‘BKB in noise’ with the clinical program and the ‘BKB in noise’ with the best research program when noise was presented on either side but not when it was presented from the front. Hence, the first sub-hypothesis was accepted and H_1 was accepted when ‘BKB in noise’ testing was done with noise presented on either side but not when noise was presented from the front. ‘BKB in noise’ was significantly better with the best research program compared to the best ‘BKB in noise’ with the clinical program when noise was presented on either side. However no significant difference was found in CRM or SRM between the best research program and the best (CRM and SRM) clinical results. This might be due to the limited number of participants or because of ‘BKB in noise’ scores reaching ceiling with noise presented from the front, thus masking any difference between ‘BKB in noise’ scores with noise presented from the front and ‘BKB in noise’ scores with noise presented from either side.

Table 9.4 Group results of all speech perception (BKB in noise with noise presented at 0°, +90° and -90° and CRM SRT in dBA) and localisation tests (at 30° and 15° separation) with each program. Percentage correct words are reported in BKB results and percentage correct responses are reported in localisation results.

Group	Program	Mean	Standard deviation	N
BKB N (0°)	Clinical	67	16.6	6
BKB N (0°)	A	65.19	9.49	6
BKB N (0°)	B	75.75	18.61	6
BKB N (+90°)	Clinical	72.3	19.04	6
BKB N (+90°)	A	71.08	15.92	6
BKB N (+90°)	B	77.45	22.27	6
BKB N (-90°)	Clinical	73.99	13.87	6
BKB N (-90°)	A	75.07	12.26	6
BKB N (-90°)	B	82.78	10.88	6
Localisation (30°)	Clinical	55.14	21.41	6
Localisation (30°)	A	74.24	16.21	6
Localisation (30°)	B	59.42	22.06	6
Localisation (15°)	Clinical	47.94	23	6
Localisation (15°)	A	55.92	20.73	6
Localisation (15°)	B	64.13	26.31	6
CRM	Clinical	2.84	3.96	6
CRM	A	2.19	1.9	6
CRM	B	4	2.39	6

Table 9.5 Group results of all AEPC results (for all frequencies, for frequencies < 1500 Hz and for frequencies > 1500 Hz) with each program. Percentage of test frequency pairs judged as the same is reported for AEPC.

Group	Program	Mean	Standard deviation	N
AEPC all frequencies	Clinical	31	20.73	6
AEPC all frequencies	A	81.5	20.84	6
AEPC all frequencies	B	61.33	21.4	6
AEPC frequencies < 1500 Hz	Clinical	20	12.65	6
AEPC frequencies < 1500 Hz	A	80	21.91	6
AEPC frequencies < 1500 Hz	B	66.67	30.11	6
AEPC frequencies > 1500 Hz	Clinical	41.67	46.55	6
AEPC frequencies > 1500 Hz	A	79.17	18.82	6
AEPC frequencies > 1500 Hz BKB N (-90°)	B	55.83	29.23	6

Table 9.6 The difference in speech perception between the best clinical scores and scores with the best research program with the application of a *t*-test. The t value, degree of freedom (df) and *p* value are reported, significance is reported at a two-tail $p < 0.05$ level. Speech perception measures include BKB in noise (with noise presented from the front at 0° azimuth, to the right at +90° and to the left -90°), CRM and SRM and asterisk indicates significance even after Bonferroni correction.

Variable compared	Including participant 5	*t*	Df	*P* value
BKB N (0°)	Yes	-1.89	5	0.11
BKB N (0°)	No	-2.5	4	0.07
BKB N (+90°)	Yes	-2.40	5	0.06
BKB N (+90°)	No	-3.18*	4	< 0.05
BKB N (-90°)	Yes	-2.54	5	0.05
BKB N (-90°)	No	-3.22*	4	< 0.05
CRM	Yes	0.42	5	0.69
CRM	No	0.53	4	0.62
SRM	Yes	-1.5	11	0.16
SRM	No	-1.5	9	0.16

t-test and Bonferroni corrections were also applied to group results to compare AEPC and localisation results (at 30° and 15° separation) with each research program, with the AEPC results and the best localisation scores (at 30° and 15° separation) with the clinical program, respectively (see Table 9.7 for results). There was a significant difference between localisation scores at both 30° and 15° separation with research program A and the best clinical localisation scores at both 30° and 15° separation. Hence H_4 was accepted, localisation was significantly better with research program A compared to the clinical program at both 30° and 15° separation. There was a significant difference between localisation scores with research program B and the best clinical localisation scores at 15° separation but not at 30° separation. Hence H_5 was accepted at 15° separation but not at 30° separation, localisation was significantly better with research program B compared to the clinical program at 15° separation only. There was a significant difference between AEPC results with research program A and the clinical AEPC results for all frequencies and for frequencies below 1500Hz. Hence H_6 was accepted for AEPC result for all frequencies and for frequencies below 1500 Hz but not for frequencies above 1500 Hz, AEPC results with research program A were significantly better than the clinical AEPC results for all frequencies and for frequencies below 1500 Hz as well. There was a significant difference between AEPC results with research program B and the clinical AEPC results for frequencies below 1500 Hz only. Hence H_7 was accepted for frequencies below 1500 Hz but not for all frequencies nor for frequencies above 1500 Hz, AEPC results with research program B were significantly better than the clinical AEPC results for frequencies below 1500 Hz only.

Table 9.7 The difference between the best clinical scores and scores with each research program on localisation tasks (at 30° and 15° separation) and AEPC (at all frequencies, for frequencies < 1500 Hz and for frequencies > 1500 Hz) with the application of a *t*-test. The t value, degree of freedom (df) and *p* value are reported, significance is reported at a two-tail *p* < 0.05 level and asterisk indicates significance even after Bonferroni correction.

Variable compared	Research program	*t*	df	*P* value
Localisation 30° separation	A	-3.03*	5	0.03
Localisation 30° separation	B	-2	5	0.1
Localisation 15° separation	A	-2.62*	5	< 0.05
Localisation 15° separation	B	-6.95**	5	< 0.005
AEPC all frequencies	A	-5.22**	5	< 0.005
AEPC all frequencies	B	-4.11	5	0.05
AEPC frequencies < 1500 Hz	A	-6.72**	5	< 0.005
AEPC frequencies < 1500 Hz	B	-4.72**	5	< 0.01
AEPC frequencies >1500 Hz	A	-1.96	5	0.11
AEPC frequencies >1500 Hz	B	-1.18	5	0.29

In the absence of a significant difference in SRM between the clinical program and the best research program, comparison was made between ‘BKB in noise’ when noise was presented from either side (± 90° left and right) with ‘BKB in noise’ when noise was presented from the front . A paired *t*-test (with Bonferroni correction) while including and excluding participant (5) was used in the analyses (see Table 9.8 for results with all programs). With the exclusion of participant (5 with severe unilateral cochlear ossification) there was a significant difference between ‘BKB in noise’ when noise was presented from front and ‘BKB in noise’ when noise was presented from either side (± 90° left and right) with research program A. This was also true with the inclusion of participant (5) with noise presented from the left. Results with the clinical program were slightly inconsistent; there was a significant difference between ‘BKB in noise’ when noise was presented from the right only compared with ‘BKB in noise’ when noise was presented from the front with the exclusion of participant (5). There was also a significant difference between ‘BKB in noise’ when noise was presented from the left only compared with ‘BKB in noise’ when noise was presented from the front with the inclusion of participant (5). Among all three programs spatial separation between speech and noise consistently (for the same participants) improved speech perception with research program A only.

Table 9.8 The difference between the BKB in noise scores when noise was presented at 0° and BKB in noise scores when noise was presented at either side ±90° with the use of the different programs with the inclusion of and exclusion of participant (5). The best clinical scores and scores with each research program were used with the application of a *t*-test. The t value, degree of freedom (df) and *p* value are reported, significance is reported at a two-tail $p < 0.05$ level and asterisk indicates significance even after Bonferroni correction.

Variables compared	Including participant 5	Program	*t*	df	*P* value
BKB N Noise (0°) and (+90°)	Yes	Clinical	-2.080	5	.09
BKB N Noise (0°) and (+90°)	No	Clinical	-5.14**	4	.007
BKB N Noise (0°) and (+90°)	Yes	A	-2.013	5	.10
BKB N Noise (0°) and (+90°)	No	A	-2.8*	4	.04
BKB N Noise (0°) and (+90°)	Yes	B	-1.251	5	.27
BKB N Noise (0°) and (+90°)	No	B	-2.213	4	.09
BKB N Noise (0°) and (-90°)	Yes	Clinical	-3.018*	5	.03
BKB N Noise (0°) and (-90°)	No	Clinical	-2.341	4	.08
BKB N Noise (0°) and (-90°)	Yes	A	-3.138*	5	.03
BKB N Noise (0°) and (-90°)	No	A	-2.85*	4	.04
BKB N Noise (0°) and (-90°)	Yes	B	-1.535	5	.19
BKB N Noise (0°) and (-90°)	No	B	-1.179	4	.30

See Table (9.9) for correlations between AEPC results and localisation (at 30° and 15° separation), and Table (9.10) for correlations between AEPC results and BKB in noise at all conditions (noise presented from the front, left and right). Localisation at 30° separation showed significant correlation with

AEPC results for all frequencies, for frequencies below 1500 Hz and for frequencies above 1500 Hz. H_8 was accepted, there was a positive relationship between AEPC results (at all frequency ranges) and localisation at 30° separation. Localisation at 15° separation showed significant correlation with AEPC results for all frequencies and for frequencies below 1500 Hz but not for frequencies above 1500 Hz. H_9 was accepted for AEPC results for all frequencies and for frequencies below 1500 Hz only; there was a positive relationship between AEPC results (for all frequencies and for frequencies below 1500 Hz) and localisation at 15° separation.

Table 9.9 The correlation between the localisation scores at all conditions (at 30° and 15° separation) and AEPC results (at all frequencies, for frequencies < 1500 Hz and for frequencies > 1500 Hz). Scores for all programs were pooled for analyses. The correlation coefficient, *p* value and number of observations used in analyses (N) are reported, significance is reported at a two-tail $p < 0.05$ level.

Variable	Correlation with the across-ears pitch comparison (AEPC)			
	AEPC frequency range	Coefficient	*p* value	N
Localisation (30°)	All	r = 0.64**	0.004	18
Localisation (30°)	< 1500 Hz	r = 0.72**	0.001	18
Localisation (30°)	> 1500 Hz	r = 0.71**	0.001	18
Localisation (15°)	All	r = 0.50*	0.033	18
Localisation (15°)	< 1500 Hz	r = 0.60**	0.008	18
Localisation (15°)	> 1500 Hz	r = 0.36	0.15	18

Table 9.10 The correlation between the BKB in noise scores at all conditions (when noise was presented at 0° and when noise was presented at either side ±90°) and AEPC results (at all frequencies, for frequencies < 1500 Hz and for frequencies > 1500 Hz). Scores for all programs were pooled for analyses. The correlation coefficient, *p* value and number of observations used in analyses (N) are reported, significance is reported at a two-tail $p < 0.05$ level.

Variable	Correlation with the across-ears pitch comparison (AEPC)			
	AEPC frequency range	Coefficient	*p* value	N
BKB N (0°)	All	$R^2 = 0.16$	0.52	18
BKB N (0°)	< 1500 Hz	$R^2 = 0.33$	0.19	18
BKB N (0°)	> 1500 Hz	$R^2 = -0.01$	0.96	18
BKB N (+90°)	All	$R^2 = 0.18$	0.48	18
BKB N (+90°)	< 1500 Hz	$R^2 = 0.25$	0.32	18
BKB N (+90°)	> 1500 Hz	$R^2 = 0.16$	0.51	18
BKB N (-90°)	All	$R^2 = 0.11$	0.66	18
BKB N (-90°)	< 1500 Hz	$R^2 = 0.19$	0.45	18
BKB N (-90°)	> 1500 Hz	$R^2 = -0.01$	0.97	18

Both research programs results (CRM, SRM, BKB in noise at all conditions, localisation (at 30° and 15° separation) and AEPC) were compared, see Table (9.11) for results. There was no significant difference between research programs A and B except in AEPC and CRM.

Table 9.11 The difference between research program A and research program B on the different performance measures with the application of a *t*-test. Measures included BKB in noise scores at all conditions (when noise was presented at 0° and when noise was presented at either side ±90°), CRM SRTs, localisation tasks (at 30° and 15° separation) and AEPC (at all frequencies, for frequencies < 1500 Hz and for frequencies > 1500 Hz). The t value, degree of freedom (df) and *p* value are reported, significance is reported at a two-tail *p* < 0.05 level and asterisk indicates significance even after Bonferroni correction.

Variable	t	df	*P* value
BKB N (0°)	1.91	5	0.11
BKB N (+90°)	0.9	5	0.41
BKB N (-90°)	1.16	5	0.3
Localisation (30°)	-3.14	5	0.03
Localisation (15°)	1.62	5	0.17
CRM	4.04*	5	0.01
SRM	-1.09	11	0.3
AEPC all frequencies	-3.73*	5	0.01
AEPC frequencies < 1500 Hz	-1.58	5	0.18
AEPC frequencies > 1500 Hz	-2.80	5	0.04

9.4.2 Individual results

With the exception of except participant (5), all participants took home at least one research program. Comparisons between performance with the clinical program and performance with each research program for BKB (at all conditions), CRM and subjective report are shown in Table (9.12). Positive reports included a more natural sound and more balanced hearing, which was reported by all participants with at least one research program. Better speech perception in some daily situations was reported by participants (1, 2, 3 and 6) and better music perception was reported by participants (1 and 6). Participant (6) also reported that he was able to identify a bird by listening to it, which he hadn't been able to do since onset of his deafness. Participant (5) had conflicting results, reporting better localisation and more balanced hearing, but poorer speech perception in her better ear (less ossification on right side) when active on its own or using the phone. For localisation and AEPC comparison results, see Table (9.13).

Table 9.12 Individual results of subjective reports and changes in speech perception measures with each research program as compared to the clinical program. Measures reported include BKB in noise with noise presented at 0° azimuth, BKB in noise with noise presented at +90°, BKB in noise with noise presented at -90°, CRM SRTs and subjective report regarding the research program. Symbols used are: (=) for no significant difference, (+) for significant improvement which is a higher BKB score and a lower CRM SRT, followed by change in score if any, (-) for significant decline, followed by change in score if any and ceiling indicates BKB scores were at ceiling level for clinical and research programs.

Participant	Program	Report	BKB in noise			CRM
			N (0°)	N (+90°)	N (-90°)	
1	A	(+)	(+) 31	(+) 28	(+) 27	(+) 8
1	B	(+)	(+) 37	(+) 28	(+) 25	(+) 5.31
2	A	(=)	(=)	(+) 13	(=)	(=)
2	B	(+)	(=)	(=)	(+) 9	(=)
3	A	(+)	(=)	(+) 22	(+) 13	(=)
3	B	(=)	(=)	(=)	(=)	(=)
4	A	(=)	(=)	(=)	(=)	(=)
4	B	(+)	(+) 17	(=)	(=)	(=)
5	A	(+) (-)	(=)	(=)	(=)	(=)
5	B	(-)	(=)	(-) 10	(=)	(=)
6	A	(+)	(+) 16	(+) 18	(=)	(=)
6	B	(+)	(+) 16	(=)	(=)	(=)

Table 9.13 Individual results of localisation tasks (at 30° and 15° separation) and AEPC (at all frequencies, for frequencies < 1500 Hz and for frequencies > 1500 Hz). Symbols used are: (=) for no difference, (+) for improvement followed by change in score if any, (-) for decline followed by change in score and ceiling indicates scores were at ceiling level for the clinical and research programs.

Participant	Program	Localisation		AEPC		
		30°	15°	All frequencies	< 1500 Hz	> 1500 Hz
1	A	(+) 31.67	(+) 3.33	(+) 67	(+) 60	(+) 75
1	B	(+) 18.33	(+) 16.67	(+) 44	(+) 60	(+) 25
2	A	(+) 6.67	(+) 3.33	(+) 33	(+) 60	(+) 40
2	B	(+) 3.33	(+) 6.67	(+) 22	(+) 60	(=) 0
3	A	(+) 46.82	(+) 6.67	(+) 34	(+) 80	(+) 35
3	B	(+) 13.49	(+) 6.67	(+) 23	(+) 40	(=) 0
4	A	(+) 6.66	(+) 20	(+) 22	(+) 20	(+) 30
4	B	(-) 6.67	(+) 20	(+) 11	(+) 20	(=) 0
5	A	(+) 18.33	(+) 23.33	(+) 67	(+) 60	(+) 55
5	B	(+) 15	(+) 16.67	(+) 22	(+) 20	(=) 0
6	A	(+) 10 Ceiling	(+) 23.33	(+) 80	(+) 80	(+) 20
6	B	(+) 3.33 Ceiling	(+) 20	(+) 60	(+) 80	(=) 0

9.5 Discussion

The group data revealed that improvements in BKB in noise did not reach significance when both speech and noise were presented from the front (at 0°azimuth) with any research program. However individual results showed significant improvements in BKB in noise when both speech and noise were presented from the front (at 0°azimuth) for three participants (1, 4 and 6) with at least one research program. Research programs may have particularly improved matching between their devices. Two of those participants (1 and 6) not only improved in the AEPC at frequencies lower than 1500 Hz, but also improved in the AEPC at higher frequencies (ranging from 1500 Hz - 5588 Hz) from a score of 0% with their clinical programs, possibly indicating that those two subjects had particularly non-matched clinical programs. Participant (4) was the only participant with two different devices, with a different frequency table in each of his original clinical programs, but was provided with identical frequency tables in both devices in his research programs. These results are also consistent with previous studies reporting inconsistent improvement in bilateral CIs versus unilateral CI when both speech and noise were presented from the front (at 0°azimuth) (Schleich et al., 2004; Ramsden et al., 2005; Eapen et al., 2009 and Wackym et al., 2007; Laszig et al.,2004; Litovsky et al., 2006) which could be due to various degrees of binaural summation. The "binaural summation" effect usually occurs in NH due to redundant information from both ears and it causes improvement in speech perception in quiet and in noise even when both (speech and noise) are presented from the same direction. Binaural summation requires the integration of the input from both ears (e.g. Wilson et al., 2003). If the signal from both implants is greatly mismatched, this may impede binaural summation because of the lack of redundant information and the lack of integration between information across ears.

Improvement in BKB scores when both speech and noise were presented from the front is usually associated with improved binaural summation (e.g.

Wilson et al., 2003). To this end, the improvement in these three participants was especially encouraging because it may provide evidence for the possibility of improving binaural summation by improving pitch-matching across implants. Further support to improved binaural summation, rather than simply a general improvement in speech perception, is provided by the absence of improved BKB in noise when noise was presented to either side, with some programs providing benefit with noise presented to the front [participants (4 and 6)]. It should be noted that one of those participants underwent pitch matching tests, although he had different devices and different strategies. This may indicate that pitch-matching is still beneficial even with different CI devices. Significant change which was improvement occurred in BKB scores with noise presented from the front for 50% of the test population with the use of at least one research program. Group results also demonstrated that significant change which was improvement occurred in BKB scores with noise presented from either side with the use of at least one research program. Group BKB results showed significant improvements with the best research program in comparison to the best BKB score with the clinical program when noise was presented on either side with the exclusion of participant (5). Participant (5) had meningitis and unilateral severe ossification in the cochlea. This may also explain the conflicting reports of improved balanced hearing and localization, which were verified in her localisation results, but negative report of worst speech perception with her better ear (alone) after matching it with the weaker ear. The weaker ear had a larger number of non-tonotopic electrodes than the stronger ear, possibly due to altered current spread or cross-turn stimulation secondary to ossification. However, in order to match the frequency table between her devices, an equal number of electrodes were deactivated in both devices. In addition, in Chapters 7 and 8 it was demonstrated that ED may not always indicate problematic electrodes in cases of cochlear ossification. The improvement with the research program when noise was presented from either side may indicate improved speech perception because of better selection of active electrodes, as demonstrated by (Zhou and Pfingst, 2012).

Another reason could be due to better frequency-matching between ears, which might have improved the use of ITD cues, when noise is presented from the side speech and noise have different ITDs. Localisation and AEPC results may shed some light on the matter; significant improvement was found in localisation and AEPC especially at frequencies below 1500 Hz with the use of the research programs. Localisation was significantly better with the research program (A) based on direct-stimulation than with the clinical program, for both 30° and 15° separation. There was also significant improvement in localisation at 15°, but not at 30°, separation with research program B compared to the clinical program. The significantly better AEPC scores (across the frequency range) observed with the use of program A in comparison to program B suggest that better frequency-matching provided by the research programs is a plausible explanation for the observed improvement in localisation skills, hence the significantly better localisation results provided by program A as compared to program B. In addition to that, when compared to the clinical program, AEPC was significantly better across the frequency range with program A and not with program B (after applying Bonferroni correction) as was localisation at 30° separation. So better frequency matching and better localisation were accomplished with program A compared to program B.

Supporting evidence for better frequency-matching giving rise to better localisation is also provided by the correlation results between localisation and AEPC results. There was significant strong to very strong positive correlation between localisation (at 30° and 15 ° separation) and AEPC results across the frequency range and at frequencies below 1500Hz and between localisation (at 30° separation) and AEPC results at frequencies higher than 1500Hz. These findings highlight that matching the bilateral CIs for pitch in the research programs especially based on direct stimulation has improved matching between CIs as measured *via* AEPC especially at frequencies below 1500 Hz. This consequentially improved localisation and speech perception in noise (especially with noise presented on either side).

There was also a significant improvement in AEPC results with both research programs compared to the clinical program at frequencies below 1500 Hz, but not at the higher frequency range. This may indicate that CI users find matching electrodes at higher frequencies more difficult than lower frequencies, which corresponds to reports of difficulty in matching pitch arising from different sound quality across their ears – the latter is more-often reported for high-frequency sounds. In addition to that, this finding has to be considered in the light of improved localisation skills with the research programs, and the association pattern between localisation (at 30° and 15° separation) and the AEPC results. Where association was found between localisation (at 30° and 15° separation) and the AEPC at all frequency ranges except between localisation (15° separation) and AEPC at higher frequencies, these findings may further suggest that improving frequency matching at lower frequencies for this population provided the better localisation skills.

The detection and utilisation of interaural differences (ILDs and ITDs) requires that signals delivered to both ears should have similar frequencies; different frequencies would negatively impact ILDs and ITDs (Colburn et al., 2006; Francart and Wouters, 2007; Nuetzel and Hafter, 1981). Improving frequency matching between the ears might therefore lead to improved interaural perception, improving localisation and speech perception with noise presented to either side. Relatively-high sensitivity for ILDs amongst CI recipients' has been reported (e.g. Lawson et al., 1998 and 2000; van Hoesel and Tyler, 2003; van Hoesel, 2004; Laback et al., 2004 and Seeber and Fastl, 2007), whilst sensitivity for ITDs is often reported to be highly variable (van Hoesel et al., 1993; van Hoesel and Clark, 1997; Lawson et al., 2000; van Hoesel and Tayler 2003 and van Hoesel, 2004). Lawson et al., (2000) demonstrated that the detection of ITDs and ILDs can be improved with the use of three electrode-pairs that were matched across-ears.

According to the duplex theory of binaural hearing (Rayleigh, 1907; Stevens and Newman, 1936), ITD cues are mainly used for localisation at frequencies lower than 1500 Hz while ILD cues are used at higher frequencies. Evidence from the current study suggests that better matching of frequencies lower than 1500 Hz might provide for the improvement observed in localisation, possibly indicating improved detection of ITDs. Nevertheless, despite the limited ILD cues available at frequencies lower than 1 kHz (e.g. Shaw, 1974), it has to be noted that ILD cues were found to be dominant over ITD cues among CI users (e.g. Poon, 2006; Grantham et al., 2008; van Hoesel et al., 2008 and Seeber and Fastl, 2008). A possible explanation for the observed improvement in localisation performance is provided by van Hoesel (2007), who proposed that electrode interactions affect sensitivity to ITDs and. consistent with this idea, the reduction of unwanted channel-interaction by employing electrodes with high differentiation only in the research programs may have positively affected ITD sensitivity.

The presence of a significant relationship between the AEPC and localisation performance, which was not found between BKB in noise scores and AEPC, might arise because the AEPC test (at the nine test frequencies) was not sensitive enough to reflect ‘BKB in noise’ demand for frequency matching at a higher resolution. It may also indicate that some processes underlying binaural hearing for localisation and speech perception might be different. This is line with Kerber and Seeber (2012), who reported no correlation between localisation and speech perception amongst bilateral CI users. However, the significant improvement in speech perception when noise was presented from either side, along with the significant improvement for three participants when both speech and noise were presented from the front, may indicate a positive effect of improved frequency-matching across ears. This finding is consistent with simulation studies evaluating the effect of frequency-mismatch between ears (Siciliano et al., 2010).

There was no statistically-significant difference in SRM between either research programs and the clinical program, but this could be due to the limited number of participants, or because BKB scores reached ceiling and thus masked any SRM effect. However, there was a statistically-significant difference between BKB scores when noise was presented on either side in comparison to BKB in noise when noise was presented from the front with program A when participant (5) was excluded from the analyses. In contrast, there was a significant difference between BKB scores when noise was presented on the right side only, compared to BKB in noise when noise was presented from the front with the use of the clinical program, again with the exclusion of participant (5). This may reflect better SRM when using program A as compared to the clinical program, and is in concordance with subjective reports of a more balanced sound provided by the research program. It should be noted, however, that the relatively, small number of participants could also be the reason that no significant improvement was found in CRM.

Individual results revealed that all participants with the exclusion of participant (5) showed improvement in at least one performance measure with the use of the research programs, and none demonstrated a decline in performance. Although program A provided significantly better CRM, localisation (at 30° separation), and AEPC scores across the frequency range, and at frequencies greater than 1500 Hz, the pattern of improvements was not identical across participants. Program B provided participant (4) with better performance than program A. Additionally, participant (4) – the only participant with a different device in each ear - preferred program B, suggesting that auditory pure-tone matching might be more suitable for bilaterally-implanted participants with different devices.

With the exception of participant (5) – who had severe post-meningitic ossification in the worst ear – no subject showed a decline in performance on any metric with either of the research programs. Matching between devices with a significantly weaker ear might be contra-indicated but another possibility could be that ossification in this subject has impacted on electrode testing, due to abnormal spread of current in the affected ear.

The main findings of this study are in line with simulation studies emphasizing the importance of frequency-matching across the ears (Siciliano et al., 2010). It may also explain why some studies (e.g. Mosnier et al., 2008) found that no pre-implantation factors can predict performance with simultaneous bilateral CI. In the absence of direct measures of ITD and ILD sensitivity, it is difficult to reach conclusions about the effect of matching frequencies on either binaural cue. However, it is most likely that matching frequencies across ears has improved use of inter-aural differences. Considering the effect that limited temporal fine structures provided by the implants on ITD (e.g. van Hoesel and Tyler, 2002) and that ITDs can be conveyed by temporal envelopes instead (e.g. Grantham et al., 2008). If improving frequency-matching across ears can within the limitation of sound processing improve the detection of ITD, this may have future clinical implications.

The lack of any measures of SRM due to ceiling BKB scores with some participants (who showed improvement), could not be avoided since the BKB scores with the initial SNR levels had to be available for comparison, and because extra testing with different SNR levels would have meant having to use repeated BKB sentences, potentially compromising results of the study.

9.6 Conclusion

Results from this study are encouraging; frequency matching across the two devices might be utilised to improve performance with bilateral CI. Determining the best method for matching and programming based on the matching process requires further investigation. Improvements in localisation with all research programs were more evident than were improvements in speech perception, suggesting that some processes underlying binaural hearing for localisation and speech perception might be different. Additionally, the strong to very strong correlation between localisation results (at both 30° and 15°) and the screening AEPC results, which was not replicated between BKB scores and AEPC, may indicate that binaural speech perception requires frequency matching at a higher resolution than that required for localisation. Nonetheless a statistically-significant improvement in speech perception was evident in this study with the use of the research programs.

9.7 Summary

- Frequency-matching between CI devices improved localisation and speech perception among bilaterally implanted individuals.
- Although preliminary results indicated that using direct stimulation in matching produced better results except in the case of mismatched devices, it is still not clear which is the best method for matching.
- Deactivation of the non-tonotopic electrodes as identified by the two methods described in the study did not produce any decline in performance except for participant (5) with program B. A significantly worst ear might be a contra-indication for matching between devices.

Chapter 10

Summary and General Discussion

The thesis aimed to improve fitting of the CI device in order to improve performance with CI among both the unilaterally and bilaterally implanted. Great variability in the performance level is demonstrated by the CI recipients, highlighting the need to find possible underlying causes for poorer performance and to address those causes. Pitch perception was used to guide re-programming of the CI device. Among the unilateral CI recipients, ED was evaluated with the clinically-viable pure-tone pitch ranking task (PTED) to uncover problematic indiscriminable electrodes and reprogramming of the CI was provided accordingly. Indiscriminable electrodes were deactivated and the effect of the research programs was evaluated. Further pitch ranking testing (PTIF) was conducted at different regions of good and poor ED before and after the deactivation of electrodes with poor ED. Results were correlated with the change in performance following the deactivation of electrodes with poor ED. Pitch matching between the two CI devices was conducted based on two methods, direct stimulation and auditory pure-tone stimulation. Results from each method were used to provide the bilaterally implanted with a research program. The efficacy of each research program was evaluated with the use of speech perception, localisation and the AEPC test. Findings not only provided information regarding the effectiveness of the research programs but they may also be used to provide information regarding factors affecting performance with CI. Imaging of the placement of the CI array in the cochlea provided further insight into factors affecting performance. This chapter provides a summary of the main findings followed by discussion of the key findings and their implications.

10.1 Summary of main findings

10.1.1 Findings reported in Chapter 3

- PTED and DED results were highly correlated indicating good validity.
- The PTED procedure had good test-retest reliability.
- Time and equipment requirements for PTED deemed it clinically viable

10.1.2 Findings reported in Chapter 4

- CRM SRTs showed good test-retest reliability.
- CRM SRTs were lower and showed a higher within-subject variability for NH compared to CI participants.
- The minimum significant change (at $p< 0.05$) for testing an individual in two conditions for CRM SRTs, was > 4dB, and > 6 dB for CI and NH participants respectively.

10.1.3 Findings reported in Chapter 5

- CI performance on speech perception measures was better in quiet than in noise.
- The percentage of discriminable electrodes was strongly correlated with speech perception measures (BKB in quiet, BKB in noise and CRM) especially in noise.
- Speech perception with CI required a larger proportion of discriminable electrodes at frequencies lower than 2600 Hz than at higher frequencies.
- The percentage of discriminable electrodes especially at frequencies below 1000Hz was the main predictor of CI performance as measured by BKB in quiet and in noise and CRM.

10.1.4 Findings reported in Chapter 6

- The angular depth of insertion of the electrode array was strongly correlated with speech perception measures in quiet and in noise and PTED revealed no signs of increased insertion trauma with deeper insertion of CI electrode array.
- There was a statistically significant relationship between the frequency shift (difference between the estimated characteristic frequency and assigned frequency in the CI program) of the most apical active electrode and BKB in noise but not BKB in quiet.
- The CBCT provided high quality images that allowed judgement regarding scalar placement of the individual electrodes of the CI electrode array. There was no relationship between scalar placement in scala tympani versus scala vestibuli and speech perception and PTED identified dead regions at interscalar cross-over points.

10.1.5 Findings reported in Chapter 7

- The deactivation of indiscriminable electrodes can improve performance with CI especially if the indiscriminable electrodes fell in the frequency region below 2600 Hz. However this was not true for CI recipients with cochlear pathology (such as fibrosis, ossification and calcification) or electrode array placement issues.
- Some participants reported improvement in sound quality after the deactivation of indiscriminable electrodes without evidence of change in performance, most of which had ceiling BKB scores in both quiet and noise.
- The positive impact of the deactivation of indiscriminable electrodes was not device specific nor was it specific to certain strategies, most likely indicating a common underlying cause for those electrodes being indiscriminable.

10.1.6 Findings reported in Chapter 8

- Pure-tone intermediate frequency (PTIF) testing revealed that participants showing improvement following the deactivation of indiscriminable electrodes (in Chapter 7) had reduced ability to rank pitch correctly in regions of indiscriminable electrodes as compared to regions of discriminable electrodes. This pattern was not replicated in participants who did not show improvement following the deactivation of indiscriminable electrodes.
- PTIF of regions of indiscriminable electrodes following deactivation revealed that participants showing benefit had improved pitch ranking in those regions following deactivation as compared to before deactivation.
- Using PTIF results for re-programming improved performance when PTED and PTIF had conflicting results; i.e. an indiscriminable electrode-pair had an equal number of intermediate frequencies (IF) to the control discriminable electrode-pair. When only indiscriminable electrodes with a smaller number of IF were deactivated, performance was better than when all indiscriminable electrodes were deactivated and better than the clinical pre-deactivation program.
- PTIF results of regions of indiscriminable electrodes following deactivation correlated with post-deactivation change in performance.

10.1.7 Findings reported in Chapter 9

- Matching the two devices for pitch and loudness in bilaterally implanted individuals had a statistically significant positive impact on localisation (at 30° and at 15° of separation) and speech perception with noise presented at either side (± 90°). Only three out of six participants showed improvement in speech perception with both speech and noise presented at the front (at 0°).

- The AEPC test revealed that devices were significantly better matched across the frequency range especially at frequencies below 1500 Hz.
- Localisation at 30° and at 15° of separation was statistically significantly associated with AEPC results. However, no significant association was found between AEPC and BKB in noise.

10.2 Summary of new findings

- The newly described PTED test is a valid, reliable and clinically viable test.
- The minimum significant change for testing an individual in two conditions for CRM SRTs, was > 4dBA, and > 6 dBA for CI and NH participants respectively.
- The percentage of discriminable electrodes especially at frequencies below 1000Hz was the main predictor of CI performance as measured by BKB in quiet and in noise and CRM. The presence of radiologically confirmed pathology was also a predictor of CI performance.
- There was a positive significant relationship between the frequency shift of the most apical active electrode and scores for BKB in noise but not BKB in quiet.
- The CBCT provided high quality images that allowed judgement regarding scalar placement of the individual electrodes of the CI electrode array in the majority of instances. Scalar placement in scala tympani versus scala vestibuli did not affect speech perception or ED.
- PTED identified regions at interscalar cross-over points.
- The deactivation of indiscriminable electrodes identified by PTED improved performance (speech perception and/or sound quality) for CI recipients excluding those with cochlear pathology (such as fibrosis, ossification and calcification) or electrode array placement issues. This was not specific to a certain manufacturer or processing strategy.

- The apical indiscriminable electrodes were more detrimental to speech perception than basal electrodes.
- PTIF testing revealed that participants showing post deactivation (of indiscriminable electrodes) improvement had less discriminable intermediate frequencies (DIF) in regions of indiscriminable electrodes as compared to regions of discriminable electrodes. This pattern was not replicated in participants who did not show post deactivation improvement.
- PTIF revealed that participants showing benefit had a larger number of DIF regions of indiscriminable electrodes following deactivation as compared to before deactivation.
- PTIF results can guide CI re-programming which improved performance when PTED and PTIF had conflicting results.
- PTIF results of regions of indiscriminable electrodes following deactivation correlated with post-deactivation change in performance.
- Based on results from the CBCT, PTED and PTIF, indiscriminable electrodes can be categorised to 1) indiscriminable electrodes stimulating dead regions, 2) indiscriminable electrodes at interscalar crossover points and 3) indiscriminable electrodes stimulating non-dead regions either due to cochlear pathology altering the current spread, obvious placement issues or sub-optimally functioning electrodes.
- Matching the two devices for pitch and loudness in bilateral CI recipients, had a statistically significant positive impact on localisation (at 30° and at 15° of separation) and speech perception with noise presented at either side (± 90°). Three out of six participants showed significant improvement in speech perception with both speech and noise presented at the front (at 0°).
- The AEPC test revealed that devices were significantly better matched across the frequency range especially at frequencies below 1500 Hz.

- Localisation at 30° and at 15° of separation was statistically significantly associated with AEPC results. However, no significant association was found between AEPC and BKB in noise.

10.3 General discussion

10.3.1 Identification of problematic electrodes or dead regions

The PTED was found to be a valid test for measuring ED when compared to the direct stimulation ED test (DED) with strong correlation between the results of the two methods (PTED and DED). It also showed high reliability and the potential to be used as a clinical tool due to the ease of testing and the short time required to conduct the test. Further validation for the PTED was sought in the experiments presented in Chapter 5, where a strong association was found between the number of discriminable electrodes as identified by PTED and the different speech perception measures (BKB in quiet and in speech-shaped noise and CRM). This finding concurred with studies that reported better speech perception as the number of perceptually distinct channels increased (Collins, et al., 1997; Henry et al., 2000; Nelson, et al., 1995; Friesen et al., 2001). This relationship was stronger with speech perception measures in noise (rather than quiet), which may have reflected the increased demand for a higher spectral resolution in order to understand speech in noise because of the need to pick out the signal from the noise (e.g. Qin and Oxenham, 2003 and Fu and Nogaki, 2005).

Stronger associations were found between speech perception and the percentage of discriminable electrodes in the lower frequency range (≤ 2600 Hz) than was observed when correlating higher frequency ED. This pattern of results was in-keeping with previous studies with CI recipients where a higher spectral resolution or a larger proportion of channels was necessary in the lower frequency range for maximal speech perception (Skinner, Holden and Holden 1995; Henry et al., 2000; Fourakis et al., 2004 and Fourakis et al., 2007). This strong association between the percentage of discriminable electrodes at low frequencies and speech perception proved to be the main significant predictor of various speech perception measures. This provided further support for the potential future use of PTED as a test for identifying problematic electrodes and/or dead regions.

In Chapter 6 the PTED was used to identify the inter-scalar cross-over points, when the electrode array crossed over from scala tympani to scala vestibuli causing mechanical damage and loss of spiral ganglion (Finley and Skinner, 2008). The deactivation of problematic electrodes identified with the PTED led to different levels of improvement for the participants, and the extent of improvement was found to be associated with the frequency region in which the electrodes were deactivated. There was a greater impact on performance when a larger proportion of deactivated electrodes were in the frequency range < 2600 Hz. This provided further support for the importance of exploring electrode differentiation in this frequency region and it was consistent with findings of studies highlighting the importance of that frequency region for speech perception (e.g. Miller and Nicely, 1955; Shannon et al., 2001; Skinner et al., 1995; Henry et al., 2000; Fourakis et al., 2004 and Foukaris et al., 2007).

The pure-tone “intermediate frequencies” (PTIF) pitch ranking test for specific regions was an adaptation of the PTED procedure intended to explore the pitch perception between physical electrode contacts. The PTIF test was conducted between electrodes that were discriminable as well as those that were not. The participants who showed significant improvement in at least one speech perception test when electrodes were deactivated were not able to utilise pitch information in regions of the deactivated indiscriminable electrodes but were able to utilise pitch information in regions of discriminable electrodes. Results potentially indicated that PTED identified underlying dead regions (Moore, 2004 and Shannon et al., 2001) in those participants that showed benefit following the deactivation of indiscriminable electrodes. This was not true with those who reported better sound quality but without significant benefit in speech perception, they were equally able to utilise pitch information in regions of discriminable and indiscriminable electrodes (equal number of correctly ranked IF). Indicating the possibility that PTED may have identified problematic electrodes rather than underlying dead regions in those participants. For the participants that showed a decline in performance following the deactivation of indiscriminable electrodes, no difference was found between their pitch ranking ability in regions of discriminable versus indiscriminable electrodes. The deactivation of electrodes stimulating a region with good pitch perception, caused a decline in performance which is consistent with the idea that de-activating those electrodes led to decreased spectral resolution (e.g. Shannon et al., 2001; Henry et al., 2000 and McKay and Henshall, 2002). The only exception was participant 9 (in Chapter 8) who was able to utilise pitch information in regions of discriminable electrodes but not in regions of indiscriminable electrodes and reported that he did not like the sound quality following the deactivation of indiscriminable electrodes. However PTIF for participant 9 demonstrated perceived pitch reversals following the deactivation of indiscriminable electrodes, hence giving rise to a distorted spectral representation which may have been the cause of perceived loss in sound quality and deterioration in performance. Participant 9 had cochlear ossification which may have altered the current pathways and increased the overall spread of current (Rotteveel et al., 2010), increasing spatial separation between electrodes in that region did not help. PTIF results of participant showing improvement in Chapter 7, showed that deactivating indiscriminable electrodes has increased spatial separation in regions of poor differentiation. Increasing spatial separation between electrodes in those regions improved their ability to utilise pitch information, which is in line with previous recommendations of Nelson et al., (1995) and studies (Zwolan et al., 2007 and Zhou and Pfingst, 2012). Those participants had a larger number of correctly ranked IF in the regions of indiscriminable electrodes following their deactivation as compared to before deactivation. Combining these results with the reduced number of correctly ranked IF in regions of indiscriminable electrodes is in concordance with studies that indicated that redirecting the information around dead regions (with reduced number of DIF) would improve performance (Faulkner, 2006 and Smith and Faulkner, 2006).

PTIF was useful as a tool for identifying electrodes that would potentially lead to improvements in performance once deactivated potentially because it aided in the identification of dead regions. It was useful for explaining different patterns and changes in performance following the deactivation of indiscriminable electrodes. In addition to that programs based on PTIF's identification of dead regions (with reduced ability to utilise pitch information and a smaller number of correctly ranked IF) when different from PTED's nomination of problematic electrodes provided further improvement over programs based on PTED.

The combined results of the studies described in Chapters 3, 5, 6, 7 and 8 provide evidence that the PTED's identification of discriminable versus indiscriminable electrodes provided a picture of the spectral resolution provided by the CI device. There was evidence that CI provided spectral resolution of the signal that varied across CI recipients partly because of underlying dead regions. In some cases PTED's identified indiscriminable electrodes that did not uncover dead regions but could be related to the electrodes' function however PTIF testing differentiated between electrodes with versus those without underlying dead regions. PTIF may have a higher specificity than PTED for the identification of dead regions, however PTIF requires more testing time if it were to be applied with all electrode-pairs unless only suspected regions are targeted for testing.

10.3.2 Types of indiscriminable electrodes

Based on results from chapter 6, 7 and 8, it was found that indiscriminable electrodes fell under one of the following categories:

1. Indiscriminable electrodes that stimulated a neuronal dead region with few or no functioning spiral ganglion cells.
2. Indiscriminable electrodes around interscalar cross over points which might be associated with insertion trauma causing mechanical damage.
3. Indiscriminable electrodes secondary to underlying cochlear pathology (fibrosis, ossification and calcification) that may affect the spread of current in the cochlea.
4. Indiscriminable electrodes due to surgical placement issues.
5. Indiscriminable electrodes that do not stimulate a dead region without the presence of obvious cochlear pathological changes that affect the spread of electrical current stimulation or obvious placement issues.

The deactivation of electrodes that fell under the first category provided CI recipients with the greatest benefit. Some of the participants showing benefit following the deactivation of indiscriminable electrodes, had some indiscriminable electrodes falling under the second category. However due to the more restricted recruitment criteria (must be musically trained and/or have a clear concept of pitch) for the PTIF study, those electrode sites were not evaluated for IFs. The deactivation of indiscriminable electrodes falling under the third and fourth category did not provide any benefit. Probably since they do not stimulate a dead region and the participants are able to use spectral information delivered to those regions, thus deactivating them can reduce spectral resolution. Electrodes falling under the third category could be indiscriminable due to the cochlear pathology changing characteristics of the tissue surrounding the electrodes. These changes affect the electrical characteristic of that tissue thus affecting the neural excitation patterns (broader spread of excitation). This in turn may affect the results of ED (i.e. the electrode fails without an underlying dead region) and the altered spread of current (of neighbouring electrodes) may produce the negative impact of deactivating electrodes at those sites. Deactivating electrodes falling under the fifth category does not provide benefit in speech perception but might improve subjective sound quality. Possible explanations could include that these electrodes have increased electrode-neuron distance or are performing sub-optimally but still provide useful information because the regions they stimulate are not dead regions.

The deactivation of indiscriminable electrodes stimulating dead regions (with no or few functioning spiral ganglion cells) provided the greatest improvement. The most likely explanation is that information delivered to those regions is lost and redirecting that information to other electrodes stimulating more viable region improves the delivered signal. The larger the dead region the greater the benefit, which is line with findings in Chapter 7 where participants who had adjacent electrodes (both failed) deactivated. Additionally stimulating electrodes in those regions requires that the level of stimulation be increased so neighbouring more viable regions can be stimulated, however this might cause distortion due to the unwanted electrode interaction and overlap of the stimulated neural population by different electrodes representing different frequency ranges.

10.3.3 Implications regarding performance with unilateral CI

Performance measures such as CRM have highlighted the discrepancy between speech perception among the NH and CI recipients in Chapter 4, where the average SRT among NH was -22.91 dBA and was 4.44 dB among CI recipients. In Chapter 5 the majority (19/20 = 95%) of the CI population tested had a CRM SRT at a positive SNR (the level of the speech was higher than the noise). The negative SNR was associated with the introduction of a loudness cue (Brungart, 2001b) which was not an issue with CI recipient because CRM SRT most likely fell at a positive SNR, making CRM a potential testing tool for speech perception with CI.

As described in Section (1.3) and appendix 1, programming the CI speech processor determines which electrodes are active and which frequency table will be used. The frequency table determines the frequency range stimulated by CI and assigns the electrodes to specific frequency ranges. Stimulation levels, rate of stimulation and other settings optimisation have been explored (e.g. Vandali et al., 2000, Dawson et al., 1997; Skinner et al., 1995 and Skinner et al., 1999). However, only a few studies have been conducted to investigate programming options following the identification of indiscriminable electrodes or cochlear dead regions in unilaterally and bilaterally implanted adults (Zwolan et al., 2007 and Zhou and Pfingst, 2012).

In Chapter 7, a study where indiscriminable electrodes (all types of indiscriminable electrodes in Section 10.3.2) were deactivated was described. 16 out of the 25 participants showed significant improvement in at least one speech perception measure and reported better sound quality following the deactivation of indiscriminable electrodes (type 1 and possibly type 2 in Section 10.3.2). An additional four participants reported better sound quality without any significant change in the speech perception scores. One possible reason for the fact that some people reported improvements that were not reflected in the speech perception testing scores could have been due to the materials not being sufficiently sensitive to detect changes in performance. It could have also been due to the fact that for three of the four participants the larger proportion of the deactivated electrodes fell in the high frequency range (>2600Hz), which has been demonstrated to be less critical for speech perception. Another explanation could be that those deactivated indiscriminable electrodes type 5 (in Section 10.3.2), where stimulated regions were not dead regions but rather stimulated by either sub-optimally functioning electrodes or electrodes with increased electrode-neuron distance. Participant with indiscriminable electrodes (types 3 and 4 in Section 10.3.2) did not show benefit or showed decline following the deactivation of the indiscriminable electrodes.

In Chapter 8, an additional research program was provided for three of the participants recruited for the PTED study described in Chapter 7. This program was based on the PTIF results because there was a discrepancy between the PTED and the PTIF results with respect to the regions indicated as having poor pitch differentiation for those participants. For the PTIF based program, only indiscriminable electrodes in regions with a smaller number of correctly ranked intermediate frequencies, as compared to the control discriminable electrode-pair, (indiscriminable electrode type 1 in Section 10.3.2) were deactivated. The three participants showed significant improvement in speech perception even as compared to their performance with the research programs based on PTED. They all showed significant improvements in speech perception with the research program based on PTED compared to the clinical program, this suggested that the PTIF procedure was a useful enhancement of the PTED to refine the selection of electrodes to deactivate (indiscriminable electrode type 1 in Section 10.3.2).

The two procedures together highlighted the different types of indiscriminable electrodes and provided sufficient information to be able to identify regions for de-activation that would lead to improvements in speech perception. It is most likely that these were dead regions and were not providing useful discriminable information or were causing distortion (indiscriminable electrode type 1 in Section 10.3.2). When these electrodes are deactivated, the speech information gets re-distributed to other regions with good discrimination, the benefit obtained was consistent with the findings relating to Shannon et al.’s (2001) work on the “holes in hearing” (dead regions) and the simulation studies of Faulkner (2006) and Faulkner and Smith (2006). Holes in hearing were found to negatively affect speech perception (Shannon et al., 2001), later Faulkner (2006) and Faulkner and Smith (2006) proposed that re-distributing speech information around (dead regions) is the optimal approach for preserving speech information. By deactivating indiscriminable electrodes that stimulate dead regions (type 1 in Section 10.3.2), information –otherwise lost- is being redirected around the dead region as recommended by Faulkner (2006) and Faulkner and Smith (2006). For electrodes that were indiscriminable but were not stimulating dead regions (types 3 and 5 in Section 10.3.2) it was proposed that deactivation may not be the best programming solution, however full exploration of alternative approaches has not been conducted.

Since the three CI manufacturers allocate the majority of the electrodes to the lower frequency region with the higher contribution to intelligibility (indicate in Chapter 5) even after redistribution of the frequency filters following the deactivation of indiscriminable electrodes, the redistribution of frequency filters was left on default (in Chapters 7, 8 and 9). When exploring other programming options for electrodes type (3, 4 and 5 in Section 10.3.2), the importance of the low frequency region has to be taken in consideration.

The angular depth of insertion was found to be positively associated with better speech perception (BKB in speech-shaped noise and in quiet) in Chapter 6. This concurred with previous studies recommending deeper insertion of the CI electrode array (Blamey et al., 1992, Fu and Shannon, 1999a; Skinner et al., 2002; Hochmair et al., 2003; Baskent and Shannon, 2003 and 2005; Yukawa et al., 2004 and Lazard et al., 2012). Deeper insertion may lead to better alignment between the electrical stimulation and the characteristic frequency of the stimulated auditory fibre which could potentially lead to better speech perception (Fu and Shannon, 1999a and Rosen et al., 1999). The frequency shift (difference between the characteristic frequency and the centre frequency allocated) of the apical electrode was statistically associated with BKB in noise but not with BKB in quiet. This finding was in line with findings by Whitford et al. (1993) who provided programs to eliminate the frequency shift and found an effect on speech perception in noise only. Combined results of the correlation results of the depth of insertion and that of the frequency shift with speech perception, indicated that the decreased frequency shift with deeper insertion of the electrode array is at least partly the reason for better speech perception with deeper insertion. It must be noted that some research groups have reported partial adaptation to severe frequency shifts (e.g. Fu and Shannon, 1999b; McKay and Henshall, 2002 and Sagi et al., 2009). Another explanation can be offered by examining the results of the two participants with the lowest speech perception scores (in Chapter 6) who did not have the largest frequency shift coupled with the results from Chapter 5. ED in Chapter 5 was found to be a significant predictor of all speech perception measures. Deep insertions of the CI electrode array are not only associated with smaller frequency shifts, but also suggest that stimulation will be spread across a wider neural population covering different spectral regions including the apical region where spiral ganglion cells are more likely to be preserved (Blamey et al., 1992). Unlike Gani et al. (2007) and Finley and Skinner (2008) who reported a negative impact of increased depth of insertion on speech perception, deeper insertions were not associated with decreased electrode differentiation of the apical electrodes in the study reported in Chapter 6. These results along with findings from Chapter 5 (ED a predictor of speech perception) may indicate that the advantage provided by deeper insertion might also be due in part to the stimulation of a wider spectral range down to lower frequencies at the apical part of the cochlea (Hochmair et al., 2003). In addition to that deeper insertions increase the possibility of stimulating regions with good neuronal survival which consequentially improves chances for having regions with good electrode differentiation which was a significant predictor of speech perception in Chapter 5. It must be emphasised that the positive effect of deeper insertion on speech perception reported was in the absence of increased pitch confusion at the apical electrodes providing evidence for deeper insertion being achieved without causing insertion trauma. Finley and Skinner (2008) also suggested that the negative impact of deeper insertion was possibly associated with over-insertion of shorter electrode arrays leaving the basal turn void of electrodes.

Another factor to be considered with respect to depth of insertion of the CI electrode array is the range of stimulated characteristic frequencies covered by the CI electrodes. The most commonly used human frequency position map is Greenwood's frequency position function (Greenwood, 1990). It uses an equation to estimate the characteristic frequencies along the organ of Corti (OC) based on percentage length. However there are a few issues when using Greenwood's function with CIs, first the path of insertion of the CI array (e.g. in ST versus SV or presence of kinks) can affect position of the electrode and the characteristic frequencies stimulated by that electrode, which may render using length of the electrode array inaccurate (Yukawa et al., 2004). A second issue is the CI design and nature of the CI stimulation, Greenwood's function relies on the use of the length of OC, however CIs stimulate spiral ganglion cells since the spiral ganglion is shorter than OC, the estimated characteristic frequencies especially of the more apical electrodes will be different. An alternative frequency-position map of the spiral ganglion was proposed by Sridhar et al. (2006) and Stakhovskaya et al. (2007) which was used in Chapter 6. In this chapter, the angular depth of insertion was used to estimate the characteristic frequency rather than the length of the inserted array to avoid the effect of path of insertion influences. Only the most apical electrode was used to calculate the frequency shift but there was still an association between the frequency shift estimated in this way and the BKB in noise score. This might highlight the effect of matching the stimulated frequency and the characteristic frequency which necessitates the use of an accurate human frequency position map. Since the results of the frequency shift reported were based only on the frequency-position map of the spiral ganglion, no direct comparison with other frequency-position maps was reported. However the frequency shift would have been larger for the most apical electrode had the Greenwood map been used as compared to the spiral ganglion map. Matching stimulated frequencies to the characteristic frequencies estimated by Greenwood's map would necessitate a deeper insertion of the CI electrode array with the increased risk of causing trauma (e.g. Gani et al., 2007) in comparison to the spiral ganglion map.

Based on the results reported in Chapter 6 to match frequencies (stimulated and characteristic), it is not advisable to reach an angular depth of insertion (ADI) > 720° even with the use of the MED-EL CIs with the lowest centre frequency assigned to the most apical electrode. The participant with an ADI = 720° and a MED-EL device had a frequency shift of -90 Hz, so based on the spiral ganglion map it would not have been advisable to have a deeper insertion unless the filters were allocated to the lower frequencies. While based on an OC map (such as Greenwood’s map) the angular depth of insertion of 810° would be the maximum recommended ADI (even for participants with MED-EL devices) in contrast to 720°. This not only might increase risk for trauma without benefit but it also may cause stimulation of a cochlear region without spiral ganglion cells. This would necessitate increasing the level of stimulation until electric current reaches neighbouring regions or causes cross-turn stimulation to reach T and M levels. This might cause confusion and have a negative impact on speech perception.

CBCT was shown to be a radiological tool that provided high quality images that can be used to evaluate insertion of the CI electrode array with relatively low radiation exposure. In contrast to Aschendorff et al. (2007) and Finley and Skinner (2008) scalar placement in ST versus SV did not affect speech perception. But in the electrode placement study described in Chapter 6 scalar placement was not associated with electrode differentiation, which may point to insertion trauma associated with SV as the underlying cause of the reduced speech perception in those studies (Aschendorff et al., 2007 and Finley and Skinner, 2008). This explanation is supported by the comparable outcomes in speech perception for both cases of intentional surgical insertion of the CI array in SV and those of intentional insertion in SV (Berrettini et al., 2002; Kiefer et al., 2000 and Lin, 2009). However, at points of inter-scalar cross-overs, evidence of dead regions most probably secondary to insertion trauma was seen with increased pitch confusion of electrodes in those regions (electrode pairs failed ED around those regions). The implications of the radiological evidence concerning CI performance indicate that deeper insertions of the electrode array in the absence of insertion trauma are associated with better performance and that scalar placement in the absence of trauma does not affect CI performance.

10.3.4 Implications regarding performance with bilateral CI

The frequency mismatch between ears has been found to affect speech perception and cannot be overcome through training and only channels that were matched provided benefit (Siciliano et al., 2010). A finding which concurs with reports that some bilaterally implanted individuals could not integrate between the signals of both implants because of the severe pitch mismatch and learned to ignore the weaker ear (Ramsden et al., 2005). Improving matching between the two cochlear implants was attempted in Chapter 9. The AEPC test revealed that improving matching between ears for pitch might be possible. AEPC scores (a screening test of how well matched the two devices were for a fixed set of frequencies that were independent of the devices' frequency table) significantly improved following matching both CIs for pitch with both research programs. There was also significant improvement in localisation at both 30° and 15° of separation with at least one research program (that matched the CI devices for pitch). Further support comes from the correlation results, localisation at both 30° and 15° of separation were strongly associated to the AEPC results. This provides a greater plausibility to the explanation that pitch matching between ears has improved with the use of the research programs, hence giving rise to the enhanced localisation exhibited.

Significant improvement was also found in 'BKB in noise' with noise presented at either side. Additionally three out of six participants showed significant improvement in 'BKB in noise' with noise presented from the front. This may indicate that matching CIs for pitch has improved binaural summation, which occurs due to redundant information provided by both ears (e.g. Wilson et al., 2003). The improvement in speech perception after matching both devices suggests that mismatched devices may impede binaural summation because of the lack of integration between information provided to both ears. A finding which is in line with findings of Siciliano et al.'s simulation study (2010) who found that only the channels that were matched across ears provided benefit in speech perception. Another interesting finding was the significant correlation between localisation (at both 15° and 30° separation) and AEPC across the frequency range and at frequencies lower than 1500 Hz but not between localisation at 15° separation and AEPC at higher frequencies. Additionally after dividing AEPC into two frequency ranges, AEPC was significantly better with both research programs at frequencies lower than 1500 Hz only. Evidence suggests that improvement in localisation was most likely caused by improvement in matching between the CI devices at frequencies lower than 1500 Hz which is interesting considering that ITD cues are mainly used at that frequency range.

According to the duplex theory (Rayleigh, 1907; Stevens and Newman, 1936), ITD cues are mainly used for localisation at frequencies lower than 1500 Hz while ILD cues are used at higher frequencies. It has also been found that for the detection and utilisation of interaural differences (ILDs and ITDs), the signals delivered to both ears must have similar frequencies (Colburn et al., 2006; Francart and Wouters, 2007; Nuetzel and Hafter, 1981). Among CI users, sensitivity to ILDs is relatively high while sensitivity to ITDs has been found to be greatly variable (van Hoesel et al., 1993; van Hoesel and Clark, 1997; Lawson et al., 2000; van Hoesel and Tayler 2003 and Van Hoesel, 2004). Findings of improvement in localisation, 'BKB in noise' and AEPC especially at frequencies lower than 1500Hz with the research programs are consistent with Lawson et al., (2000) who demonstrated that the detection of both ITDs and ILDs improved with the use of three electrode-pairs that were matched across-ears. It is possible that improvement could be due to better use of ITD cues that can be conveyed by temporal envelopes instead of temporal fine structure (e.g. Grantham et al., 2008). It is also possible that the observed improvement is due to better utilisation of ILDs since ILD cues can be dominate ITD cues in CI users (e.g.

Poon, 2006; Grantham et al., 2008; van Hoesel et al., 2008 and Seeber and Fastl, 2008).

There was no significant correlation between BKB results and the results of the screening AEPC test. The AEPC test (at nine test frequencies only) may not be sensitive enough to detect the pitch matching at the resolution required for speech perception in noise. Another explanation is that some of the processes underlying binaural speech perception with CI may be different from those underlying binaural localisation. This is consistent with studies reporting no correlation between speech perception and localisation among the bilaterally implanted (Kerber and Seeber, 2012).

Matching between CIs did not improve performance for the CI recipient with unilaterally severe ossification which was the weaker ear. It is not clear whether this was due to abnormal current spread affecting the electrode matching process because of ossification or due to matching a significantly stronger ear with the weaker one and consequently reducing the number of active electrodes in the better ear. Further investigation is required.

Matching between ears with the use of direct stimulation was reported to be easier and provided significantly better results than auditory-stimulation. This was possibly attributed to increased difficulty in matching between tones across ears because of the different quality of sound each CI device provides. Differences between the two devices in processing, the varying degrees of neuronal survival for each ear and the frequency shift (between the characteristic frequency and stimulated frequency) difference across ears might have caused this difference in sound quality between ears.

Matching bilateral CIs for pitch can provide benefit in localisation and speech perception. However it is too early to determine which method of matching (direct stimulation versus pure-tone) is the best method and to what extent matching can be accomplished within the boundaries of the current CI designs. The effect of matching the level of stimulation and that of matching the pitch of stimulation between the two ears on performance and how they both may interact is also still not clear.

10.3.4 CI design implications

In view of the positive effects of deeper insertion of the CI electrode array in the absence of insertion trauma, the evidence provided by the analysis of the frequency shift and PTED may shed more light on possible specifications of a favourable electrode array design.

The extent of the effects of the frequency shift (between the characteristic and stimulated frequencies) for the entire array on speech perception was not evaluated and only the effects of the frequency shift at the apical electrode was evaluated. However, results reported in Chapter 6 concurred with previous results reported by Whitford et al. (1993) who provided programs with the intention of eliminating the frequency shift at all active electrodes and only speech perception in noise was improved. This was in line with the correlation found between the frequency shift of the most apical active electrode and BKB in noise but not with BKB in quiet (in Chapter 6) and is supported by Fu and Shannon (1999a) who reported a greater effect of the frequency shift at the apical electrodes than that at the more basal electrodes.

The combined evidence provided throughout Chapters 5-8 does not implicate the frequency shift as the main contributor to the variance observed in post-implantation performance or as the only reason for the positive impact of deeper insertion. Another reason for the positive effect of deep insertion of the CI array discussed in Section 10.2.1 is the wider region stimulated by the CI from the basal to the apical region, hence increasing the possibility of stimulating different regions by the CI including those with good neuronal survival. Since the percentage of discriminable electrodes has been found as the main significant predictor of CI performance and in light of the fact that indiscriminable electrodes might be associated with dead regions increasing the stimulated region along the cochlea might enhance performance.

It has been demonstrated that redirecting stimulation around dead regions by the deactivation of electrodes produced benefit in speech perception which was in line with findings of Faulkner (2006) and Smith and Faulkner (2006). However this was the only approach that was explored and other programming or design options may lead to even greater improvements in performance. Among those possible options that have not been yet explored include increasing points or sources of stimulation across the array, thus providing more flexibility and control in programming CIs around dead regions.

The matching between the two CI devices for pitch might produce improvement among the bilaterally implanted but is inherently limited by CI design and stimulation restrictions; i.e. physical contacts of the two devices might not stimulate similar pitches across ears and cannot be matched. Although current steering (see Section 1.4.3.3) might in theory increase possible stimulation sites, programming options available do not allow control over specific stimulation sites; i.e. matching between virtual channels across ears is not possible.

In light of the above, an electrode array that allows atraumatic deeper insertion, is long enough to cover a wider range of cochlear regions and has a larger number of possible stimulation sites might improve CI performance. It is outside the scope of this thesis to discuss CI design issues however it is the opinion of the author that a new CI design which allows a new mode of stimulation delivery that is not restricted by physical contacts (electrodes) might have an impact on performance with CI in both the unilaterally and bilaterally implanted. A new more flexible mode of stimulation may also support better processing strategies that better represents the sound.

10.4 Limitations of the studies described

One of the limitations of studies involving multiple visits is the time commitments that cannot be met by young professionals, hence the age range and average age of the CI recipients was somewhat limited and older adults dominated the studies' populations in Chapters 3-9.

Only 13 CI users were recruited for the CRM test-retest study described in Chapter 4, however the inclusion criteria and testing restrictions (they had to have been using the program used in testing for a minimum of two months) increased difficulty for recruiting participants. There were also more females than males due to the restrictions described above. The NH group were younger than the CI group this was partially because the younger CI recipients did not volunteer for testing while the NH were younger in order to avoid hearing losses secondary to presbycusis, in addition to that the NH were volunteers from the UCL staff and students.

There were no corresponding objective measures because of time constraints, especially since non adjacent electrode pairs were tested for ED in the procedure followed, in addition to that several performance measures were administered with each program. However this is considered in future research. Long-term follow up including the effect of adaptation to the new programs and program use were not included in the studies but is being considered in the future.

The focus of the work with bilateral implantees was not specifically to look at the measurement of ITD or ILD however the results indicated that measuring the effect of matching pitch between ears on ITD and ILD can further improve our understanding of the underlying processes involved in localisation and speech perception with bilateral CI. Especially since greater improvement in AEPC was found at low frequencies (below 1500 Hz) which is usually associated with the use of ITD cues rather than ILD cues. Only 6 participants were recruited for the bilateral testing due to the limited number of bilaterally implanted adults available for testing in the UK. The current NICE (the National Institute for Health and Clinical Excellence) guidance does not recommend bilateral implantation for adults unless they have visual impairment or other disabilities so the numbers of potential participants was very low and most of them were sequentially implanted so the results may be different to what would be expected with simultaneous implantation.

The BKB sentences were used for testing (2 lists in each condition), because it was considered to be the most well established test for speech perception used within the UK. This limited testing options; in order to avoid the learning effect the same list was never used twice. However since there were only ten sets (of two lists each), this could not be avoided and the clinical program was retested in the final session with two sentence lists that were used in the first session. Additionally the ceiling effect could not be avoided when improvement occurred; i.e. in order to allow comparison, the same initial SNR was used across all testing sessions even when scores were ceiling and additional testing was not possible due to the limited number of sentence lists. The CRM test was introduced in an attempt to introduce an additional speech perception measure and minimise the effect of a relatively small number of BKB lists. But limitations faced in these studies highlighted the need for different testing material with varying degrees of difficulty in order to detect differences especially with the use of bilateral CI (e.g. Wackym et al., 2007).

The characteristic frequency was estimated and the frequency shift was calculated for the most apical electrode only and not for all electrodes. Although the effect of the frequency shift on speech perception was not the main objective, it must be noted that the frequency shift for the other electrodes is not uniform (non-linear in nature). Other factors that would've been considered include the interaction between the effect of the frequency shift and effect of stimulating the low frequency range which is important for speech perception. In Whitford et al.'s study (1993) only participants with a certain minimum depth of insertion were recruited to reduce the frequency shift without cutting off the low frequencies vital for good speech perception.

10.5 Future research

10.5.1 The identification of dead regions and the applied intervention to improve performance with CI

Future investigation with the use of PTED and PTIF, in addition to other objective measures and radiological evaluation of the CI array placement in the cochlea, can help in pinpointing problematic regions or electrodes that may affect CI performance. Having corresponding objective measures, such as ECAPs and measures of SOE, can help enhance our understanding of the underlying processes. It can also allow including populations which are more difficult to test, such as young children or individuals who may not be able to rank pitch.

Some of the participants that took part in the research of this thesis have continued to use at least one of the research programs that they tried in the study. It would be informative to follow up with these participants and determine if they liked the programme after a longer period of time. It would be interesting to assess if their improvements continue to grow or whether they had stabilised in performance.

Deactivation of electrodes stimulating potential “dead regions” produced positive results for speech perception. However, other options for programming around the indiscriminable electrodes should be explored. These may include adjusting the band-pass cut off frequencies of the filters to send less information to the dead regions and greater information to regions with good discrimination or altering frequency to electrode allocation to better match the electrodes with the appropriate characteristic frequency. Perhaps with the use of more recent speech processing strategies and more focussed stimulation, such as partial tripolar stimulation, the impact of the dead regions could be reduced (e.g. Bierer et al., 2005; Bonham et al., 2005; Litvak et al., 2007; Zhu et al., 2012). The partial tripolar stimulation can allow more control over stimulation when reprogramming around dead regions, especially if coupled with manipulation of the frequency filters in order to minimise stimulation to dead regions.

The use and development of more sensitive performance measures for speech perception, questionnaires for the evaluation of objective reports regarding sound quality and music perception may also be warranted. This will allow the detection of changes in performance which are not picked up by measures of speech perception regularly used. Speech perception measures that use speech in speech masking, for instance, can add an extra level of difficulty. Long-term evaluations may also provide more insight about the success of interventions taken.

Other testing options that could evaluate CI recipients with cochlear pathology must be investigated, since ossification and cochlear pathology have been observed to affect testing with the PTED for problematic regions. Possible options might include the use of the more focussed partial tripolar stimulation, for instance; the PTIF has also been shown to be more effective than the PTED in identifying dead regions. However, more research is required.

10.5.2 Improving performance with bilateral CIs

During testing for the study reported in Chapter 9, an unexpected adaptation process that has not been reported in previous studies was observed by the author for some of the participants. After which a pilot study was carried out with five participants, all of whom exhibited the same adaptation with the use of four different stimuli and settings. The adaptation process was not found in the NH and seemed to be specific to CI recipients. Further investigation in order to understand this adaptation process and its’ impact on balancing across the ears and performance will be explored in depth.

The optimum approach to program bilateral CI requires further research into the selection of the best electrodes/sites and possibly the best matching process between the two CI devices, more participants are to be recruited. Investigation can also address the effect of both pitch and loudness cues on binaural perception. Greater improvement in AEPC was found at low frequencies (below 1500 Hz) in addition to that, correlation between localisation and AEPC was found at that region and not the higher frequencies. Localisation of frequencies in this region is usually associated with the use of ITD cues rather than ILD cues, this warrants further investigation. Future research could also investigate psychophysical measures that might aid in determining the optimal matching between CIs. Comparison can be made between individuals with simultaneous implants versus those with sequential CIs.

Different programming options for matching including strategy selection, frequency tables used and perhaps even specially designed speech processors might improve performance in the bilaterally implanted.

10.6 Conclusion

CI recipients demonstrate varying degrees of post-implantation performance. Some exhibit very limited benefit and have little or no open set speech perception without the aid of lip reading while others can use the telephone. Understanding the underlying factors that might explain this disparity in performance can provide guidance when it comes to providing management with the intention of improving speech perception.

Problematic electrodes were evaluated as a possible cause of poor speech perception. The PTED procedure was found to be the main significant predictor of speech perception indicating that problematic electrodes have a detrimental effect on speech perception. PTED was used to identify indiscriminable electrodes based on pitch perception. Research programs were created by deactivating indiscriminable electrodes. The deactivation of indiscriminable electrodes improved performance for 20 out of 25 CI recipients. Further testing with the PTIF procedure revealed that the deactivation of indiscriminable electrodes that stimulated underlying “dead regions” led to improvements in performance. Additionally PTIF showed that deactivating indiscriminable electrodes and increasing spatial separation in those regions, improved pitch perception. Programming based on PTIF provided additional benefit over the initial PTED programs when there were cases of discrepancy between PTED and PTIF. Both PTED and PTIF are potentially valuable tools that can help to enhance performance with CI within clinical practice.

The CBCT was demonstrated to be a useful imaging tool for evaluating CI electrode array placement within the cochlea, providing high resolution images with less metallic artefacts and reduced radiation exposure compared to MSCT. Such a tool could be valuable for identifying contacts that have ruptured the basilar membrane and will most likely lead to dead regions. It is also useful for looking at insertion depth and the positioning of the electrode array. It will not pick up dead regions that already existed prior to implantation but may highlight ones that may have occurred due to insertion trauma. It is most likely that these would occur nearer to the apical end which would be the most important region for having an impact on speech perception. The evaluation tools (PTED, PTIF and CBCT) can be used together to help investigate and provide potential solutions for CI recipients with suboptimal performance. They can be used to identify dead regions, placement issues or non-functional electrodes. Finding the cause of poor performance can guide management and programming of CIs.

With the increasing number of children receiving bilateral implants nowadays, investigation of methods for the optimisation of the fitting of bilaterally implanted individuals has become a necessity. Matching between the bilateral CI devices for pitch in six adults, produced improvement in both localisation and speech perception, it also highlighted the need for the development of specialised protocols specifically for the programming of bilateral CIs in order to achieve better binaural benefit.

This thesis has provided evidence to show that the performance of adults with CIs should be evaluated and monitored and in cases of sub-optimal performance, attempts should be made to re-program the sound processors with the intention of improving outcomes. PTED, PTIF and matching bilateral implants for pitch perception can be used to improve speech perception with CIs. Additionally, this thesis has uncovered for the first time different types of indiscriminable/problematic electrodes. The effect of deactivating each type is different, with benefit most likely occurring following the deactivation of indiscriminable electrodes stimulating neuronal dead regions. In contrast, no benefit was observed following the deactivation of indiscriminable electrodes that do not stimulate dead regions when active. PTIF can be used to differentiate between indiscriminable electrodes that stimulate dead regions and those that do not.

Re-programming the sound processors based on pitch perception can help select optimum sites of stimulation (electrodes) and help to match ears when there are implants fitted on both sides to achieve better performance with CIs.

Appendix A

Procedures involved in the programming of the speech processor (a brief programming protocol)

Programming the speech processor involves carrying out several measurements and procedures, all of which have to be conducted in a formalized and safe manner with the aim of providing optimum individualised fitting. This appendix provides the basic procedures involved in the fitting of cochlear implants, some of which have been discussed earlier in section 1.3.

A.1 The CI fitting station

The fitting station consists of a computer with the specialised fitting (programming) software provided by the manufacturer and at least one clinical programming interface (CPI) connected to it, two are required to fit the bilaterally implanted. Some CPIs require a power supply. See Figure (A.1) for an example of a CI fitting station.

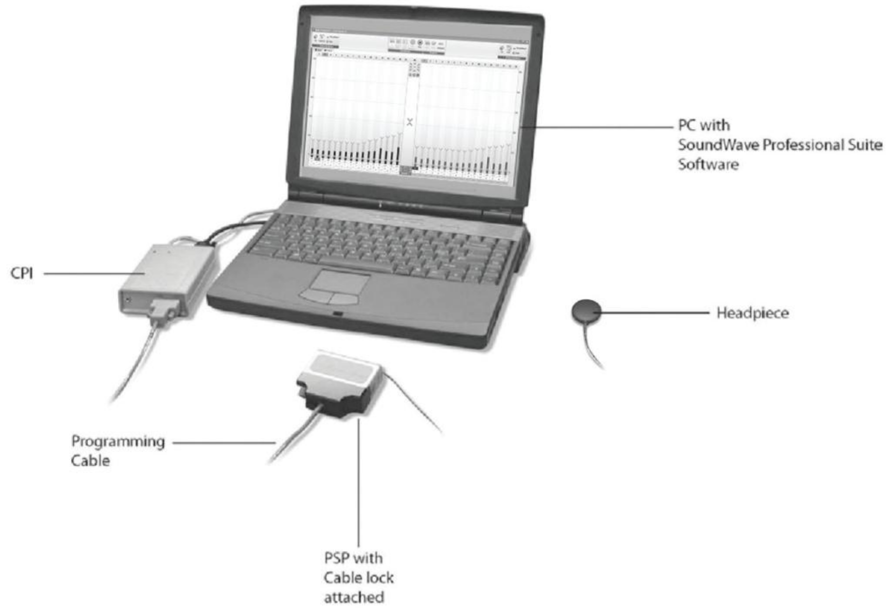


Figure A.1 An Advanced Bionics (AB) CI fitting station, adapted from the AB website

A.2 The fitting procedure

The fitting of the CI speech processor involves four main procedures:

(a) The connection of the speech processor to the fitting station, (b) impedance telemetry, (c) the creation of a CI program and (d) the downloading of the program to the speech processor.

For the basic procedures of fitting and key points/actions involved in each procedure see Table (A.1).

A.2.1 Manufacturer-specific stimulation level settings

As discussed in section 3.1 there are two stimulation levels that should be optimized for each CI recipient. The manufacturer-specific guidelines for setting these lower (threshold/ T/ THR) and upper (most comfortable level/ M/ C/ MCL) stimulation levels are as follows:

Advanced Bionics: T levels are either set at the lowest level of electrical stimulation that is audible to the CI recipient 50% of the time for each electrode or at a default 10% of the measured M levels. M levels are usually established at the most comfortable loudness level with the use of speech bursts which stimulate three to four electrodes simultaneously. A speech burst is white noise filtered through three to four bands that represent electrodes grouped for fitting by the fitting software. These speech bursts resemble more complex spectral attributes of speech and account for summation in real life situations, making them superior to tone bursts that stimulate single electrodes.
Cochlear: T levels are set for each electrode at the lowest level of electrical stimulation that is audible to the CI recipient 100% of the time, and C levels are usually set at loud but comfortable levels.
Med-El: THR levels are set for each electrode at either 10% of the measured MCL levels or set at the highest level of electrical stimulation that is inaudible to the CI recipient. These are measured by establishing threshold levels at a 50% audible levels, then reducing the levels by one to two steps. MCL levels are usually set at loud and comfortable levels.

Table A.1 A brief description of the procedures involved in fitting CI speech processors

Procedure	Key points and actions involved
Connecting the speech processor	The speech processor must be first connected to the clinical programming interface with a special programming cable.
	Different styles of speech processors require different and specific programming cables which are usually provided by the CI manufacturers.
	Once the speech processor is connected and identified by the fitting software, it is usually associated with a specific CI recipient to allow for programming/fitting.
Impedance telemetry	Telemetry provides essential information about the function of the CI electrodes.
	Electrodes demonstrating short circuits or open circuits (low or high impedances) must be deactivated.
	Telemetry reflects changes in the tissue surrounding those electrodes.
Creating a CI program	Selection of a speech processing strategy.
	Determination of the per channel rate of stimulation (per second).
	Selection of the frequency table (frequency range and frequency to electrode assignment).
	Selection of the active (and deactivated) electrodes
	Selection of the value of n “maxima” in the n of m strategies
	Measurement of the lower and upper stimulation levels.
	Sweeping and balancing between the upper stimulation levels.
Downloading the program in the speech processor	Programs are tested in live mode (check if the program is comfortable with the microphone on) before downloading.
	Selection of the pre-processing algorithms which are available for some devices including ADRO.
	Selection of the mixing ratio between the auxiliary input and the microphone.
	Selection of volume which controls loudness.
	Selection of sensitivity which controls how sensitive the microphone is in picking up sounds.
	Downloading the programs and settings in the speech processor, each speech processor has a specific number of slots ranging from 2 to 4.

Appendix B

Strategies involving explicit feature extraction

Table B.1 Strategies involving explicit feature extraction

Strategy	Information extracted	Use of extracted information
F0/F2	F0 (fundamental frequency)	F0 information determines the rate of stimulation; for voiced sounds at F0 pulses/sec.
	F2 (2nd formant)	F2 information determines which electrode among the 22 to be stimulated and the amplitude of stimulation.
F0/F1/F2	F0 (fundamental frequency)	F0 information determines the rate of stimulation; for voiced sounds at F0 pulses/sec.
	F1 (1st formant)	F1 information determines which electrode among the most apical five electrodes (in the 280Hz-1kHz frequency range) to be stimulated and the amplitude of stimulation.
	F2 (2nd formant)	F2 information determines which electrode among the remaining 15 electrodes (representing frequencies higher than 1kHz) to be stimulated and the amplitude of stimulation.
MPEAK	F0 (fundamental frequency)	F0 information determines the rate of stimulation; for voiced sounds at F0 pulses/sec.
	F1 (1st formant)	For voiced sounds F1 information determines which electrode among the most apical electrodes (in the 280Hz-1kHz frequency range) to be stimulated and the amplitude of stimulation. F1 information is not used with unvoiced sounds.
	F2 (2nd formant)	F2 information determines which electrode among the remaining more basal electrodes except electrodes 1,4 & 7 (representing frequencies higher than 1kHz) to be stimulated and the amplitude of stimulation.
	Amplitude at (2-2.8 kHz) band. Amplitude at (2.8-4kHz) band. Amplitude at (4-6 kHz) band.	For voiced sounds the envelope outputs of the frequency bands (2-2.8 kHz & 2.8-4 kHz) are delivered to electrodes 7 & 4 respectively. For unvoiced sounds the envelope output of the frequency band (4-6 kHz) is delivered to electrode 1 as well.

Appendix C

Data used in analyses in Chapter 5

Table C.1 BKB in quiet (RAU) and data used in analyses for correlations and multiple regression. Pathology as defined by the presence of radiologically confirmed pathology was given the value 2, aetiology associated with fibrosis, calcification or ossification was given the value 2, DD and DDY for duration of deafness categorical data and years respectively, AAI and AAIY for age at implant categorical data and in years respectively, percentage of discriminable electrodes (DEL) for the full CI array, DELA, DELM and DELB for the percentage of discriminable electrodes at frequencies $\leq$ 1000 Hz, 1000 Hz < frequencies $\leq$ 2600 Hz and at frequencies > 2600 Hz respectively.

Pathology	Aetiology	DD	AAI	DDY	AAIY	DEL	BKBQ	DELA	DELM	DELB
2.00	2.00	2.00	1.00	40.00	61.00	80.00	49.07	75.00	50.00	75.00
1.00	1.00	2.00	1.00	12.00	61.00	72.73	77.62	60.00	100.00	75.00
2.00	2.00	2.00	1.00		49.00	73.08	75.41	85.71	57.14	50.00
1.00	1.00	2.00	1.00	15.00	40.00	78.95	64.16	83.33	83.33	75.00
1.00	1.00	2.00	2.00	25.00	78.00	68.75	55.59	60.00	100.00	100.00
2.00	1.00	2.00	1.00	19.00	57.00	84.62	41.59	100.00	50.00	14.29
2.00	1.00	1.00	1.00	4.00	44.00	87.50	48.14	50.00	100.00	100.00
1.00	1.00	1.00	1.00	6.00	47.00	42.22	38.74	42.86	.00	100.00
1.00	1.00	1.00	2.00	5.00	70.00	78.57	69.12	40.00	66.67	50.00
1.00	1.00	1.00	1.00	6.00	52.00	75.68	91.58	71.43	71.43	100.00
1.00	1.00	1.00	2.00	9.00	69.00	88.89	66.12	100.00	100.00	83.33
1.00	1.00	1.00	2.00	1.00	70.00	82.00	81.08	80.00	100.00	66.67
1.00	1.00	1.00	1.00	7.00	60.00	88.00	79.91	85.71	66.67	75.00
1.00	1.00	1.00	1.00	5.00	15.00	55.56	23.49	.00	50.00	57.14
1.00	1.00	2.00	1.00	33.00	51.00	90.91	90.12	100.00	100.00	100.00
1.00	1.00	1.00	1.00	7.00	60.00	44.12	48.14	16.67	16.67	75.00
1.00	1.00		2.00		66.00	62.50	90.12	71.43	80.00	33.33
2.00	2.00	1.00	1.00	2.00	58.00	93.33	91.58	100.00	100.00	50.00
1.00	1.00	1.00	2.00	7.00	73.00	73.33	94.68	83.33	100.00	75.00
1.00	1.00	2.00	1.00	25.00	59.00	82.00	94.68	100.00	100.00	25.00
1.00	1.00		1.00		47.00	79.41	98.11	50.00	83.33	33.33
1.00	1.00	1.00	1.00	6.00	57.00	73.08	96.35	28.57	50.00	25.00
1.00	1.00	2.00	1.00	12.00	63.00	86.67	104.28	85.71	83.33	42.86
1.00	1.00	1.00	1.00	9.00	20.00	86.67	104.28	100.00	66.67	62.50
1.00	1.00	1.00	1.00	2.00	48.00	100.00	100.00	80.00	100.00	75.00
1.00	1.00	2.00	2.00	40.00	72.00	100.00	123.00	100.00	100.00	75.00
1.00	1.00	1.00	2.00	7.00	71.00	100.00	109.81	100.00	100.00	100.00
1.00	1.00	1.00	1.00	5.00	57.00	100.00	123.00	100.00	100.00	100.00
1.00	1.00	1.00	1.00	6.00	57.00	100.00	73.27	100.00	100.00	28.57
1.00	1.00	1.00	1.00	1.00	2.00	100.00	123.00	100.00	100.00	100.00
1.00	1.00		1.00		56.00	100.00	123.00	100.00	100.00	100.00
1.00	1.00	2.00	1.00	53.00	64.00	73.08	104.28	100.00	100.00	100.00
2.00	1.00	1.00	1.00	3.00	46.00	73.08	71.17	75.00	100.00	100.00
1.00	1.00	2.00	1.00	15.00	40.00	14.13	52.79	.00	.00	14.29
1.00	1.00	2.00	1.00	15.00	22.00	40.00	69.12	33.33	28.57	28.57

Table C.2 BKB in noise (RAU) and data used in analyses for correlations and multiple regression. Pathology as defined by the presence of radiologically confirmed pathology was given the value 2, aetiology associated with fibrosis, calcification or ossification was given the value 2, DD and DDY for duration of deafness categorical data and years respectively, AAI and AAIY for age at implant categorical data and in years respectively, percentage of discriminable electrodes (DEL) for the full CI array, DELA, DELM and DELB for the percentage of discriminable electrodes at frequencies ≤ 1000 Hz, 1000 Hz < frequencies ≤ 2600 Hz and at frequencies > 2600 Hz respectively.

Pathology	Aetiology	DD	AAI	DDY	AAIY	DEL	BKBN	DELA	DELM	DELB
1.00	1.00	2.00	1.00	12.00	61.00	72.73	50.00	60.00	100.00	75.00
1.00	1.00	2.00	1.00	15.00	40.00	78.95	30.88	83.33	83.33	75.00
1.00	1.00	2.00	2.00	25.00	78.00	68.75	13.96	60.00	100.00	100.00
1.00	1.00	2.00	1.00	15.00	40.00	14.13	29.86	.00	.00	14.29
1.00	1.00	1.00	1.00	6.00	47.00	42.22	10.00	42.86	.00	50.00
1.00	1.00	1.00	2.00	5.00	70.00	78.57	72.21	40.00	66.67	100.00
1.00	1.00	1.00	1.00	6.00	52.00	75.68	32.89	71.43	71.43	83.33
1.00	1.00	1.00	2.00	9.00	69.00	88.89	54.66	100.00	100.00	66.67
1.00	1.00	1.00	2.00	1.00	70.00	82.00	78.75	80.00	100.00	75.00
1.00	1.00	1.00	1.00	7.00	60.00	88.00	49.07	85.71	66.67	57.14
1.00	1.00	2.00	1.00	33.00	51.00	90.91	72.21	100.00	100.00	75.00
1.00	1.00		2.00		66.00	62.50	44.41	71.43	80.00	50.00
2.00	2.00	1.00	1.00	2.00	58.00	93.33	52.79	100.00	100.00	75.00
1.00	1.00	1.00	2.00	7.00	73.00	73.33	60.31	83.33	100.00	25.00
1.00	1.00	2.00	1.00	25.00	59.00	82.00	87.36	100.00	100.00	33.33
1.00	1.00		1.00		47.00	79.41	82.28	50.00	83.33	25.00
1.00	1.00	1.00	1.00	6.00	57.00	73.08	48.14	28.57	50.00	42.86
1.00	1.00	2.00	1.00	12.00	63.00	86.67	86.04	85.71	83.33	62.50
1.00	1.00	1.00	1.00	9.00	20.00	86.67	100.00	100.00	66.67	75.00
1.00	1.00	1.00	1.00	2.00	48.00	100.00	84.75	80.00	100.00	75.00
1.00	1.00	2.00	2.00	40.00	72.00	100.00	100.00	100.00	100.00	100.00
1.00	1.00	1.00	2.00	7.00	71.00	100.00	100.00	100.00	100.00	100.00
1.00	1.00	1.00	1.00	5.00	57.00	100.00	123.00	100.00	100.00	100.00
1.00	1.00	2.00	1.00	15.00	22.00	40.00	3.65	33.33	28.57	28.57
1.00	1.00	1.00	1.00	6.00	57.00	100.00	104.28	100.00	100.00	100.00
1.00	1.00	1.00	1.00	1.00	2.00	100.00	106.82	100.00	100.00	100.00
1.00	1.00		1.00		56.00	100.00	109.81	100.00	100.00	100.00
1.00	1.00	2.00	1.00	53.00	64.00	73.08	86.04	100.00	100.00	100.00
2.00	2.00	1.00	1.00	3.00	46.00	73.08	87.36	75.00	100.00	100.00

Table C.3 CRM SRT in dBA and data used in analyses for correlations and multiple regression. Pathology as defined by the presence of radiologically confirmed pathology was given the value 2, aetiology associated with fibrosis, calcification or ossification was given the value 2, DD and DDY for duration of deafness categorical data and years respectively, AAI and AAIY for age at implant categorical data and in years respectively, percentage of discriminable electrodes (DEL) for the full CI array, DELA, DELM and DELB for the percentage of discriminable electrodes at frequencies ≤ 1000 Hz, 1000 Hz < frequencies ≤ 2600 Hz and at frequencies > 2600 Hz respectively.

Pathology	Aetiology	DD	AAI	DDY	AAIY	DEL	CRM	DELA	DELM	DELB
1.00	1.00	1.00	1.00	6.00	52.00	75.68	5.31	71.43	71.43	83.33
1.00	1.00	1.00	2.00	9.00	69.00	88.89	8.75	100.00	100.00	66.67
1.00	1.00	1.00	2.00	1.00	70.00	82.00	20.94	80.00	100.00	75.00
1.00	1.00	1.00	1.00	7.00	60.00	88.00	6.26	85.71	66.67	57.14
1.00	1.00	1.00	1.00	5.00	15.00	55.56	23.44	.00	50.00	100.00
1.00	1.00	2.00	1.00	33.00	51.00	90.91	6.88	100.00	100.00	75.00
1.00	1.00		2.00		66.00	62.50	10.00	71.43	80.00	50.00
2.00	2.00	1.00	1.00	2.00	58.00	93.33	6.25	100.00	100.00	75.00
1.00	1.00		2.00		73.00	73.00	6.15	83.33	100.00	25.00
1.00	1.00	2.00	1.00	25.00	59.00	82.00	4.38	100.00	100.00	33.33
1.00	1.00		1.00		47.00	79.41	14.38	50.00	83.33	25.00
1.00	1.00	1.00	1.00	6.00	57.00	73.08	.15	28.57	50.00	42.86
1.00	1.00	2.00	1.00	7.00	63.00	86.67	1.88	85.71	83.33	62.50
1.00	1.00	1.00	1.00	9.00	20.00	86.67	.00	100.00	66.67	75.00
1.00	1.00	1.00	2.00	7.00	71.00	100.00	4.06	100.00	100.00	100.00
1.00	1.00	1.00	1.00	5.00	57.00	100.00	-4.60	100.00	100.00	100.00
1.00	1.00	1.00	1.00	6.00	57.00	100.00	4.00	100.00	100.00	100.00
1.00	1.00		1.00		56.00	100.00	-4.60	100.00	100.00	100.00
1.00	1.00	1.00	1.00	7.00	60.00	44.12	29.53	16.67	16.67	33.33

Appendix D

Raw data used in analyses in Chapter 7 and figures

Table D.1 BKB in quiet (raw scores) with the best research program compared to the best BKB score with the clinical program in group I.

BKB (best clinical)	BKB (best research program
49.00	35.00
78.00	88.00
76.00	68.00
65.00	73.00
56.00	83.00
53.00	71.00
41.00	39.00
48.00	55.00
38.00	64.00
70.00	91.00
89.00	85.00
67.00	76.00
81.00	89.00
80.00	94.00
23.00	35.00
88.00	94.00
48.00	54.00
88.00	92.00
91.00	91.00
91.00	94.00
92.00	94.00
96.00	99.00
96.00	90.00
94.00	97.00
93.00	94.00

Table D.2 BKB in quiet (raw scores) with the best research program compared to the best BKB score with the clinical program in group II.

BKB (best clinical)	BKB (best research program
49.00	35.00
78.00	88.00
76.00	68.00
65.00	73.00
56.00	83.00
53.00	71.00
41.00	39.00
48.00	55.00
38.00	64.00
70.00	91.00
48.00	54.00
67.00	76.00
88.00	94.00
88.00	92.00
91.00	91.00
91.00	94.00
96.00	99.00
96.00	90.00
94.00	97.00
93.00	94.00

Table D.3 BKB in noise (raw scores) with the best research program compared to the best BKB score with the clinical program in group I.

BKB (best clinical)	BKB (best research program
14	59
50	69
29	41
31	40
84	88
82	78
0	24
73	80
32	32
55	64
79	91
61	82
73	65
86	85
82	78
48	55
44	47
85	94
94	89
49	54

Table D.4 BKB in noise (raw scores) with the best research program compared to the best BKB score with the clinical program in group II.

BKB (best clinical)	BKB (best research program
14	59
50	69
29	41
31	40
84	88
82	78
0	24
73	80
55	64
61	82
73	65
86	85
82	78
48	55
44	47
85	94
94	89

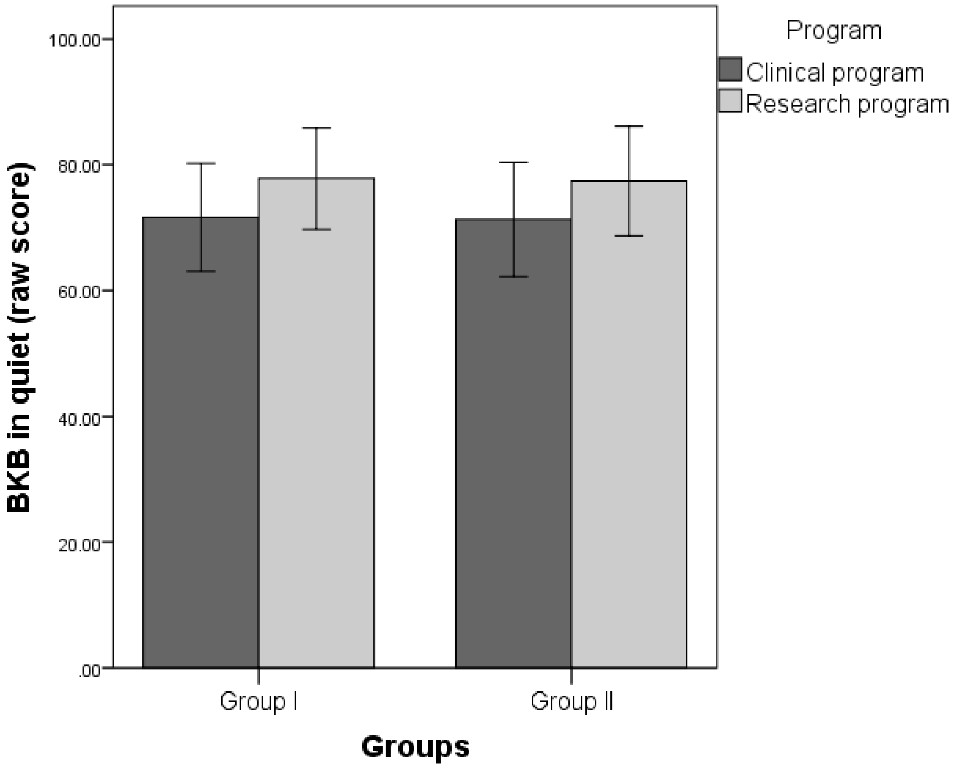


Figure D.1 Mean BKB Sentence Test in quiet (raw score) for the two sub-groups with the use of the clinical program (dark grey bars) and the best research program (light grey bars).The bars show mean scores, error bars show ± 2SE.

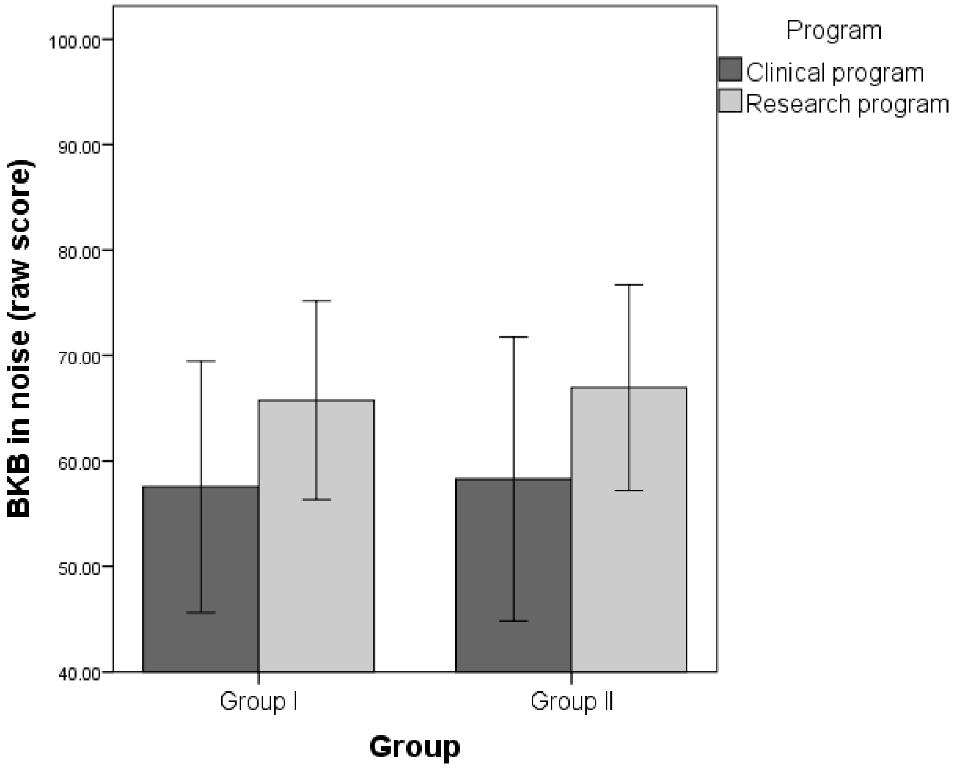


Figure D.2 Mean BKB Sentence Test in noise (raw score) for the two sub-groups with the use of the clinical program (dark grey bars) and the best research program (light grey bars).The bars show mean scores, error bars show ± 2SE.

2005, "European consensus statement on cochlear implant failures and explantations", *Otol.Neurotol.*, vol. 26, no. 6, pp. 1097-1099.

Abbas, P. J., Hughes, M. L., Brown, C. J., Miller, C. A., & South, H. 2004, "Channel interaction in cochlear implant users evaluated using the electrically evoked compound action potential", *Audiology and Neuro-Otology*, vol. 9, no. 4, pp. 203-213.

Adunka, O., Unkelbach, M. H., Mack, M., Hambek, M., Gstoettner, W., & Kiefer, J. 2004, "Cochlear implantation via the round window membrane minimizes trauma to cochlear structures: a histologically controlled insertion study", *Acta Otolaryngol.*, vol. 124, no. 7, pp. 807-812.

Adunka, O. F., Pillsbury, H. C., & Kiefer, J. 2006, "Combining perimodiolar electrode placement and atraumatic insertion properties in cochlear implantation -- fact or fantasy?", *Acta Otolaryngol.*, vol. 126, no. 5, pp. 475-482.

Agresti A., and Finlay B. 1997, "Statistical Methods for the Social Sciences", New Jerse: Prentice Hall.

Alexiades, G., Roland, J. T., Fishman, A. J., Shapiro, W., Waltzman, S. B., & Cohen, N. L. 2001, "Cochlear reimplantation: Surgical techniques and functional results", *Laryngoscope*, vol. 111, no. 9, pp. 1608-1613.

Alexander, A. J., Bartel, L., Friesen, L., Shipp, D., & Chen, J. 2011, "From Fragments to the Whole: A Comparison between Cochlear Implant Users and Normal-Hearing Listeners in Music Perception and Enjoyment", *Journal of Otolaryngology-Head & Neck Surgery*, vol. 40, no. 1, pp. 1-7.

Amoodi, H. A., Mick, P. T., Shipp, D. B., Friesen, L. M., Nedzelski, J. M., Chen, J. M., & Lin, V. Y. W. 2011, "The Effects of Unilateral Cochlear Implantation on the Tinnitus Handicap Inventory and the Influence on Quality of Life", *Laryngoscope*, vol. 121, no. 7, pp. 1536-1540.

Arbogast, T. L., Mason, C. R., & Kidd, G. 2002, "The effect of spatial separation on informational and energetic masking of speech", *Journal of the Acoustical Society of America*, vol. 112, no. 5, pp. 2086-2098.

Arbogast, T. L., Mason, C. R., & Kidd, G. 2005, "The effect of spatial separation on informational masking of speech in normal-hearing and hearing-impaired listeners", *Journal of the Acoustical Society of America*, vol. 117, no. 4, pp. 2169-2180.

Arlinger, S., Lunner, T., Lyxell, B., & Pichora-Fuller, M. K. 2009, "The emergence of Cognitive Hearing Science", *Scandinavian Journal of Psychology*, vol. 50, no. 5, pp. 371-384.

Arnoldner, C., Riss, D., Brunner, M., Durisin, M., Baumgartner, W. D., & Hamzavi, J. S. 2007, "Speech and music perception with the new fine structure speech coding strategy: preliminary results", *Acta Oto-Laryngologica*, vol. 127, no. 12, pp. 1298-1303.

Arora, K., Dawson, P., Dowell, R., & Vandali, A. 2009, "Electrical stimulation rate effects on speech perception in cochlear implants", *Int.J.Audiol.*, vol. 48, no. 8, pp. 561-567.

Aschendorff, A., Klenzner, T., Richter, B., Kubalek, R., Nagursky, H., & Laszig, R. 2003, "Evaluation of the HiFocus (R) electrode array with positioner in human temporal bones", *Journal of Laryngology and Otology*, vol. 117, no. 7, pp. 527-531.

Aschendorff, A., Kromeier, J., Klenzner, T., & Laszig, R. 2007, "Quality control after insertion of the nucleus contour and contour advance electrode in adults", *Ear and Hearing*, vol. 28, no. 2, pp. 75S-79S.

Aschendorff, A., Kubalek, R., Hochmuth, A., Bink, A., Kurtz, C., Lohnstein, P., Klenzner, T., & Laszig, R. 2004, "Imaging procedures in cochlear implant patients - Evaluation of different radiological techniques", *Acta Oto-Laryngologica*, vol. 124, pp. 46-49.

Aschendorff, A., Kubalek, T., Turowski, B., Zanella, T., Hochmuth, T., Schumacher, T., Klenzner, T., & Laszig, R. 2005, "Quality control after cochlear implant surgery by means of rotational tomography", *Otology & Neurotology*, vol. 26, no. 1, pp. 34-37.

Balkany, T. J., Hodges, A. V., Buchman, C. A., Luxford, W. M., Pillsbury, C. H., Roland, P. S., Shallop, J. K., Backous, D. D., Franz, D., Graham, J. M., Hirsch, B., Luntz, M., Niparko, J. K., Patrick, J., Payne, S. L., Staller, S., Telischi, F. F., Tobey, E. A., & Truy, E. 2005, "Cochlear implant soft failures consensus development conference statement", *Cochlear.Implants.Int.*, vol. 6, no. 3, pp. 105-122.

Barretto, R. L. & Pfingst, B. E. 1992, "Electrical-Stimulation of the Auditory-Nerve - Effects of Pulse Width on Frequency Discrimination", *Hearing Research*, vol. 62, no. 2, pp. 245-249.

Barry, J. G., Ferguson, M. A., Moore, D. R. 2010, "Making Sense of Listening: The IMAP Test Battery", *Journal of Visualized Experiments*, 44, e2139, DOI: 10.3791/2139.

Bartling, S. H., Gupta, R., Torkos, A., Dullin, C., Eckhardt, G., Lenarz, T., Becker, H., & Stover, T. 2006, "Flat-panel volume computed tomography for cochlear implant electrode array examination in isolated temporal bone specimens", *Otology & Neurotology*, vol. 27, no. 4, pp. 491-498.

Barton, G., Summerfield, A., Marshall, D., and Bloor, K. (2001). Choice of instrument for measuring the gain in utility from cochlear implantation. Paper prepared for The Health Economics Study Group, Oxford.

Bas, E., Dinh, C. T., Garnham, C., Polak, M., & Van De Water, T. R. 2012, "Conservation of hearing and protection of hair cells in cochlear implant patients' with residual hearing", *Anatomical Record-Advances in Integrative Anatomy and Evolutionary Biology*, vol. 295, no. 11, pp. 1909-1927.

Baskent, D. & Shannon, R. V. 2003, "Speech recognition under conditions of frequency-place compression and expansion", *J.Acoust.Soc.Am.*, vol. 113, no. 4 Pt 1, pp. 2064-2076.

Baskent, D. & Shannon, R. V. 2005, "Interactions between cochlear implant electrode insertion depth and frequency-place mapping", *J.Acoust.Soc.Am.*, vol. 117, no. 3 Pt 1, pp. 1405-1416.

Baskent, D. & Shannon, R. V. 2006, " Frequency transposition around dead regions simulated with a noiseband vocoder ", *J.Acoust.Soc.Am.*, vol. 119, no. 2, pp. 1156-1163.

Battmer, R. D., Gupta, S. P., Allum-Mecklenburg, D. J., & Lenarz, T. 1995, "Factors influencing cochlear implant perceptual performance in 132 adults", *Ann.Otol.Rhinol.Laryngol.Suppl*, vol. 166, pp. 185-187.

Battmer, R. D., Zilberman, Y., Haake, P., & Lenarz, T. 1999, "Simultaneous Analog Stimulation (SAS)--Continuous Interleaved Sampler (CIS) pilot comparison study in Europe", *Ann.Otol.Rhinol.Laryngol.Suppl*, vol. 177, pp. 69-73.

Baumgartner, W. D., Jappel, A., Morera, C., Gstottner, W., Muller, J., Kiefer, J., Van De, H. P., Anderson, I., & Nielsen, S. B. 2007, "Outcomes in adults implanted with the FLEXsoft electrode", *Acta Otolaryngol.*, vol. 127, no. 6, pp. 579-586.

Bench, J., Kowal, A., & Bamford, J. (1979). The BKB (Bamford-Kowal-Bench) sentence lists for partially-hearing children. *British Journal of Audiology*, vol. 13, no. 3, pp.108-12.

Berrettini, S., Forli, F., Neri, E., Segnini, G., & Franceschini, S. S. 2002, "Scala vestibuli cochlear implantation in patients with partially ossified cochleas", *Journal of Laryngology and Otology*, vol. 116, no. 11, pp. 946-950.

Berrettini, S., Forli, F., & Passetti, S. 2008, "Preservation of residual hearing following cochlear implantation: comparison between three surgical techniques", *J.Laryngol.Otol.*, vol. 122, no. 3, pp. 246-252.

Bhatt, Y. M., Green, K. M., Mawman, D. J., Aplin, Y., O'Driscoll, M. P., Saeed, S. R., & Ramsden, R. T. 2005, "Device nonuse among adult cochlear implant recipients", *Otol.Neurotol.*, vol. 26, no. 2, pp. 183-187.

Benki, J. R. 2001, "Place of articulation and first formant transition pattern both affect perception of voicing in English", *Journal of Phonetics*, vol. 29, no. 1, pp. 1-22.

Bierer, J. A. 2007, "Threshold and channel interaction in cochlear implant users: Evaluation of the tripolar electrode configuration", *Journal of the Acoustical Society of America*, vol. 121, no. 3, pp. 1642-1653.

Bierer, J. A., Bierer, S. M., & Middlebrooks, J. C. 2010, "Partial tripolar cochlear implant stimulation: Spread of excitation and forward masking in the inferior colliculus", *Hearing Research*, vol. 270, no. 1-2, pp. 134-142.

Bierer, S., Bonham, B., Snyder, R. 2005, "Inferior colliculus responses to two channel cochlear implant stimulation", Twenty-Eighth Annual Midwinter Research Meeting Association for Research in Otolaryngology. New Orleans, Louisiana 19-24 February. Assoc Res Otolaryngol Abst, New Jersey: Association for Research in Otolaryngology pp. 356. Retrieved 27 October 2012 from http://www.aro.org/mwm/05_Abstract_Book.pdf.

Bierer, J. A. & Faulkner, K. F. 2010, "Identifying Cochlear Implant Channels with Poor Electrode-Neuron Interface: Partial Tripolar, Single-Channel Thresholds and Psychophysical Tuning Curves", *Ear and Hearing*, vol. 31, no. 2, pp. 247-258.

Bierer, J. A. & Faulkner, K. F. 2011, "Identifying Cochlear Implant Channels with Poor Electrode-Neuron Interface: Partial Tripolar, Single-Channel Thresholds and Psychophysical Tuning Curves (vol 31, pg 247, 2010)", *Ear and Hearing*, vol. 32, no. 5, p. 633.

Bierer, J. A., Faulkner, K. F., & Tremblay, K. L. 2011, "Identifying Cochlear Implant Channels With Poor Electrode-Neuron Interfaces: Electrically Evoked Auditory Brain Stem Responses Measured With the Partial Tripolar Configuration", *Ear and Hearing*, vol. 32, no. 4, pp. 436-444.

Bierer, J. A. & Middlebrooks, J. C. 2002, "Auditory cortical images of cochlear-implant stimuli: Dependence on electrode configuration", *Journal of Neurophysiology*, vol. 87, no. 1, pp. 478-492.

Bierer, J. A. & Middlebrooks, J. C. 2004, "Cortical responses to cochlear implant stimulation: Channel interactions", *Jaro-Journal of the Association for Research in Otolaryngology*, vol. 5, no. 1, pp. 32-48.

Blamey P., Arndt P., Bergeron F., Bredberg G., Brimacombe J., Facer G, Larky J., Lindstrom B., Nedzelski J., Peterson A., Shipp D., Staller S., Whitford L. 1996, "Factors affecting auditor performance of postlinguistically deaf adults using cochlear implants”. *Audiol Neurootol*. vol. 1, no. 5, pp. 293-306.

Blamey P., Artieres F., Başkent D., Bergeron F., Beynon A. et al. 2013, “Factors Affecting Auditory Performance of Postlinguistically Deaf Adults Using Cochlear Implants: An Update with 2251 Patients”, *Audiol Neurotol*., vol. 18, pp. 36-47.

Blamey, P. J., Pyman, B. C., Gordon, M., Clark, G. M., Brown, A. M., Dowell, R. C., & Hollow, R. D. 1992, "Factors predicting postoperative sentence scores in postlinguistically deaf adult cochlear implant patients", *Ann.Otol.Rhinol.Laryngol.*, vol. 101, no. 4, pp. 342-348.

Boisvert, I., Lyxell, B., Maki-Torkko, E., McMahon, C. M., & Dowell, R. C. 2012, "Choice of Ear for Cochlear Implantation in Adults With Monaural Sound-Deprivation and Unilateral Hearing Aid", *Otology & Neurotology*, vol. 33, no. 4, pp. 572-579.

Boisvert, I., McMahon, C. M., Tremblay, G., & Lyxell, B. 2011, "Relative Importance of Monaural Sound Deprivation and Bilateral Significant Hearing Loss in Predicting Cochlear Implantation Outcomes", *Ear and Hearing*, vol. 32, no. 6, pp. 758-766.

Bonham, B. H. & Litvak, L. M. 2008, "Current focusing and steering: Modeling, physiology, and psychophysics", *Hearing Research*, vol. 242, no. 1-2, pp. 141-153.

Bonham, B., Snyder, S., Corbett, S., Johnson, T., Rebscher, S. 2005, Physiological Measures of Auditory Nerve Activation by Current Steering. Twenty-Eighth Annual Midwinter Research Meeting Association for Research in Otolaryngology. New Orleans, Louisiana 19-24 February. Assoc Res Otolaryngol Abst, New Jersey: Association for Research in Otolaryngology. Pp. 359. Retrieved 27 October 2012from http://www.aro.org/mwm/05_Abstract_Book.pdf.

Bovo, R., Ciorba, A., Trevisi, P., Aimoni, C., Cappiello, L., Castiglione, A., Govoni, M., & Martini, A. 2011, "Cochlear implant in Cogan syndrome", *Acta Oto-Laryngologica*, vol. 131, no. 5, pp. 494-497.

Briaire, J. J. & Frijns, J. H. M. 2006, "The consequences of neural degeneration regarding optimal cochlear implant position in scala tympani: A model approach", *Hearing Research*, vol. 214, no. 1-2, pp. 17-27.

Briggs, R. J., Tykocinski, M., Stidham, K., & Roberson, J. B. 2005, "Cochleostomy site: implications for electrode placement and hearing preservation", *Acta Otolaryngol.*, vol. 125, no. 8, pp. 870-876.

Bronkhorst, A. W. 2000, "The cocktail party phenomenon: A review of research on speech intelligibility in multiple-talker conditions", *Acustica*, vol. 86, no. 1, pp. 117-128.

Bronkhorst, A. W. & Plomp, R. 1992, "Effect of Multiple Speech-Like Maskers on Binaural Speech Recognition in Normal and Impaired Hearing", *Journal of the Acoustical Society of America*, vol. 92, no. 6, pp. 3132-3139.

Brown, A. M., Clark, G. M., Dowell, R. C., Martin, L. F., & Seligman, P. M. 1985, "Telephone use by a multi-channel cochlear implant patient. An evaluation using open-set CID sentences", *J.Laryngol.Otol.*, vol. 99, no. 3, pp. 231-238.

Brown, K. D., Connell, S. S., Balkany, T. J., Eshraghi, A. E., Telischi, F. F., & Angeli, S. A. 2009, "Incidence and indications for revision cochlear implant surgery in adults and children", *Laryngoscope*, vol. 119, no. 1, pp. 152-157.

Bruce, I. A., Bates, J. E. H. M., Melling, C., Mawman, D., & Green, K. M. J. 2011, "Hearing Preservation Via a Cochleostomy Approach and Deep Insertion of a Standard Length Cochlear Implant Electrode", *Otology & Neurotology*, vol. 32, no. 9, pp. 1444-1447.

Brungart, D. S. 2001a, "Evaluation of speech intelligibility with the coordinate response measure", *Journal of the Acoustical Society of America*, vol. 109, no. 5, pp. 2276-2279.

Brungart, D. S. 2001b, "Informational and energetic masking effects in the perception of two simultaneous talkers", *Journal of the Acoustical Society of America*, vol. 109, no. 3, pp. 1101-1109.

Brungart, D. S., Simpson, B. D., Ericson, M. A., & Scott, K. R. 2001, "Informational and energetic masking effects in the perception of multiple simultaneous talkers", *Journal of the Acoustical Society of America*, vol. 110, no. 5, pp. 2527-2538.

Burian, K., Hochmair, E., Hochmairdesoyer, I., & Lessel, M. R. 1979, "Designing of and Experience with Multichannel Cochlear Implants", *Acta Oto-Laryngologica*, vol. 87, no. 3-4, pp. 190-195.

Carlyon, R. P., Long, C. J., Deeks, J. M., & McKay, C. M. 2007, "Concurrent sound segregation in electric and acoustic hearing", *Jaro-Journal of the Association for Research in Otolaryngology*, vol. 8, no. 1, pp. 119-133.

Chan, V., Tong, M., Yue, V., Wong, T., Leung, E., Yuen, K., & van Hasselt, A. 2007, "Performance of older adult cochlear implant users in Hong Kong", *Ear Hear.*, vol. 28, no. 2 Suppl, pp. 52S-55S.

Chatelin, V., Kim, E. J., Driscoll, C., Larky, J., Polite, C., Price, L., & Lalwani, A. K. 2004, "Cochlear implant outcomes in the elderly", *Otol.Neurotol.*, vol. 25, no. 3, pp. 298-301.

Chatterjee, M. & Yu, J. 2010, "A relation between electrode discrimination and amplitude modulation detection by cochlear implant listeners", *Journal of the Acoustical Society of America*, vol. 127, no. 1, pp. 415-426.

Chikar, J. A., Batts, S. A., Pfingst, B. E., & Raphael, Y. 2009, "Visualization of spiral ganglion neurites within the Scala tympani with a cochlear implant in situ", *Journal of Neuroscience Methods*, vol. 179, no. 2, pp. 201-207.

Chikar, J. A., Colesa, D. J., Swiderski, D. L., Di Polo, A., Raphael, Y., & Pfingst, B. E. 2008, "Over-expression of BDNF by adenovirus with concurrent electrical stimulation improves cochlear implant thresholds and survival of auditory neurons", *Hearing Research*, vol. 245, no. 1-2, pp. 24-34.

Chouard, C. H., Macleod, P., Meyer, B., & Pialoux, P. 1977, "Electronic Device for Multichannel Cochlear Implant", *Annales D Oto-Laryngologie et de Chirurgie Cervico-Faciale*, vol. 94, no. 7-8, pp. 353-363.

Clark, G. M. 2008, "Personal reflections on the multichannel cochlear implant and a view of the future", Journal of Rehabilitation Research and Development, vol. 45, no. 5, pp. 651-693.

Clark, G. M., Hallworth, R. J., & Zdanius, K. 1975, "Cochlear Implant Electrode", Journal of Laryngology and Otology, vol. 89, no. 8, pp. 787-792.

Clark, G. M., Tong, Y. C., & Dowell, R. C. 1984, "Comparison of 2 Cochlear Implant Speech-Processing Strategies", *Annals of Otology Rhinology and Laryngology*, vol. 93, no. 2, pp. 127-131.

Clark, G. M., Tong, Y. C., & Martin, L. F. A. 1981, "A Multiple-Channel Cochlear Implant - An Evaluation Using Open-Set Cid Sentences", *Laryngoscope*, vol. 91, no. 4, pp. 628-634.

Cohen, L. T., Xu, J., Xu, S. A., & Clark, G. M. 1996, "Improved and simplified methods for specifying positions of the electrode bands of a cochlear implant array", *American Journal of Otology*, vol. 17, no. 6, pp. 859-865.

Cohen, N. L. & Waltzman, S. B. 1993, "Partial Insertion of the Nucleus Multichannel Cochlear Implant - Technique and Results", *American Journal of Otology*, vol. 14, no. 4, pp. 357-361.

Colburn, H. S., Shinn-Cunningham, B., Kidd, G., & Durlach, N. 2006, "The perceptual consequences of binaural hearing", *International Journal of Audiology*, vol. 45, p. S34-S44.

Collins, L. M. & Throckmorton, C. S. 2000, "Investigating perceptual features of electrode stimulation via a multidimensional scaling paradigm", *Journal of the Acoustical Society of America*, vol. 108, no. 5, pp. 2353-2365.

Collins, L. M., Wakefield, G. H., & Feinman, G. R. 1994, "Temporal Pattern-Discrimination and Speech Recognition Under Electrical-Stimulation", *Journal of the Acoustical Society of America*, vol. 96, no. 5, pp. 2731-2737.

Collins, L. M., Zwolan, T. A., & Wakefield, G. H. 1997, "Comparison of electrode discrimination, pitch ranking, and pitch scaling data in postlingually deafened adult cochlear implant subjects", *Journal of the Acoustical Society of America*, vol. 101, no. 1, pp. 440-455.

Collins, M. M., Hawthorne, M. H., & Elhmd, K. 1997, "Cochlear implantation in a district general hospital: Problems and complications in the first five years", *Journal of Laryngology and Otology*, vol. 111, no. 4, pp. 325-332.

Cords, S. M., Reuter, G., Issing, P. R., Sommer, A., Kuzma, J., & Lenarz, T. 2000, "A silastic positioner for a modiolus-hugging position of intracochlear electrodes: Electrophysiologic effects", *American Journal of Otology*, vol. 21, no. 2, pp. 212-217.

Cote, M., Ferron, P., Bergeron, F., & Bussieres, R. 2007, "Cochlear reimplantation: causes of failure, outcomes, and audiologic performance", *Laryngoscope*, vol. 117, no. 7, pp. 1225-1235.

Cooper, F. S., Delattre, P. C., Liberman, A. M., Borst, J. M., & Gerstman, L. J. 1952, "Some Experiments on the Perception of Synthetic Speech Sounds", *Journal of the Acoustical Society of America*, vol. 24, no. 6, pp. 597-606.

Cushing, S. L., Daly, M. J., Treaba, C. G., Chan, H., Irish, J. C., Blaser, S., Gordon, K. A., & Papsin, B. C. 2012, "High-resolution cone-beam computed tomography: a potential tool to improve atraumatic electrode design and position", *Acta Oto-Laryngologica*, vol. 132, no. 4, pp. 361-368.

Dawson, P. W., Busby, P. A., McKay, C. M., & Clark, G. M. 2002, "Short-term auditory memory in children using cochlear implants and its relevance to receptive language", *Journal of Speech Language and Hearing Research*, vol. 45, no. 4.

Dawson, P. W., McKay, C. M., Busby, P. A., Grayden, D. B., & Clark, G. M. 2000, "Electrode discrimination and speech perception in young children using cochlear implants", *Ear and Hearing*, vol. 21, no. 6, pp. 597-607.

Dawson, P. W., Vandali, A. E., Knight, M. R., & Heasman, J. M. 2007, "Clinical evaluation of expanded input dynamic range in nucleus cochlear implants", Ear and Hearing, vol. 28, no. 2, pp. 163-176.

Djourno, A. & EYRIES, C. 1957, "[Auditory prosthesis by means of a distant electrical stimulation of the sensory nerve with the use of an indwelt coiling.]", *Presse Med.*, vol. 65, no. 63, p. 1417.

Doll, T. J. & Hanna, T. E. 1995, "Spatial and Spectral Release from Masking in 3-Dimensional Auditory Displays", *Human Factors*, vol. 37, no. 2, pp. 341-355.

Donaldson, G. S., Kreft, H. A., & Litvak, L. 2005, "Place-pitch discrimination of single- versus dual-electrode stimuli by cochlear implant users (L)", *J.Acoust.Soc.Am.*, vol. 118, no. 2, pp. 623-626.

Donaldson, G. S. & Nelson, D. A. 2000, "Place-pitch sensitivity and its relation to consonant recognition by cochlear implant listeners using the MPEAK and SPEAK speech processing strategies", *Journal of the Acoustical Society of America*, vol. 107, no. 3, pp. 1645-1658.

Dorman M.F., Spahr A.J., 2006, "Speech perception by adults with multichannel cochlear implants". In: Waltzman SB, Roland JT Jr, editors. Cochlear implants. 2nd ed. New York (NY): Thieme. pp. 193–204.

Douek, E. 1985, "Cochlear implants", *Br.Med.J.(Clin.Res.Ed)*, vol. 290, no. 6466, pp. 415-416.

Drennan, W. R. & Pfingst, B. E. 2005, "Current-level discrimination using bipolar and monopolar electrode configurations in cochlear implants", *Hearing Research*, vol. 202, no. 1-2, pp. 170-179.

Dunn, C. C., Noble, W., Tyler, R. S., Kordus, M., Gantz, B. J., & Ji, H. H. 2010, "Bilateral and Unilateral Cochlear Implant Users Compared on Speech Perception in Noise", *Ear and Hearing*, vol. 31, no. 2, pp. 296-298.

Dunn, C. C., Tyler, R. S., Witt, S. A., & Gantz, B. J. 2006, "Effects of converting bilateral cochlear implant subjects to a strategy with increased rate and number of channels", Annals of Otology Rhinology and Laryngology, vol. 115, no. 6, pp. 425-432.

Durisin, M., Bartling, S., Arnoldner, C., Ende, M., Prokein, J., Lesinski-Schiedat, A., Lanfermann, H., Lenarz, T., & Stover, T. 2010, "Cochlear Osteoneogenesis After Meningitis in Cochlear Implant Patients: A Retrospective Analysis", *Otology & Neurotology*, vol. 31, no. 7, pp. 1072-1078.

Durlach, N. I. 1963, "Equalization and Cancellation Theory of Binaural Masking-Level Differences", *Journal of the Acoustical Society of America*, vol. 35, no. 8, p. 1206-&.

Eapen, R. J., Buss, E., Adunka, M. C., Pillsbury, H. C., & Buchman, C. A. 2009, "Hearing-in-Noise Benefits After Bilateral Simultaneous Cochlear Implantation Continue to Improve 4 Years After Implantation", *Otology & Neurotology*, vol. 30, no. 2, pp. 153-159.

Erixon, E., Kobler, S., & Rask-Andersen, H. 2012, "Cochlear implantation and hearing preservation: Results in 21 consecutively operated patients using the round window approach", *Acta Oto-Laryngologica*, vol. 132, no. 9, pp. 923-931.

Eshraghi, A. A., Yang, N. W., & Balkany, T. J. 2003, "Comparative study of cochlear damage with three perimodiolar electrode designs", *Laryngoscope*, vol. 113, no. 3, pp. 415-419.

Faccioli, N., Barillari, M., Guariglia, S., Zivelonghi, E., Rizzotti, A., Cerini, R., & Mucelli, R. P. 2009, "Radiation dose saving through the use of cone-beam CT in hearing-impaired patients", *Radiologia Medica*, vol. 114, no. 8, pp. 1308-1318.

Faulkner, A. 2006, "Adaptation to distorted frequency-to-place maps: implications of simulations in normal listeners for cochlear implants and electroacoustic stimulation", *Audiol.Neurootol.*, vol. 11 Suppl 1, pp. 21-26.

Faulkner, A., Rosen, S., & Norman, C. 2006, "The right information may matter more than frequency-place alignment: simulations of frequency-aligned and upward shifting cochlear implant processors for a shallow electrode array insertion", *Ear Hear.*, vol. 27, no. 2, pp. 139-152.

Ferguson, W. D., Collins, L. M., & Smith, D. W. 2003, "Psychophysical threshold variability in cochlear implant subjects", *Hearing Research*, vol. 180, no. 1-2, pp. 101-113.

Finley, C. C. & Skinner, M. W. 2008, "Role of electrode placement as a contributor to variability in cochlear implant outcomes", *Otol.Neurotol.*, vol. 29, no. 7, pp. 920-928.

Firszt, J. B., 2003. Hiresolution sound processing retrieved from Advanced Bionics website, [online] Advanced Bionics. Available at: http://www.advancedbionics.com/content/dam/ab/Global/en_ce/documents/libraries/Professional%20Library/AB%20Technical%20Reports/Sound%20Processing/HiResolution_Sound_Processing_article.pdf. [Retrieved December 30, 2012].

Firszt, J. B., Holden, L. K., Reeder, R. M., & Skinner, M. W. 2009, "Speech recognition in cochlear implant recipients: comparison of standard HiRes and HiRes 120 sound processing", *Otol.Neurotol.*, vol. 30, no. 2, pp. 146-152.

Firszt, J. B., Koch, D. B., Downing, M., & Litvak, L. 2007, "Current steering creates additional pitch percepts in adult cochlear implant recipients", Otology & Neurotology, vol. 28, no. 5, pp. 629-636.

Fourakis, M. S., Hawks, J. W., Holden, L. K., Skinner, M. W., & Holden, T. A. 2004, "Effect of frequency boundary assignment on vowel recognition with the Nucleus 24 ACE speech coding strategy", J.Am.Acad.Audiol., vol. 15, no. 4, pp. 281-299.

Fourakis, M. S., Hawks, J. W., Holden, L. K., Skinner, M. W., & Holden, T. A. 2007, "Effect of frequency boundary assignment on speech recognition with the nucleus 24 ACE speech coding strategy", *Journal of the American Academy of Audiology*, vol. 18, no. 8, pp. 700-717.

Francart, T., & Wouters, J. 2007, "Perception of across-frequency interaural level differences", *The Journal of the Acoustical Society of America*, vol. 122, no. 5, pp. 2826-2831.

Francis, H. W., Yeagle, J. D., Brightwell, T., & Venick, H. 2004, "Central effects of residual hearing: implications for choice of ear for cochlear implantation", *Laryngoscope*, vol. 114, no. 10, pp. 1747-1752.

Franck, K. H., Xu, L., & Pfingst, B. E. 2003, "Effects of stimulus level on speech perception with cochlear prostheses", *Jaro*, vol. 4, no. 1, pp. 49-59.

Franco-Vidal, V., Songu, M., Blanchet, H., Barreau, X., & Darrouzet, V. 2007, "Intracochlear hemorrhage after gamma knife radiosurgery", *Otol.Neurotol.*, vol. 28, no. 2, pp. 240-244.

Freyman, R. L., Helfer, K. S., Mccall, D. D., & Clifton, R. K. 1999, "The role of perceived spatial separation in the unmasking of speech", *Journal of the Acoustical Society of America*, vol. 106, no. 6, pp. 3578-3588.

Friedland, D. R. & Runge-Samuelson, C. 2009, "Soft cochlear implantation: rationale for the surgical approach", *Trends Amplif.*, vol. 13, no. 2, pp. 124-138.

Friedland, D. R., Runge-Samuelson, C., Baig, H., & Jensen, J. 2010, "Case-control analysis of cochlear implant performance in elderly patients", *Arch.Otolaryngol.Head Neck Surg.*, vol. 136, no. 5, pp. 432-438.

Friedland, D. R., Venick, H. S., & Niparko, J. K. 2003, "Choice of ear for cochlear implantation: the effect of history and residual hearing on predicted postoperative performance", *Otol.Neurotol.*, vol. 24, no. 4, pp. 582-589.

Friesen, L. M. & Picton, T. W. 2010, "A method for removing cochlear implant artifact", *Hearing Research*, vol. 259, no. 1-2, pp. 95-106.

Friesen, L. M., Shannon, R. V., Baskent, D., & Wang, X. 2001, "Speech recognition in noise as a function of the number of spectral channels: Comparison of acoustic hearing and cochlear implants", *Journal of the Acoustical Society of America*, vol. 110, no. 2, pp. 1150-1163.

Friesen, L. M., Shannon, R. V., & Cruz, R. J. 2005, "Effects of stimulation rate on speech recognition with cochlear implants", *Audiology and Neuro-Otology*, vol. 10, no. 3, pp. 169-184.

Friesen, L. M., Shannon, T. V., & Slattery, W. H. 1999, "The effect of frequency allocation on phoneme recognition with the nucleus 22 cochlear implant", *American Journal of Otology*, vol. 20, no. 6, pp. 729-734.

Friesen, L. M. & Tremblay, K. L. 2006, "Acoustic change complexes recorded in adult cochlear implant listeners", *Ear and Hearing*, vol. 27, no. 6, pp. 678-685.

Friesen, L. M., Tremblay, K. L., Rohila, N., Wright, R. A., Shannon, R. V., Baskent, D., & Rubinstein, J. T. 2009, "Evoked cortical activity and speech recognition as a function of the number of simulated cochlear implant channels", *Clinical Neurophysiology*, vol. 120, no. 4, pp. 776-782.

Frijns, J. H., Klop, W. M., Bonnet, R. M., & Briaire, J. J. 2003, "Optimizing the number of electrodes with high-rate stimulation of the clarion CII cochlear implant", *Acta Otolaryngol.*, vol. 123, no. 2, pp. 138-142.

Fu, Q. J. 2002, "Temporal processing and speech recognition in cochlear implant users", *Neuroreport*, vol. 13, no. 13, pp. 1635-1639.

Fu, Q. J. & Nogaki, G. 2005, "Noise susceptibility of cochlear implant users: the role of spectral resolution and smearing", J.Assoc.Res.Otolaryngol., vol. 6, no. 1, pp. 19-27.

Fu, Q. J. & Shannon, R. V. 1999a, "Effects of electrode configuration and frequency allocation on vowel recognition with the Nucleus-22 cochlear implant", *Ear Hear.*, vol. 20, no. 4, pp. 332-344.

Fu, Q. J. & Shannon, R. V. 1999b, "Recognition of spectrally degraded and frequency-shifted vowels in acoustic and electric hearing", *Journal of the Acoustical Society of America*, vol. 105, no. 3, pp. 1889-1900.

Fu, Q. J., Shannon, R. V., & Wang, X. 1998, "Effects of noise and spectral resolution on vowel and consonant recognition: acoustic and electric hearing", *J.Acoust.Soc.Am.*, vol. 104, no. 6, pp. 3586-3596.

Fu, Q. J., Zeng, F. G., Shannon, R. V., & Soli, S. D. 1998, "Importance of tonal envelope cues in Chinese speech recognition", Journal of the Acoustical Society of America, vol. 104, no. 1, pp. 505-510.

Gani, M., Valentini, G., Sigrist, A., Kos, M. I., & Boex, C. 2007, "Implications of deep electrode insertion on cochlear implant fitting", *J.Assoc.Res.Otolaryngol.*, vol. 8, no. 1, pp. 69-83.

Gantz, B. J. & Turner, C. 2004, "Combining acoustic and electrical speech processing: Iowa/Nucleus hybrid implant", *Acta Otolaryngol.*, vol. 124, no. 4, pp. 344-347.

Gantz, B. J. & Turner, C. W. 2003, "Combining acoustic and electrical hearing", *Laryngoscope*, vol. 113, no. 10, pp. 1726-1730.

Gantz, B. J., Woodworth, G. G., Knutson, J. F., Abbas, P. J., & Tyler, R. S. 1993, "Multivariate predictors of audiological success with multichannel cochlear implants", *Ann.Otol.Rhinol.Laryngol.*, vol. 102, no. 12, pp. 909-916.

Garadat, S. N. & Pfingst, B. E. 2011, "Relationship between gap detection thresholds and loudness in cochlear-implant users", *Hearing Research*, vol. 275, no. 1-2, pp. 130-138.

Garadat, S. N., Zwolan, T. A., & Pfingst, B. E. 2012, "Across-site patterns of modulation detection: Relation to speech recognition", *Journal of the Acoustical Society of America*, vol. 131, no. 5, pp. 4030-4041.

Garcia-Ibanez, L., Macias, A. R., Morera, C., Rodriguez, M. M., Szyfter, W., Skarszynski, H., Emamdjomeh, H., & Baumgartner, W. D. 2009, "An evaluation of the preservation of residual hearing with the Nucleus Contour Advance electrode", *Acta Oto-Laryngologica*, vol. 129, no. 6, pp. 651-664.

Gfeller, K., Christ, A., Knutson, J., Witt, S., & Mehr, M. 2003, "The effects of familiarity and complexity on appraisal of complex songs by cochlear implant recipients and normal hearing adults", *J.Music.Ther.*, vol. 40, no. 2, pp. 78-112.

Gfeller, K., Oleson, J., Knutson, J. F., Breheny, P., Driscoll, V., & Olszewski, C. 2008, "Multivariate predictors of music perception and appraisal by adult cochlear implant users", *J.Am.Acad.Audiol.*, vol. 19, no. 2, pp. 120-134.

Gfeller, K., Witt, S., Adamek, M., Mehr, M., Rogers, J., Stordahl, J., & Ringgenberg, S. 2002a, "Effects of training on timbre recognition and appraisal by postlingually deafened cochlear implant recipients", *J.Am.Acad.Audiol.*, vol. 13, no. 3, pp. 132-145.

Gfeller, K., Witt, S., Woodworth, G., Mehr, M. A., & Knutson, J. 2002b, "Effects of frequency, instrumental family, and cochlear implant type on timbre recognition and appraisal", *Ann.Otol.Rhinol.Laryngol.*, vol. 111, no. 4, pp. 349-356.

Goldwyn, J. H., Bierer, S. M., & Bierer, J. A. 2010, "Modeling the electrode-neuron interface of cochlear implants: Effects of neural survival, electrode placement, and the partial tripolar configuration", *Hearing Research*, vol. 268, no. 1-2, pp. 93-104.

Gomaa, N. A., Rubinstein, J. T., Lowder, M. W., Tyler, R. S., & Gantz, B. J. 2003, "Residual speech perception and cochlear implant performance in postlingually deafened adults", *Ear Hear.*, vol. 24, no. 6, pp. 539-544.

Gosepath, J., Lippert, K., Keilmann, A., & Mann, W. J. 2009, "Analysis of fifty-six cochlear implant device failures", *ORL J.Otorhinolaryngol.Relat Spec.*, vol. 71, no. 3, pp. 142-147.

Grantham, D. W., Ashmead, D. H., Ricketts, T. A., Haynes, D. S., & Labadie, R. F. 2008, "Interaural time and level difference thresholds for acoustically presented signals in post-lingually deafened adults fitted with bilateral cochlear implants using CIS plus processing", *Ear and Hearing*, vol. 29, no. 1, pp. 33-44.

Grayden,D.B., and Graeme,M.C., 2006, "Implant design and development". In Cochlear Implants: A practical Guide, H.R. Cooper, and L.C. Craddock, eds. London: Whurr.

Green, K. M., Bhatt, Y. M., Mawman, D. J., O'Driscoll, M. P., Saeed, S. R., Ramsden, R. T., & Green, M. W. 2007, "Predictors of audiological outcome following cochlear implantation in adults", *Cochlear.Implants.Int.*, vol. 8, no. 1, pp. 1-11.

Gstoettner, W., Kiefer, J., Baumgartner, W. D., Pok, S., Peters, S., & Adunka, O. 2004, "Hearing preservation in cochlear implantation for electric acoustic stimulation", *Acta Otolaryngol.*, vol. 124, no. 4, pp. 348-352.

Gstoettner, W., Plenk, H., Jr., Franz, P., Hamzavi, J., Baumgartner, W., Czerny, C., & Ehrenberger, K. 1997, "Cochlear implant deep electrode insertion: extent of insertional trauma", *Acta Otolaryngol.*, vol. 117, no. 2, pp. 274-277.

Guldner, C., Wiegand, S., Weiss, R., Bien, S., Sesterhenn, A., Teymoortash, A., & Diogo, I. 2012, "Artifacts of the electrode in cochlea implantation and limits in analysis of deep insertion in cone beam tomography (CBT)", *European Archives of Oto-Rhino-Laryngology*, vol. 269, no. 3, pp. 767-772.

Gupta, R., Bartling, S. H., Basu, S. K., Ross, W. R., Becker, H., Pfoh, A., Brady, T., & Curtin, H. D. 2004, "Experimental flat-panel high-spatial-resolution volume CT of the temporal bone", *American Journal of Neuroradiology*, vol. 25, no. 8, pp. 1417-1424.

Halliday, L.F., Taylor, J.L., Millward, K.E. & Moore, D.R. 2012, "Lack of generalization of auditory learning in typically developing children", *Journal of Speech, Language and Hearing Research*, vol. 55, no. 1, pp. 168-181.

Hargunani, C. A., Kempton, J. B., DeGagne, J. M., & Trune, D. R. 2006, "Intratympanic injection of dexamethasone: time course of inner ear distribution and conversion to its active form", *Otol.Neurotol.*, vol. 27, no. 4, pp. 564-569.

Harnack, D., Winter, C., Meissner, W., Reum, T., Kupsch, A., & Morgenstern, R. 2004, "The effects of electrode material, charge density and stimulation duration on the safety of high-frequency stimulation of the subthalamic nucleus in rats", *J.Neurosci.Methods*, vol. 138, no. 1-2, pp. 207-216.

Hartrampf R., Weber B., Dahm M. C., Lenarz T. 1995, “Management of obliteration of the cochlea in cochlear implantation”, *Ann Otol Rhinol Laryngol Suppl*., vol. 166, pp. 416-418.

Hawley, M. L., Litovsky, R. Y., & Colburn, H. S. 1999, "Speech intelligibility and localization in a multi-source environment", *Journal of the Acoustical Society of America*, vol. 105, no. 6, pp. 3436-3448.

Hawley, M. L., Litovsky, R. Y., & Culling, J. F. 2004, "The benefit of binaural hearing in a cocktail party: Effect of location and type of interferer", *Journal of the Acoustical Society of America*, vol. 115, no. 2, pp. 833-843.

Hedrick, M. S. & Carney, A. E. 1997, "Effect of relative amplitude rind formant transitions on perception of place of articulation by adult listeners with cochlear implants", *Journal of Speech Language and Hearing Research*, vol. 40, no. 6, pp. 1445-1457.

Helbig, S., Van de Heyning, P., Kiefer, J., Baumann, U., Kleine-Punte, A., Brockmeier, H., Anderson, I., & Gstoettner, W. 2011, "Combined electric acoustic stimulation with the PULSARCI(100) implant system using the FLEXEAS electrode array", *Acta Oto-Laryngologica*, vol. 131, no. 6, pp. 585-595.

Helfer, K. S., Chevalier, J., & Freyman, R. L. 2010, "Aging, spatial cues, and single- versus dual-task performance in competing speech perception", *Journal of the Acoustical Society of America*, vol. 128, no. 6, pp. 3625-3633.

Helfer, K. S. & Freyman, R. L. 2008, "Aging and speech-on-speech masking", *Ear and Hearing*, vol. 29, no. 1, pp. 87-98.

Henry, B. A., McKay, C. M., McDermott, H. J., & Clark, G. M. 2000, "The relationship between speech perception and electrode discrimination in cochlear implantees", *Journal of the Acoustical Society of America*, vol. 108, no. 3, pp. 1269-1280.

Hiraumi, H., Tsuji, J., Kanemaru, S., Fujino, K., & Ito, J. 2007, "Cochlear implants in post-lingually deafened patients", *Acta Otolaryngol.Suppl.,* no. 557, pp. 17-21.

Hochmair, I., Arnold, W., Nopp, P., Jolly, C., Muller, J., & Roland, P. 2003, "Deep electrode insertion in cochlear implants: apical morphology, electrodes and speech perception results", *Acta Otolaryngol.*, vol. 123, no. 5, pp. 612-617.

HochmairDesoyer, I. J., Hochmair, E. S., Burian, K., & Stiglbrunner, H. K. 1983, "Percepts from the Vienna Cochlear-Prosthesis", *Annals of the New York Academy of Sciences*, vol. 405, no. JUN, pp. 295-306.

Hodez C. Griffaton-Taillandier, C. Bensimon I. 2011, "Cone-beam imaging: Applications in ENT", *European Annals of Otorhinolaryngology, Head and Neck diseases,* vol. 128, no. 2, PP. 65-78.

Hodges, A. V., Dolan, A. M., Balkany, T. J., Schloffman, J. J., & Butts, S. L. 1999, "Speech perception results in children with cochlear implants: contributing factors", *Otolaryngol.Head Neck Surg.*, vol. 121, no. 1, pp. 31-34.

Holden, L. K., Skinner, M. W., Holden, T. A., & Demorest, M. E. 2002, "Effects of stimulation rate with the nucleus 24 ACE speech coding strategy", *Ear and Hearing*, vol. 23, no. 5, pp. 463-476.

Hornsby, B. W. Y., Ricketts, T. A., & Johnson, E. E. 2006, "The effects of speech and speechlike maskers on unaided and aided speech recognition in persons with hearing loss", *Journal of the American Academy of Audiology*, vol. 17, no. 6, pp. 432-447.

House WF, Urban J. 1973, "Long term results of electrode implantation and electronic stimulation of the cochlea in man", *Ann Otol Rhinol Laryngol*, vol. 82, no. 4, pp. 504.

Huang, C. Q., Tykocinski, M., Stathopoulos, D., & Cowan, R. 2007, "Effects of steroids and lubricants on electrical impedance and tissue response following cochlear implantation", *Cochlear Implants International*, vol. 8, no. 3, pp. 123-147.

Hughes, M. L. 2008, "A re-evaluation of the relation between physiological channel interaction and electrode pitch ranking in cochlear implants", *Journal of the Acoustical Society of America*, vol. 124, no. 5, pp. 2711-2714.

Hughes, M. L. & Abbas, P. J. 2006, "The relation between electrophysiologic channel interaction and electrode pitch ranking in cochlear implant recipients", *Journal of the Acoustical Society of America*, vol. 119, no. 3, pp. 1527-1537.

Hughes, M. L., Werff, K. R. V., Brown, C. J., Abbas, P. J., Kelsay, D. M. R., Teagle, H. F. B., & Lowder, M. W. 2001, "A longitudinal study of electrode impedance, the electrically evoked compound action potential, and behavioral measures in Nucleus 24 cochlear implant users", *Ear and Hearing*, vol. 22, no. 6, pp. 471-486.

International Organization for Standardization. Implants for surgery - active implantable medical devices - part 1: General requirements for safety, marking, and for information to be provided by the manufacturer, 2000. ISO 14708-1.

James, C., Albegger, K., Battmer, R., Burdo, S., Deggouj, N., Deguine, O., Dillier, N., Gersdorff, M., Laszig, R., Lenarz, T., Rodriguez, M. M., Mondain, M., Offeciers, E., Macias, A. R., Ramsden, R., Sterkers, O., Von Wallenberg, E., Weber, B., & Fraysse, B. 2005, "Preservation of residual hearing with cochlear implantation: how and why", *Acta Otolaryngol.*, vol. 125, no. 5, pp. 481-491.

James, C. J., Blamey, P. J., Martin, L., Swanson, B., Just, Y., & Macfarlane, D. 2002, "Adaptive dynamic range optimization for cochlear implants: A preliminary study", *Ear and Hearing*, vol. 23, no. 1, pp. 49S-58S.

James, C. J., Skinner, M. W., Martin, L. F. A., Holden, L. K., Galvin, K. L., Holden, T. A., & Whitford, L. 2003, "An investigation of input level range for the nucleus 24 cochlear implant system: Speech perception performance, program preference, and loudness comfort ratings", *Ear and Hearing*, vol. 24, no. 2, pp. 157-174.

Jerger, J., Jerger, S., Oliver, T., & Pirozzolo, F. 1989a, "Speech understanding in the elderly", *Ear Hear.*, vol. 10, no. 2, pp. 79-89.

Jerger, J., Stach, B., Pruitt, J., Harper, R., & Kirby, H. 1989b, "Comments on "Speech Understanding and Aging"", *J.Acoust.Soc.Am.*, vol. 85, no. 3, pp. 1352-1354.

Kang, S. Y., Colesa, D. J., Swiderski, D. L., Su, G. L., Raphael, Y., & Pfingst, B. E. 2010, "Effects of Hearing Preservation on Psychophysical Responses to Cochlear Implant Stimulation", *Jaro-Journal of the Association for Research in Otolaryngology*, vol. 11, no. 2, pp. 245-265.

Kang, S. Y., Zwolan, T. A., Kileny, P. R., Niparko, J. K., Driscoll, C. L., Shelton, C., & Telian, S. A. 2009, "Incomplete electrode extraction during cochlear implant revision", *Otol.Neurotol.*, vol. 30, no. 2, pp. 160-164.

Kerber, S. & Seeber, B. U. 2012, "Sound Localization in Noise by Normal-Hearing Listeners and Cochlear Implant Users", *Ear and Hearing*, vol. 33, no. 4, pp. 445-457.

Ketten, D. R., Vannier, M. W., Skinner, M. W., Gates, G. A., Wang, G., & Neely, J. G. 1998, "In vivo measures of cochlear length and insertion depth of nucleus cochlear implant electrode arrays", *Annals of Otology Rhinology and Laryngology*, vol. 107, no. 11, pp. 1-16.

Kidd, G., Mason, C. R., Rohtla, T. L., & Deliwala, P. S. 1998, "Release from masking due to spatial separation of sources in the identification of nonspeech auditory patterns", *Journal of the Acoustical Society of America*, vol. 104, no. 1, pp. 422-431.

Kidd, G., Mason, C. R., Deliwala, P. S., Woods, W. S., & Colburn, H. S. 1994, "Reducing Informational Masking by Sound Segregation", *Journal of the Acoustical Society of America*, vol. 95, no. 6, pp. 3475-3480.

Kidd, G., Mason, C. R., & Rohtla, T. L. 1995, "Binaural Advantage for Sound Pattern Identification", *Journal of the Acoustical Society of America*, vol. 98, no. 4, pp. 1977-1986.

Kiefer, J., Gstoettner, W., Baumgartner, W., Pok, S. M., Tillein, J., Ye, Q., & Von Ilberg, C. 2004, "Conservation of low-frequency hearing in cochlear implantation", *Acta Oto-Laryngologica*, vol. 124, no. 3, pp. 272-280.

Kiefer, J., Weber, A., Pfennigdorff, T., & Von Ilberg, C. 2000, "Scala vestibuli insertion in cochlear implantation: A valuable alternative for cases with obstructed scala tympani", *Orl-Journal for Oto-Rhino-Laryngology and Its Related Specialties*, vol. 62, no. 5, pp. 251-256.

Kiefer, J., Ye, Q., Tillein, J., Adunka, O., Arnold, W., & Gstottner, W. 2007, "Protecting the cochlea during stapes surgery: is there a role for corticosteroids?", *Adv.Otorhinolaryngol.*, vol. 65, pp. 300-307.

Kitterick, P. T., Bailey, P. J., & Summerfield, A. Q. 2010, "Benefits of knowing who, where, and when in multi-talker listening", *Journal of the Acoustical Society of America*, vol. 127, no. 4, pp. 2498-2508.

Kitterick P. T. , Lovett R. E.S., Goman A. M., Summerfield A. Q. 2011 "The AB-York Crescent of Sound: an apparatus for assessing spatial-listening skills in children and adults", *Cochlear Implants International*, vol. 12, no. 3, pp. 164-9

Knutson,J.F. (2006). Psychological aspects of cochlear implantation. In Cochlear Implants: A practical Guide, H.R. Cooper, and L.C. Craddock, eds. London: Whurr Publishing.

Knutson, J. F., Hinrichs, J. V., Tyler, R. S., Gantz, B. J., Schartz, H. A., & Woodworth, G. 1991, "Psychological predictors of audiological outcomes of multichannel cochlear implants: preliminary findings", *Ann.Otol.Rhinol.Laryngol.*, vol. 100, no. 10, pp. 817-822.

Koch, D. B., Downing, M., Osberger, M. J., & Litvak, L. 2007, Using current steering to increase spectral resolution in CII and HiRes 90K users, *Ear and Hearing*, vol. 28, no. 2, pp. 38S-41S.

Koehnke, J. & Besing, J. M. 1996, "A procedure for testing speech intelligibility in a virtual listening environment", *Ear and Hearing*, vol. 17, no. 3, pp. 211-217.

Kontorinis, G., Giourgas, A., Neuburger, J., Lesinski-Schiedat, A., & Lenarz, T. 2010, "Long-Term Evaluation of Cochlear Implantation in Cogan Syndrome", *Orl-Journal for Oto-Rhino-Laryngology and Its Related Specialties*, vol. 72, no. 5, pp. 275-279.

Kontorinis, G., Scheper, V., Wissel, K., Stover, T., Lenarz, T., & Paasche, G. 2012, "In vitro modifications of the scala tympani environment and the cochlear implant array surface", *Laryngoscope*, vol. 122, no. 9, pp. 2057-2063.

Kreft, H. A., Donaldson, G. S., & Nelson, D. A. 2004a, "Effects of pulse rate and electrode array design on intensity discrimination in cochlear implant users", *Journal of the Acoustical Society of America*, vol. 116, no. 4, pp. 2258-2268.

Kreft, H. A., Donaldson, G. S., & Nelson, D. A. 2004b, "Effects of pulse rate on threshold and dynamic range in Clarion cochlear-implant users (L)", *Journal of the Acoustical Society of America*, vol. 115, no. 5, pp. 1885-1888.

Kwon, B. J. & van den Honert, C. 2006, "Dual-electrode pitch discrimination with sequential interleaved stimulation by cochlear implant users", *Journal of the Acoustical Society of America*, vol. 120, no. 1, p. EL1-EL6.

Laback, B., Pok, S. M., Baumgartner, W. D., Deutsch, W. A., & Schmid, K. 2004, "Sensitivity to interaural level and envelope time differences of two bilateral cochlear implant listeners using clinical sound processors", *Ear and Hearing*, vol. 25, no. 5, pp. 488-500.

Labadie, R. F., Carrasco, V. N., Gilmer, C. H., & Pillsbury, H. C., III 2000, "Cochlear implant performance in senior citizens", *Otolaryngol.Head Neck Surg.*, vol. 123, no. 4, pp. 419-424.

Landis, J. R. & Koch, G. G. 1977, "Measurement of Observer Agreement for Categorical Data", *Biometrics*, vol. 33, no. 1, pp. 159-174.

Landsberger, D. M. & McKay, C. M. 2005, "Perceptual differences between low and high rates of stimulation on single electrodes for cochlear implantees", *Journal of the Acoustical Society of America*, vol. 117, no. 1, pp. 319-327.

Laszig, R., Aschendorff, A., Stecker, M., Muller-Deile, J., Maune, S., Dillier, N., Weber, B., Hey, M., Begall, K., Lenarz, T., Battmer, R. D., Bohm, M., Steffens, T., Strutz, J., Linder, T., Probst, R., Allum, J., Westhofen, M., & Doering, W. 2004, "Benefits of bilateral electrical stimulation with the nucleus cochlear implant in adults: 6-month postoperative results", *Otology & Neurotology*, vol. 25, no. 6, pp. 958-968.

Laszig, R., Ridder, G. J., & Fradis, M. 2002, "Intracochlear insertion of electrodes using hyaluronic acid in cochlear implant surgery", *J.Laryngol.Otol.*, vol. 116, no. 5, pp. 371-372.

Lawson, D. T., Wilson, B. S., Zerbi, M., van den Honert, C., Finley, C. C., Farmer, J. C., McElveen, J. T., & Roush, P. A. 1998, "Bilateral cochlear implants controlled by a single speech processor", *American Journal of Otology*, vol. 19, no. 6, pp. 758-761.

Lazard D.S., Vincent C., Venail F., Van de Heyning P., Truy E, et al. 2012, " Pre-, Per- and Postoperative Factors Affecting Performance of Postlinguistically Deaf Adults Using Cochlear Implants: A New Conceptual Model over Time", *PLoS ONE* vol. 7, no. 11, e48739. doi:10.1371/journal.pone.0048739

Leake P. A., Kessler D. K., and Merzenich M. M. 1990, “Application and safety of cochlear prostheses,” in Neural Prostheses: Fundamental Studies, W. F. Agnew and D. B. McCreery, Eds. Englewood Cliffs, NJ: Prentice-Hall, pp. 253-296.

Lehnhardt, E. 1993, "[Intracochlear placement of cochlear implant electrodes in soft surgery technique]", *HNO*, vol. 41, no. 7, pp. 356-359.

Lenarz, M., Sonmez, H., Joseph, G., Buchner, A., & Lenarz, T. 2012, "Cochlear implant performance in geriatric patients", *Laryngoscope*, vol. 122, no. 6, pp. 1361-1365.

Lenarz, T., Buchner, A., Tasche, C., Cristofoli, T., Lesinski-Schiedat, A., Wallenberg, E. V., Battmer, R. D., Busby, P. A., & Frohne, C. 2002, "The results in patients implanted with the nucleus double array cochlear implant: pitch discrimination and auditory performance", *Ear Hear.*, vol. 23, no. 1 Suppl, pp. 90S-101S.

Lenarz, T., Lesinski-Schiedat, A., Weber, B. P., Issing, P. R., Frohne, C., Buchner, A., Battmer, R. D., Parker, J., & Von Wallenberg, E. 2001, "The nucleus double array cochlear implant: a new concept for the obliterated cochlea", *Otol.Neurotol.*, vol. 22, no. 1, pp. 24-32.

Lenarz, T., Stover, T., Buechner, A., Lesinski-Schiedat, A., Patrick, J., & Pesch, J. 2009, "Hearing Conservation Surgery Using the Hybrid-L Electrode Results from the First Clinical Trial at the Medical University of Hannover", *Audiology and Neuro-Otology*, vol. 14, pp. 22-31.

Lenarz, T., Stover, T., Buechner, A., Paasche, G., Briggs, R., Risi, F., Pesch, J., & Battmer, R. D. 2006, "Temporal bone results and hearing preservation with a new straight electrode", *Audiol.Neurootol.*, vol. 11 Suppl 1, pp. 34-41.

Leung, J., Wang, N. Y., Yeagle, J. D., Chinnici, J., Bowditch, S., Francis, H. W., & Niparko, J. K. 2005, "Predictive models for cochlear implantation in elderly candidates", *Arch.Otolaryngol.Head Neck Surg.*, vol. 131, no. 12, pp. 1049-1054.

Li, P. M. M. C., Wang, H. B., Northrop, C., Merchant, S. N., & Nadol, J. B. 2007, "Anatomy of the round window and hook region of the cochlea with implications for cochlear implantation and other endocochlear surgical procedures", *Otology & Neurotology*, vol. 28, no. 5, pp. 641-648.

Lin, Y. S. 2009, "Clinical outcomes of scala vestibuli cochlear implantation in children with partial labyrinthine ossification", *Acta Otolaryngol.*, vol. 129, no. 3, pp. 273-280.

Litvak LM, Spahr AJ, Emadi G. 2007, "Loudness growth observed under partially tripolar stimulation: model and data from cochlear implant listeners", *Journal of the Acoustical Society of America,* vol. 122, no. 2, pp. 967-981.

Litovsky, R., Parkinson, A., Arcaroli, J., & Sammeth, C. 2006, "Simultaneous bilateral cochlear implantation in adults: A multicenter clinical study", *Ear and Hearing*, vol. 27, no. 6, pp. 714-731.

Loizou, P. C. 1998, "Mimicking the human ear", Ieee Signal Processing Magazine, vol. 15, no. 5, pp. 101-130.

Loizou, P. C. 1999, "Introduction to cochlear implants", Ieee Engineering in Medicine and Biology Magazine, vol. 18, no. 1, pp. 32-42.

Loizou, P. C., Stickney, G., Mishra, L., & Assmann, P. 2003, "Comparison of speech processing strategies used in the Clarion implant processor", *Ear Hear.*, vol. 24, no. 1, pp. 12-19.

Luo, X., Fu, Q. J., Wei, C. G., & Cao, K. L. 2008, "Speech Recognition and Temporal Amplitude Modulation Processing by Mandarin-Speaking Cochlear Implant Users", *Ear and Hearing*, vol. 29, no. 6, pp. 957-970.

Lustig, L. R., Yeagle, J., Niparko, J. K., & Minor, L. B. 2003, "Cochlear implantation in patients with bilateral Meniere's syndrome", *Otology & Neurotology*, vol. 24, no. 3, pp. 397-403.

Lyxell, B. 1996, "Cognitive predictors of speech understanding following a cochlear implant operation", *International Journal of Psychology*, vol. 31, no. 3-4, p. 4738.

Lyxell, B., Andersson, J., Andersson, U., Arlinger, S., Bredberg, G., & Harder, H. 1998, "Phonological representation and speech understanding with cochlear implants in deafened adults", *Scandinavian Journal of Psychology*, vol. 39, no. 3, pp. 175-179.

Lyxell, B., Andersson, U., Borg, E., & Ohlsson, I. S. 2003, "Working-memory capacity and phonological processing in deafened adults and individuals with a severe hearing impairment", *International Journal of Audiology*, vol. 42, p. S86-S89.

Lyxell, B., Ronnberg, J., & Samuelsson, S. 1994, "Internal Speech Functioning and Speechreading in Deafened and Normal-Hearing Adults", *Scandinavian Audiology*, vol. 23, no. 3, pp. 179-185.

Lyxell, B., Sahlen, B., Wass, M., Ibertsson, T., Larsby, B., Hallgren, M., & Maki-Torkko, E. 2008, "Cognitive development in children with cochlear implants: Relations to reading and communication", *International Journal of Audiology*, vol. 47, p. S47-S52.

Magnusson, L. 2011, "Comparison of the fine structure processing (FSP) strategy and the CIS strategy used in the MED-EL cochlear implant system: Speech intelligibility and music sound quality", International Journal of Audiology, vol. 50, no. 4, pp. 279-287.

McAlpine, D. 2005, "Creating a sense of auditory space", *Journal of Physiology-London*, vol. 566, no. 1, pp. 21-28.

McDermott, H. J. & McKay, C. M. 1994, "Pitch Ranking with Nonsimultaneous Dual-Electrode Electrical-Stimulation of the Cochlea", *Journal of the Acoustical Society of America*, vol. 96, no. 1, pp. 155-162.

McDermott, H. J. & McKay, C. M. 1997, "Musical pitch perception with electrical stimulation of the cochlea", *Journal of the Acoustical Society of America*, vol. 101, no. 3, pp. 1622-1631.

McDermott, H. J., McKay, C. M., Richardson, L. M., & Henshall, K. R. 2003, "Application of loudness models to sound processing for cochlear implants", *Journal of the Acoustical Society of America*, vol. 114, no. 4, pp. 2190-2197.

McElveen, J. T., Jr., Wolford, R. D., Jr., & Miyamoto, R. T. 1995, "Implications of bone pate in cochlear implant surgery", *Otolaryngol.Head Neck Surg.*, vol. 112, no. 3, pp. 457-460.

McKay, C. M. 2005, "Spectral processing in cochlear implants", *Auditory Spectral Processing*, vol. 70, pp. 473-509.

McKay, C. M. & Carlyon, R. P. 1999, "Dual temporal pitch percepts from acoustic and electric amplitude-modulated pulse trains", *Journal of the Acoustical Society of America*, vol. 105, no. 1, pp. 347-357.

McKay, C. M. & Henshall, K. R. 2002, "Frequency-to-electrode allocation and speech perception with cochlear implants", *Journal of the Acoustical Society of America*, vol. 111, no. 2, pp. 1036-1044.

McKay, C. M., Henshall, K. R., Farrell, R. J., & McDermott, H. J. 2003, "A practical method of predicting the loudness of complex electrical stimuli", *Journal of the Acoustical Society of America*, vol. 113, no. 4, pp. 2054-2063.

McKay, C. M., Henshall, K. R., & Hull, A. E. 2005, "The effect of rate of stimulation on perception of spectral shape by cochlear implantees", *Journal of the Acoustical Society of America*, vol. 118, no. 1, pp. 386-392.

McKay, C. M. & McDermott, H. J. 1993, "Perceptual Performance of Subjects with Cochlear Implants Using the Spectral Maxima Sound Processor (Smsp) and the Mini Speech Processor (Msp)", *Ear and Hearing*, vol. 14, no. 5, pp. 350-367.

McKay, C. M. & McDermott, H. J. 1996, "The perception of temporal patterns for electrical stimulation presented at one or two intracochlear sites", *Journal of the Acoustical Society of America*, vol. 100, no. 2, pp. 1081-1092.

McKay, C. M. & McDermott, H. J. 1999, "The perceptual effects of current pulse duration in electrical stimulation of the auditory nerve", *Journal of the Acoustical Society of America*, vol. 106, no. 2, pp. 998-1009.

McKay, C. M., McDermott, H. J., & Clark, G. M. 1996, "The perceptual dimensions of single-electrode and nonsimultaneous dual-electrode stimuli in cochlear implantees", *Journal of the Acoustical Society of America*, vol. 99, no. 2, pp. 1079-1090.

McKay, C. M., McDermott, H. J., Vandali, A. E., & Clark, G. M. 1992, "A Comparison of Speech-Perception of Cochlear Implantees Using the Spectral Maxima Sound Processor (Smsp) and the Msp(Multipeak) Processor", *Acta Oto-Laryngologica*, vol. 112, no. 5, pp. 752-761.

McKay, C. M., O'Brien, A., & James, C. J. 1999, "Effect of current level on electrode discrimination in electrical stimulation", *Hearing Research*, vol. 136, no. 1-2, pp. 159-164.

McKay, C. M., Remine, M. D., & McDermott, H. J. 2001, "Loudness summation for pulsatile electrical stimulation of the cochlea: Effects of rate, electrode separation, level, and mode of stimulation", *Journal of the Acoustical Society of America*, vol. 110, no. 3, pp. 1514-1524.

McKay, M. C., Dworetzky, S. I., Meanwell, N. A., Olesen, S. P., Reinhart, P. H., Levitan, I. B., Adelman, J. P., & Gribkoff, V. K. 1994, "Opening of Large-Conductance Calcium-Activated Potassium Channels by the Substituted Benzimidazolone Ns004", *Journal of Neurophysiology*, vol. 71, no. 5, pp. 1873-1882.

McKay, N. G., Kinsella, J. M., Campbell, C. M., & Ashford, M. L. J. 2000, "Sensitivity of Kir6.2-SUR1 currents, in the absence and presence of sodium azide, to the K-ATP channel inhibitors, ciclazindol and englitazone", *British Journal of Pharmacology*, vol. 130, no. 4, pp. 857-866.

Michelson, R.P. 1971, "Electrical stimulation of the human cochlea: A preliminary report", *Arch. Otolaryngol*. vol. 93, no. 3, pp. 317-323.

Middlebrooks, J. C. & Bierer, J. A. 2002, "Auditory cortical images of cochlear-implant stimuli: Coding of stimulus channel and current level", *Journal of Neurophysiology*, vol. 87, no. 1, pp. 493-507.

Middlebrooks, J. C., Bierer, J. A., & Snyder, R. L. 2005, "Cochlear implants: the view from the brain", *Current Opinion in Neurobiology*, vol. 15, no. 4, pp. 488-493.

Miller, A. L., Arenberg, J. G., Middlebrooks, J. C., & Pfingst, B. E. 2001, "Cochlear implant thresholds: comparison of middle latency responses with psychophysical and cortical-spike-activity thresholds", *Hearing Research*, vol. 152, no. 1-2, pp. 55-66.

Miller, A. L., Morris, D. J., & Pfingst, B. E. 1997, "Interactions between pulse separation and pulse polarity order in cochlear implants", *Hearing Research*, vol. 109, no. 1-2, pp. 21-33.

Miller, A. L., Morris, D. J., & Pfingst, B. E. 2000, "Effects of time after deafening and implantation on guinea pig electrical detection thresholds", *Hearing Research*, vol. 144, no. 1-2, pp. 175-186.

Miller, A. L., Smith, D. W., & Pfingst, B. E. 1999a, "Across-species comparisons of psychophysical detection thresholds for electrical stimulation of the cochlea: I. Sinusoidal stimuli", *Hearing Research*, vol. 134, no. 1-2, pp. 89-104.

Miller, A. L., Smith, D. W., & Pfingst, B. E. 1999b, "Across-species comparisons of psychophysical detection thresholds for electrical stimulation of the cochlea: II. Strength-duration functions for single, biphasic pulses", *Hearing Research*, vol. 135, no. 1-2, pp. 47-55.

Miller, C. A., Faulkner, M. J., & Pfingst, B. E. 1995, "Functional responses from guinea pigs with cochlear implants .2. Changes in electrophysiological and psychophysical measures over time", *Hearing Research*, vol. 92, no. 1-2, pp. 100-111.

Miller, G. A. & Nicely, P. E. 1955, "An Analysis of Perceptual Confusions Among Some English Consonants", *Journal of the Acoustical Society of America*, vol. 27, no. 2, pp. 338-352.

Miller, C. A., Woodruff, K. E., & Pfingst, B. E. 1995, "Functional responses from guinea pigs with cochlear implants .1. Electrophysiological and psychophysical measures", *Hearing Research*, vol. 92, no. 1-2, pp. 85-99.

Miracle, A. C. & Mukherji, S. K. 2009, "Conebeam CT of the Head and Neck, Part 2: Clinical Applications", *American Journal of Neuroradiology*, vol. 30, no. 7, pp. 1285-1292.

Mishra, L. N. 2000, “Analysis of Speech Processing Strategies for the Clarion Implant Processor,” M.Sc. thesis, The University of Texas, Dallas.

Moon, A. K., Zwolan, T. A., & Pfingst, B. E. 1993, "Effects of Phase Duration on Detection of Electrical-Stimulation of the Human Cochlea", *Hearing Research*, vol. 67, no. 1-2, pp. 166-178.

Moore, B. C. J. 2004, "Dead regions in the cochlea: Conceptual foundations, diagnosis, and clinical applications", *Ear and Hearing*, vol. 25, no. 2, pp. 98-116.

Morton, K. D., Torrione, P. A., Throckmorton, C. S., & Collins, L. M. 2008, "Mandarin Chinese tone identification in cochlear implants: Predictions from acoustic models", *Hearing Research*, vol. 244, no. 1-2, pp. 66-76.

Mosnier, I., Sterkers, O., Bebear, J. P., Godey, B., Robier, A., Deguine, O., Fraysse, B., Bordure, P., Mondain, M., Bouccara, D., Bozorg-Grayeli, A., Borel, S., Ambert-Dahan, E., & Ferrary, E. 2009, "Speech Performance and Sound Localization in a Complex Noisy Environment in Bilaterally Implanted Adult Patients", *Audiology and Neuro-Otology*, vol. 14, no. 2, pp. 106-114.

Munson, B., Donaldson, G. S., Allen, S. L., Collison, E. A., & Nelson, D. A. 2003, "Patterns of phoneme perception errors by listeners with cochlear implants as a function of overall speech perception ability", *Journal of the Acoustical Society of America*, vol. 113, no. 2, pp. 925-935.

Munson, B. & Nelson, P. B. 2005, "Phonetic identification in quiet and in noise by listeners with cochlear implants", *Journal of the Acoustical Society of America*, vol. 118, no. 4, pp. 2607-2617.

Nadol, J. B. & Hsu, W. C. 1991, "Histopathologic Correlation of Spiral Ganglion-Cell Count and New Bone-Formation in the Cochlea Following Meningogenic Labyrinthitis and Deafness", *Annals of Otology Rhinology and Laryngology*, vol. 100, no. 9, pp. 712-716.

Nadol, J. B., Jr., Young, Y. S., & Glynn, R. J. 1989, "Survival of spiral ganglion cells in profound sensorineural hearing loss: implications for cochlear implantation", *Ann.Otol.Rhinol.Laryngol.*, vol. 98, no. 6, pp. 411-416.

National Institute on Deafness and Other Communication Disorders . 2012, "Cochlear implants". Retrieved December 22, 2012, from http://www.nidcd.nih.gov/health/hearing/pages/coch.aspx

Nelson, D. A., Donaldson, G. S., & Kreft, H. 2008, "Forward-masked spatial tuning curves in cochlear implant users", *Journal of the Acoustical Society of America*, vol. 123, no. 3, pp. 1522-1543.

Nelson, D. A., Vantasell, D. J., Schroder, A. C., Soli, S., & Levine, S. 1995, "Electrode Ranking of Place Pitch and Speech Recognition in Electrical Hearing", *Journal of the Acoustical Society of America*, vol. 98, no. 4, pp. 1987-1999.

Nelson, P. B. & Jin, S. H. 2004, "Factors affecting speech understanding in gated interference: Cochlear implant users and normal-hearing listeners", *Journal of the Acoustical Society of America*, vol. 115, no. 5, pp. 2286-2294.

Nelson, P. B., Jin, S. H., Carney, A. E., & Nelson, D. A. 2003, "Understanding speech in modulated interference: Cochlear implant users and normal-hearing listeners", *Journal of the Acoustical Society of America*, vol. 113, no. 2, pp. 961-968.

Nelson, P. C., Ewert, S. D., Carney, L. H., & Dau, T. 2007, "Comparison of level discrimination, increment detection, and comodulation masking release in the audio- and envelope-frequency domains", *Journal of the Acoustical Society of America*, vol. 121, no. 4, pp. 2168-2181.

Neuman, A. C., Haravon, A., Sislian, N., & Waltzman, S. B. 2007, "Sound-direction identification with bilateral cochlear implants", *Ear and Hearing*, vol. 28, no. 1, pp. 73-82.

Nie, K. B., Bierer, S. M., Ling, L., Oxford, T., Rubinstein, J. T., & Phillips, J. O. 2011, "Characterization of the Electrically Evoked Compound Action Potential of the Vestibular Nerve", *Otology & Neurotology*, vol. 32, no. 1, pp. 88-97.

Nikolopoulos, T. P., Archbold, S. M., & O'Donoghue, G. M. 2006, "Does cause of deafness influence outcome after cochlear implantation in children?", *Pediatrics*, vol. 118, no. 4, pp. 1350-1356.

Nilsson, M., Soli, S. D., & Sullivan, J. A. 1994, "Development of the Hearing in Noise Test for the Measurement of Speech Reception Thresholds in Quiet and in Noise", *Journal of the Acoustical Society of America*, vol. 95, no. 2, pp. 1085-1099.

Niparko, J. K., Kileny, P. R., Pfingst, B. E., Kemink, J. L., Johansson, C., & Tjellstrom, A. 1993, "Cochlear Wall Titanium Implants for Auditory-Nerve Stimulation", *Annals of Otology Rhinology and Laryngology*, vol. 102, no. 6, pp. 447-454.

Nobbe, A., Schleich, P., Zierhofer, C., & Nopp, P. 2007, "Frequency discrimination with sequential or simultaneous stimulation in MED-EL cochlear implants", *Acta Oto-Laryngologica*, vol. 127, no. 12, pp. 1266-1272.

Nogueira, W., Litvak, L., Edler, B., Ostermann, J., & Buchner, A. 2009, "Signal Processing Strategies for Cochlear Implants Using Current Steering", *Eurasip Journal on Advances in Signal Processing*.

Nopp, P., Schleich, P., & D'Haese, P. 2004, "Sound localization in bilateral users of MED-EL COMBI 40/40+cochlear implants", *Ear and Hearing*, vol. 25, no. 3, pp. 205-214.

Nuetzel, J. M., & Hafter, E. R. 1981, "Discrimination of interaural delays in complex waveforms: Spectral effects", *The Journal of the Acoustical Society of America*, vol. 69, no. 4, pp.1112-1118.

Orabi, A. A., Mawman, D., Al Zoubi, F., Saeed, S. R., & Ramsden, R. T. 2006, "Cochlear implant outcomes and quality of life in the elderly: Manchester experience over 13 years", *Clinical Otolaryngology*, vol. 31, no. 2, pp. 116-122.

Otake, H., Sugiura, M., Naganawa, S., & Nakashima, T. 2006, "3D-FLAIR magnetic resonance imaging in the evaluation of mumps deafness", *Int.J.Pediatr.Otorhinolaryngol.*, vol. 70, no. 12, pp. 2115-2117.

Papsin, B. C. & Gordon, K. A. 2007, "Cochlear implants for children with severe-to-profound hearing loss", *N.Engl.J.Med.*, vol. 357, no. 23, pp. 2380-2387.

Parisier, S. C., Chute, P. M., Popp, A. L., & Suh, G. D. 2001, "Outcome analysis of cochlear implant reimplantation in children", *Laryngoscope*, vol. 111, no. 1, pp. 26-32.

Parkinson, A. J., Arcaroli, J., Staller, S. J., Arndt, P. L., Cosgriff, A., & Ebinger, K. 2002, "The nucleus 24 contour cochlear implant system: adult clinical trial results", *Ear Hear.*, vol. 23, no. 1 Suppl, pp. 41S-48S.

Pasanisi, E., Bacciu, A., Vincenti, V., Guida, M., Barbot, A., Berghenti, M. T., & Bacciu, S. 2003, "Speech recognition in elderly cochlear implant recipients", *Clin.Otolaryngol.Allied Sci.*, vol. 28, no. 2, pp. 154-157.

Pasanisi, E., Vincenti, V., Bacciu, A., Guida, M., & Bacciu, S. 2002, "The nucleus contour electrode array: an electrophysiological study", *Laryngoscope*, vol. 112, no. 9, pp. 1653-1656.

Peissig, J. & Kollmeier, B. 1997, "Directivity of binaural noise reduction in spatial multiple noise-source arrangements for normal and impaired listeners", *Journal of the Acoustical Society of America*, vol. 101, no. 3, pp. 1660-1670.

Pfingst, B. E. 2011, "Effects of electrode configuration on cochlear implant modulation detection thresholds", *Journal of the Acoustical Society of America*, vol. 129, no. 6, pp. 3908-3915.

Pfingst, B. E., Burkholder-Juhasz, R. A., Zwolan, T. A., & Xu, L. 2008, "Psychophysical assessment of stimulation sites in auditory prosthesis electrode arrays", *Hearing Research*, vol. 242, no. 1-2, pp. 172-183.

Pfingst, B. E., Franck, K. H., Xu, L., Bauer, E. M., & Zwolan, T. A. 2001, "Effects of electrode configuration and place of stimulation on speech perception with cochlear prostheses", *Jaro*, vol. 2, no. 2, pp. 87-103.

Pfingst, B. E., Holloway, L. A., Poopat, N., Subramanya, A. R., Warren, M. F., & Zwolan, T. A. 1994, "Effects of Stimulus Level on Nonspectral Frequency Discrimination by Human-Subjects", *Hearing Research*, vol. 78, no. 2, pp. 197-209.

Pfingst, B. E., Holloway, L. A., & Razzaque, S. A. 1996, "Effects of pulse separation on detection thresholds for electrical stimulation of the human cochlea", *Hearing Research*, vol. 98, no. 1-2, pp. 77-92.

Pfingst, B. E., Holloway, L. A., Zwolan, T. A., & Collins, L. M. 1999, "Effects of stimulus level on electrode-place discrimination in human subjects with cochlear implants", *Hearing Research*, vol. 134, no. 1-2, pp. 105-115.

Pfingst, B. E., Morris, D. J., & Miller, A. L. 1995, "Effects of Electrode Configuration on Threshold Functions for Electrical-Stimulation of the Cochlea", *Hearing Research*, vol. 85, no. 1-2, pp. 76-84.

Pfingst, B. E. & Rai, D. T. 1990, "Effects of Level on Nonspectral Frequency Difference Limens for Electrical and Acoustic Stimuli", *Hearing Research*, vol. 50, no. 1-2, pp. 43-56.

Pfingst, B. E. & Sutton, D. 1983, "Relation of Cochlear-Implant Function to Histopathology in Monkeys", *Annals of the New York Academy of Sciences*, vol. 405, no. JUN, pp. 224-239.

Pfingst, B. E. & Xu, L. 2004, "Across-site variation in detection thresholds and maximum comfortable loudness levels for cochlear implants", *Jaro-Journal of the Association for Research in Otolaryngology*, vol. 5, no. 1, pp. 11-24.

Pfingst, B. E. & Xu, L. 2005, "Psychophysical metrics and speech recognition in cochlear implant users", *Audiology and Neuro-Otology*, vol. 10, no. 6, pp. 331-341.

Pfingst, B. E., Xu, L., & Thompson, C. S. 2004, "Across-site threshold variation in cochlear implants: Relation to speech recognition", *Audiology and Neuro-Otology*, vol. 9, no. 6, pp. 341-352.

Pfingst, B. E., Xu, L., & Thompson, C. S. 2007, "Effects of carrier pulse rate and stimulation site on modulation detection by subjects with cochlear implants", *Journal of the Acoustical Society of America*, vol. 121, no. 4, pp. 2236-2246.

Pfingst, B. E., Zwolan, T. A., & Holloway, L. A. 1997, "Effects of stimulus configuration on psychophysical operating levels and on speech recognition with cochlear implants", *Hearing Research*, vol. 112, no. 1-2, pp. 247-260.

Philippon, D., Bergeron, F., Ferron, P., & Bussieres, R. 2010, "Cochlear Implantation in Postmeningitic Deafness", *Otology & Neurotology*, vol. 31, no. 1, pp. 83-87.

Pialoux, P., Chouard, C. H., & Macleod, P. 1976, "Physiological and Clinical Aspects of Rehabilitation of Total Deafness by Implantation of Multiple Intracochlear Electrodes", *Acta Oto-Laryngologica*, vol. 81, no. 5-6, pp. 436-441.

Pialoux, P., Chouard, C. H., Meyer, B., & Fugain, C. 1979, "Indications and Results of the Multichannel Cochlear Implant", *Acta Oto-Laryngologica*, vol. 87, no. 3-4, pp. 185-189.

Plomp, R. & Mimpen, A. M. 1981, "Effect of the Orientation of the Speakers Head and the Azimuth of A Noise Source on the Speech-Reception Threshold for Sentences", *Acustica*, vol. 48, no. 5, pp. 325-328.

Plontke, S. K., Biegner, T., Kammerer, B., Delabar, U., & Salt, A. N. 2008, "Dexamethasone concentration gradients along scala tympani after application to the round window membrane", *Otol.Neurotol.*, vol. 29, no. 3, pp. 401-406.

Poon, B. B. 2006, “Sound localization and interaural time sensitivity with bilateral cochlear implants,” Ph.D. thesis, Massachusetts Institute of Technology, Cambridge.

Prentiss, S., Sykes, K., & Staecker, H. 2010, "Partial Deafness Cochlear Implantation at the University of Kansas: Techniques and Outcomes", *Journal of the American Academy of Audiology*, vol. 21, no. 3, pp. 197-203.

Qin, M. K. & Oxenham, A. J. 2003, "Effects of simulated cochlear-implant processing on speech reception in fluctuating maskers", *Journal of the Acoustical Society of America*, vol. 114, no. 1, pp. 446-454.

Rafferty, M. A., Siewerdsen, J. H., Chan, Y., Daly, M. J., Moseley, D. J., Jaff, D. A., & Irish, J. C. 2006, "Intraoperative cone-beam CT for guidance of temporal bone surgery", *Otolaryngology-Head and Neck Surgery*, vol. 134, no. 5, pp. 801-808.

Ramsden, R., Greenham, P., O'Driscoll, M., Mawman, D., Proops, D., Craddock, L., Fielden, C., Graham, J., Meerton, L., Verschuur, C., Toner, J., McAnallen, T., Osborne, J., Doran, M., Gray, R., & Pickerill, M. 2005, "Evaluation of bilaterally implanted adult subjects with the nucleus 24 cochlear implant systems", *Otology & Neurotology*, vol. 26, no. 5, pp. 988-998.

Rayleigh 1907, "On our perception of sound direction", *Philosophical Magazine*, vol. 13, no. 73-78, pp. 214-232.

Rebscher, S. J., Hetherington, A., Bonham, B., Wardrop, P., Whinney, D., & Leake, P. A. 2008, "Considerations for design of future cochlear implant electrode arrays: electrode array stiffness, size, and depth of insertion", *J.Rehabil.Res.Dev.*, vol. 45, no. 5, pp. 731-747.

Reiss, L. A., Gantz, B. J., & Turner, C. W. 2008, "Cochlear implant speech processor frequency allocations may influence pitch perception", *Otol.Neurotol.*, vol. 29, no. 2, pp. 160-167.

Reiss, L. A., Turner, C. W., Erenberg, S. R., & Gantz, B. J. 2007, "Changes in pitch with a cochlear implant over time", *J.Assoc.Res.Otolaryngol.*, vol. 8, no. 2, pp. 241-257.

Reiss, L. A. J., Lowder, M. W., Karsten, S. A., Turner, C. W., & Gantz, B. J. 2011, "Effects of Extreme Tonotopic Mismatches Between Bilateral Cochlear Implants on Electric Pitch Perception: A Case Study", *Ear and Hearing*, vol. 32, no. 4, pp. 536-540.

Remus, J. J. & Collins, L. M. 2005, "The effects of noise on speech recognition in cochlear implant subjects: Predictions and analysis using acoustic models", *Eurasip Journal on Applied Signal Processing*, vol. 2005, no. 18, pp. 2979-2990.

Remus, J. J., Throckmorton, C. S., & Collins, L. M. 2007, "Expediting the identification of impaired channels in cochlear implants via analysis of speech-based confusion matrices", *Ieee Transactions on Biomedical Engineering*, vol. 54, no. 12, pp. 2193-2204.

Richter, B., Aschendorff, A., Lohnstein, P., Husstedt, H., Nagursky, H., & Laszig, R. 2001, "The Nucleus Contour electrode array: a radiological and histological study", *Laryngoscope*, vol. 111, no. 3, pp. 508-514.

Ricketts, T. A., Grantham, D. W., Ashmead, D. H., Haynes, D. S., & Labadie, R. F. 2006, "Speech recognition for unilateral and bilateral cochlear implant modes in the presence of uncorrelated noise sources", *Ear and Hearing*, vol. 27, no. 6, pp. 763-773.

Rinia, A. B., Olphen, A. F., & Dunnebier, E. A. 2006, "Cochlear implantation in obstructed cochleas: the effect of the degree of obstruction on the number of activated electrodes and the amount of postoperative speech perception", *Clin.Otolaryngol.*, vol. 31, no. 4, pp. 280-286.

Roditi, R. E., Poissant, S. F., Bero, E. M., & Lee, D. J. 2009, "A predictive model of cochlear implant performance in postlingually deafened adults", *Otol.Neurotol.*, vol. 30, no. 4, pp. 449-454.

Roland, J. T., Jr., Coelho, D. H., Pantelides, H., & Waltzman, S. B. 2008, "Partial and double-array implantation of the ossified cochlea", *Otol.Neurotol.*, vol. 29, no. 8, pp. 1068-1075.

Ronnberg, J. 1993, "Cognitive Characteristics of Skilled Tactiling - the Case of Gs", *European Journal of Cognitive Psychology*, vol. 5, no. 1, pp. 19-33.

Rosen, S., Faulkner, A., & Wilkinson, L. 1999, "Adaptation by normal listeners to upward spectral shifts of speech: implications for cochlear implants", *J.Acoust.Soc.Am.*, vol. 106, no. 6, pp. 3629-3636.

Rotteveel, L. J. C., Snik, A. F. M., Cooper, H., Mawman, D. J., van Olphen, A. F., & Mylanus, E. A. M. 2010, "Speech Perception after Cochlear Implantation in 53 Patients with Otosclerosis: Multicentre Results", *Audiology and Neuro-Otology*, vol. 15, no. 2, pp. 128-136.

Rotteveel, L. J. C., Snik, A. F. M., Vermeulen, A. M., & Mylanus, E. A. M. 2005, "Three-year follow-up of children with postmeningitic deafness and partial cochlear implant insertion", *Clinical Otolaryngology*, vol. 30, no. 3, pp. 242-248.

Rubinstein, J. T., Parkinson, W. S., Tyler, R. S., & Gantz, B. J. 1999, "Residual speech recognition and cochlear implant performance: Effects of implantation criteria", *American Journal of Otology*, vol. 20, no. 4, pp. 445-452.

Ruivo, J., Mermuys, K., Bacher, K., Kuhweide, R., Offeciers, E., & Casselman, J. W. 2009, "Cone Beam Computed Tomography, A Low-Dose Imaging Technique in the Postoperative Assessment of Cochlear Implantation", *Otology & Neurotology*, vol. 30, no. 3, pp. 299-303.

Saeed, S. R., Ramsden, R. T., Hartley, C., Woolford, T. J., & Boyd, P. 1995, "Cochlear Reimplantation", Journal of Laryngology and Otology, vol. 109, no. 10, pp. 980-985.

Sagi, E., Fu, Q. J., Galvin, J. J., & Svirsky, M. A. 2010, "A Model of Incomplete Adaptation to a Severely Shifted Frequency-to-Electrode Mapping by Cochlear Implant Users", *Jaro-Journal of the Association for Research in Otolaryngology*, vol. 11, no. 1, pp. 69-78.

Sarant, J. Z., Blamey, P. J., Dowell, R. C., Clark, G. M., & Gibson, W. P. R. 2001, "Variation in speech perception scores among children with cochlear implants", *Ear and Hearing*, vol. 22, no. 1, pp. 18-28.

Saunders, E., Cohen, L., Aschendorff, A., Shapiro, W., Knight, M., Stecker, M., Richter, B., Waltzman, S., Tykocinski, M., Roland, T., Laszig, R., & Cowan, R. 2002, "Threshold, comfortable level and impedance changes as a function of electrode-modiolar distance", *Ear Hear.*, vol. 23, no. 1 Suppl, pp. 28S-40S.

Saxman, J. H. & Burk, K. W. 1967, "Speaking Fundamental Frequency Characteristics of Middle-Aged Females", *Folia Phoniatrica*, vol. 19, no. 3, pp. 167-172.

Schindle.R.A & Merzenic M. M. 1974, "Chronic Intracochlear Electrode Implantation - Cochlear Pathology and Acoustic Nerve Survival", Annals of Otology Rhinology and Laryngology, vol. 83, no. 2, pp. 202-215.

Schleich, P., Nopp, P., & D'Haese, P. 2004, "Head shadow, squelch, and summation effects in bilateral users of the MED-EL COMBI 40/40+cochlear implant", *Ear and Hearing*, vol. 25, no. 3, pp. 197-204.

Shannon, R. V., Galvin, J. J., & Baskent, D. 2001, "Holes in hearing", *Jaro*, vol. 3, no. 2, pp. 185-199.

Sherbecoe, R. L. & Studebaker, G. A. 2004, "Supplementary formulas and tables for calculating and interconverting speech recognition scores in transformed arcsine units (vol 43, pg 442, 2004)", *International Journal of Audiology*, vol. 43, no. 9, p. 554.

Shibata, S. B., Cortez, S. R., Beyer, L. A., Wiler, J. A., Di Polo, A., Pfingst, B. E., & Raphael, Y. 2010, "Transgenic BDNF induces nerve fiber regrowth into the auditory epithelium in deaf cochleae", *Experimental Neurology*, vol. 223, no. 2, pp. 464-472.

Shin, Y. J., Fraysse, B., Deguine, O., Vales, O., Laborde, M. L., Bouccara, D., Sterkers, O., & Uziel, A. 2000, "Benefits of cochlear implantation in elderly patients", *Otolaryngol.Head Neck Surg.*, vol. 122, no. 4, pp. 602-606.

Shinn-Cunningham, B. G., Schickler, J., Kopco, N., & Litovsky, R. 2001, "Spatial unmasking of nearby speech sources in a simulated anechoic environment", *Journal of the Acoustical Society of America*, vol. 110, no. 2, pp. 1118-1129.

Shuttleworth, M. 2009, "Types of Validity". Retrieved 08 August 2012 from Experiment Resources: http://www.experiment-resources.com/types-of-validity.html.

Siciliano, C. M., Faulkner, A., Rosen, S., & Mair, K. 2010, "Resistance to learning binaurally mismatched frequency-to-place maps: Implications for bilateral stimulation with cochlear implants", *Journal of the Acoustical Society of America*, vol. 127, no. 3, pp. 1645-1660.

Simmons, F. B. 1966, "Electrical stimulation of the auditory nerve in man", *Arch Otolaryngology*, vol 84, no. 1, pp. 2-54.

Simon, H. A. & Kotovsky, K. 1963, "Human Acquisition of Concepts For Sequential Patterns", *Psychol.Rev.*, vol. 70, pp. 534-546.

Skarzynski, H., Lorens, A., D'Haese, P., Walkowiak, A., Piotrowska, A., Sliwa, L., & Anderson, I. 2002, "Preservation of residual hearing in children and post-lingually deafened adults after cochlear implantation: An initial study", *Orl-Journal for Oto-Rhino-Laryngology and Its Related Specialties*, vol. 64, no. 4, pp. 247-253.

Skarzynski, H., Lorens, A., Piotrowska, A., & Anderson, I. 2007, "Preservation of low frequency hearing in partial deafness cochlear implantation (PDCI) using the round window surgical approach", *Acta Oto-Laryngologica*, vol. 127, no. 1, pp. 41-48.

Skellam, J. G. 1948, "A Probability Distribution Derived from the Binomial Distribution by Regarding the Probability of Success As Variable Between the Sets of Trials", *Journal of the Royal Statistical Society Series B-Statistical Methodology*, vol. 10, no. 2, pp. 257-261.

Skinner, M. W., Clark, G. M., Whitford, L. A., Seligman, P. M., Staller, S. J., Shipp, D. B., Shallop, J. K., Everingham, C., Menapace, C. M., Arndt, P. L., & . 1994, "Evaluation of a new spectral peak coding strategy for the Nucleus 22 Channel Cochlear Implant System", *Am.J.Otol.*, vol. 15 Suppl 2, pp. 15-27.

Skinner, M. W., Fourakis, M. S., Holden, T. A., Holden, L. K., & Demorest, M. E. 1996, "Identification of speech by cochlear implant recipients with the multipeak (MPEAK) and spectral peak (SPEAK) speech coding strategies .1. Vowels", *Ear and Hearing*, vol. 17, no. 3, pp. 182-197.

Skinner, M. W., Holden, L. K., Demorest, M. E., & Holden, T. A. 1995, "Use of test-retest measures to evaluate performance stability in adults with cochlear implants", *Ear Hear.*, vol. 16, no. 2, pp. 187-197.

Skinner, M. W., Holden, L. K., & Holden, T. A. 1995, "Effect of frequency boundary assignment on speech recognition with the SPEAK speech-coding strategy", Ann.Otol.Rhinol.Laryngol.Suppl, vol. 166, pp. 307-311.

Skinner, M. W., Holden, L. K., & Holden, T. A. 1997, "Parameter selection to optimize speech recognition with the Nucleus implant", *Otolaryngology-Head and Neck Surgery*, vol. 117, no. 3, pp. 188-195.

Skinner, M. W., Holden, L. K., Holden, T. A., & Demorest, M. E. 1999, "Comparison of two methods for selecting minimum stimulation levels used in programming the nucleus 22 cochlear implant", *Journal of Speech Language and Hearing Research*, vol. 42, no. 4, pp. 814-828.

Skinner, M. W., Holden, L. K., Holden, T. A., Dowell, R. C., Seligman, P. M., Brimacombe, J. A., & Beiter, A. L. 1991, "Performance of postlinguistically deaf adults with the Wearable Speech Processor (WSP III) and Mini Speech Processor (MSP) of the Nucleus Multi-Electrode Cochlear Implant", *Ear Hear.*, vol. 12, no. 1, pp. 3-22.

Skinner, M. W., Holden, T. A., Whiting, B. R., Voie, A. H., Brunsden, B., Neely, J. G., Saxon, E. A., Hullar, T. E., & Finley, C. C. 2007, "In vivo estimates of the position of advanced bionics electrode arrays in the human cochlea", *Ann.Otol.Rhinol.Laryngol.Suppl*, vol. 197, pp. 2-24.

Skinner, M. W., Ketten, D. R., Holden, L. K., Harding, G. W., Smith, P. G., Gates, G. A., Neely, J. G., Kletzker, G. R., Brunsden, B., & Blocker, B. 2002, "CT-derived estimation of cochlear morphology and electrode array position in relation to word recognition in nucleus-22 recipients", *Jaro-Journal of the Association for Research in Otolaryngology*, vol. 3, no. 3, pp. 332-350.

Sly, D. J., Heffer, L. F., White, M. W., Shepherd, R. K., Birch, M. G. J., Minter, R. L., Nelson, N. E., Wise, A. K., & O'Leary, S. J. 2007, "Deafness alters auditory nerve fibre responses to cochlear implant stimulation", *European Journal of Neuroscience*, vol. 26, no. 2, pp. 510-522.

Smith, M. W. & Faulkner, A. 2006, "Perceptual adaptation by normally hearing listeners to a simulated "hole" in hearing", *Journal of the Acoustical Society of America*, vol. 120, no. 6, pp. 4019-4030.

Snyder, R. L., Bierer, J. A., & Middlebrooks, J. C. 2004, "Topographic spread of inferior colliculus activation in response to acoustic and intracochlear electric stimulation", *Jaro-Journal of the Association for Research in Otolaryngology*, vol. 5, no. 3, pp. 305-322.

Sridhar D., Stakhovskaya O., Leake P. 2006, "A frequency–position function

for the human cochlear spiral ganglion", *Audiol. Neurootol Suppl,* vol. 11, pp. 16–20, 2006.

Spahr, A. J., Dorman, M. F., & Loiselle, L. H. 2007, "Performance of patients using different cochlear implant systems: Effects of input dynamic range", *Ear and Hearing*, vol. 28, no. 2, pp. 260-275.

Staecker, H., Chow, H., & Nadol, J. B. 1999, "Osteomyelitis, lateral sinus thrombosis, and temporal lobe infarction caused by infection of a percutaneous cochlear implant", *American Journal of Otology*, vol. 20, no. 6, pp. 726-728.

Stakhovskaya, O., Sridhar, D., Bonham, B. H., & Leake, P. A. 2007, "Frequency map for the human cochlear spiral ganglion: Implications for cochlear implants", *Jaro-Journal of the Association for Research in Otolaryngology*, vol. 8, no. 2, pp. 220-233.

Stevens, S. S. & Newman, E. B. 1936, "The localization of actual sources of sound", *American Journal of Psychology*, vol. 48, pp. 297-306.

Stickney, G. S., Zeng, F. G., Litovsky, R., & Assmann, P. 2004, "Cochlear implant speech recognition with speech maskers", *Journal of the Acoustical Society of America*, vol. 116, no. 2, pp. 1081-1091.

Stoddart, R. L. & Cooper, H. R. 1999, "Electrode complications in 100 adults with multichannel cochlear implants", *Journal of Laryngology and Otology*, vol. 113, pp. 18-20.

Stohl, J. S., Throckmorton, C. S., & Collins, L. M. 2008, "Assessing the pitch structure associated with multiple rates and places for cochlear implant users", *Journal of the Acoustical Society of America*, vol. 123, no. 2, pp. 1043-1053.

Stohl, J. S., Throckmorton, C. S., & Collins, L. M. 2009, "Investigating the effects of stimulus duration and context on pitch perception by cochlear implant users", *Journal of the Acoustical Society of America*, vol. 126, no. 1, pp. 318-326.

Studebaker, G. A. 1985, "A Rationalized Arcsine Transform", *Journal of Speech and Hearing Research*, vol. 28, no. 3, pp. 455-462.

Su, G. L., Colesa, D. J., & Pfingst, B. E. 2008, "Effects of deafening and cochlear implantation procedures on postimplantation psychophysical electrical detection thresholds", *Hearing Research*, vol. 241, no. 1-2, pp. 64-72.

Summerfield, A. Q. & Marshall, D. H. 1995, "Preoperative predictors of outcomes from cochlear implantation in adults: performance and quality of life", *Ann.Otol.Rhinol.Laryngol.Suppl*, vol. 166, pp. 105-108.

Summerfield, Q., Palmer, A. R., Foster, J. R., Marshall, D. H., & Twomey, T. 1994, "Clinical-Evaluation and Test-Retest Reliability of the Ihr-Mccormick

Automated Toy Discrimination Test", *British Journal of Audiology*, vol. 28, no. 3, pp. 165-179.

Sutton, D., Miller, J. M., & Pfingst, B. E. 1980, "Comparison of Cochlear Histopathology Following 2 Implant Designs for Use in Scala Tympani", *Annals of Otology Rhinology and Laryngology*, vol. 89, no. 2, pp. 11-14.

Throckmorton, C. S. & Collins, L. M. 1999, "Investigation of the effects of temporal and spatial interactions on speech-recognition skills in cochlear implant subjects", *Journal of the Acoustical Society of America*, vol. 105, no. 2, pp. 861-873.

Throckmorton, C. S. & Collins, L. M. 2001, "A comparison of two loudness balancing tasks in cochlear implant subjects using bipolar stimulation", *Ear and Hearing*, vol. 22, no. 5, pp. 439-448.

Throckmorton, C. S. & Collins, L. M. 2002, "The effect of channel interactions on speech recognition in cochlear implant subjects: Predictions from an acoustic model", *Journal of the Acoustical Society of America*, vol. 112, no. 1, pp. 285-296.

Throckmorton, C. S., Kucukoglu, M. S., Remus, J. J., & Collins, L. M. 2006, "Acoustic model investigation of a multiple carrier frequency algorithm for encoding fine frequency structure: Implications for cochlear implants", *Hearing Research*, vol. 218, no. 1-2, pp. 30-42.

Throckmorton, C. S., Kucukoglu, M. S., Remus, J. J., & Collins, L. M. 2007, "The effect of frequency estimation on speech recognition using an acoustic model of a cochlear implant", *Hearing Research*, vol. 228, no. 1-2, pp. 230-231.

Trieger, A., Schulze, A., Schneider, M., Zahnert, T., & Murbe, D. 2011, "In Vivo Measurements of the Insertion Depth of Cochlear Implant Arrays Using Flat-Panel Volume Computed Tomography", *Otology & Neurotology*, vol. 32, no. 1, pp. 152-157.

Turner, C. W., Gantz, B. J., Vidal, C., Behrens, A., & Henry, B. A. 2004, "Speech recognition in noise for cochlear implant listeners: benefits of residual acoustic hearing", *J.Acoust.Soc.Am.*, vol. 115, no. 4, pp. 1729-1735.

Tykocinski, M., Saunders, E., Cohen, L. T., Treaba, C., Briggs, R. J., Gibson, P., Clark, G. M., & Cowan, R. S. 2001, "The contour electrode array: safety study and initial patient trials of a new perimodiolar design", *Otol.Neurotol.*, vol. 22, no. 1, pp. 33-41.

Tyler, R. S., Dunn, C. C., Witt, S. A., & Noble, W. G. 2007, "Speech perception and localization with adults with bilateral sequential cochlear implants", *Ear and Hearing*, vol. 28, no. 2, pp. 86S-90S.

U.S. Food and Drug Administration. 1984. Approval of first cochlear implant 3M brand cochlear implant system/House design. Retrieved December 30, 2012,from http://www.accessdata.fda.gov/scripts/cdrh/devicesatfda/index.cfm?db=pma&id=2512

Van de Heyning, P. H., Vermeire, K., Cochet, E., Hofkens, A., & De Bodt, M. 2004, "Cochlear implantation: a bionic system to restore hearing in severely hearing impaired patients", *Verh.K.Acad.Geneeskd.Belg.*, vol. 66, no. 4, pp. 253-267.

van Hoesel, R. J. M. 2004, "Exploring the benefits of bilateral cochlear implants", *Audiology and Neuro-Otology*, vol. 9, no. 4, pp. 234-246.

van Hoesel, R. J. M. 2007, "Sensitivity to binaural timing in bilateral cochlear implant users", *Journal of the Acoustical Society of America*, vol. 121, no. 4, pp. 2192-2206.

van Hoesel, R. J. M. 2008, "Observer weighting of level and timing cues in bilateral cochlear implant users", *Journal of the Acoustical Society of America*, vol. 124, no. 6, pp. 3861-3872.

van Hoesel, R. J. M. & Clark, G. M. 1997, "Psychophysical studies with two binaural cochlear implant subjects", *Journal of the Acoustical Society of America*, vol. 102, no. 1, pp. 495-507.

van Hoesel, R., Ramsden, R., & O'Driscoll, M. 2002, "Sound-direction identification, interaural time delay discrimination, and speech intelligibility advantages in noise for a bilateral cochlear implant user", *Ear and Hearing*, vol. 23, no. 2, pp. 137-149.

van Hoesel, R. J. M. & Tyler, R. S. 2003, "Speech perception, localization, and lateralization with bilateral cochlear implants", *Journal of the Acoustical Society of America*, vol. 113, no. 3, pp. 1617-1630.

Vandali, A. E., Whitford, L. A., Plant, K. L., & Clarke, G. M. 2000, "Speech perception as a function of electrical stimulation rate: Using the nucleus 24 cochlear implant system", *Ear and Hearing*, vol. 21, no. 6, pp. 608-624.

Verschuur, C. A., Lutman, M. E., Ramsden, R., Greenham, P., & O'Driscoll, M. 2005, "Auditory localization abilities in bilateral cochlear implant recipients", *Otology & Neurotology*, vol. 26, no. 5, pp. 965-971.

Wackym, P. A., Runge-Samuelson, C. L., Firszt, J. B., Alkaf, F. M., & Burg, L. S. 2007, "More challenging speech-perception tasks demonstrate binaural benefit in bilateral cochlear implant users", *Ear and Hearing*, vol. 28, no. 2, pp. 80S-85S.

Waltzman, S. B., Fisher, S. G., Niparko, J. K., & Cohen, N. L. 1995, "Predictors of postoperative performance with cochlear implants", *Ann.Otol.Rhinol.Laryngol.Suppl*, vol. 165, pp. 15-18.

Wang, J. R., Yuen, H. W., Shipp, D. B., Stewart, S., Lin, V. Y. W., Chen, J. M., & Nedzelski, J. M. 2010, "Cochlear Implantation in Patients With Autoimmune Inner Ear Disease Including Cogan Syndrome: A Comparison With Age- and Sex-Matched Controls", *Laryngoscope*, vol. 120, no. 12, pp. 2478-2483.

Wardrop, P., Whinney, D., Rebscher, S. J., Luxford, W., & Leake, P. 2005a, "A temporal bone study of insertion trauma and intracochlear position of cochlear implant electrodes. II: Comparison of Spiral Clarion (TM) and HiFocus II (TM) electrodes", *Hearing Research*, vol. 203, no. 1-2, pp. 68-79.

Wardrop, P., Whinney, D., Rebscher, S. J., Roland, J. T., Luxford, W., & Leake, P. A. 2005b, "A temporal bone study of insertion trauma and intracochlear position of cochlear implant electrodes. 1: comparison of Nucleus banded and Nucleus Contour (TM) electrodes", *Hearing Research*, vol. 203, no. 1-2, pp. 54-67.

Watson, C. S., Kelly, W. J., & Wroton, H. W. 1976, "Factors in the discrimination of tonal patterns II. Selective attention and learning under various levels of stimulus uncertainty", *Journal of the Acoustical Society of America,* vol. 60, no. 5, pp. 1176-1186.

Whitford, L. A., Seligman, P. M., Blamey, P. J., McDermott, H. J., & Patrick, J. F. 1993, "Comparison of current speech coding strategies", *Advances in Otorhinolaryngology*, vol. 48, pp. 85–90.

Wilson, B. S. & Dorman, M. F. 2008, "Cochlear implants: Current designs and future possibilities", *Journal of Rehabilitation Research and Development*, vol. 45, no. 5, pp. 695-730.

Wilson, B. S., Finley, C. C., Lawson, D. T., Wolford, R. D., & Zerbi, M. 1993, "Design and evaluation of a continuous interleaved sampling (CIS) processing strategy for multichannel cochlear implants", *J.Rehabil.Res.Dev.*, vol. 30, no. 1, pp. 110-116.

Wilson, B. S., Lawson, D. T., Finley, C. C., & Wolford, R. D. 1991, "Coding strategies for multichannel cochlear prostheses", *Am.J.Otol.*, vol. 12 Suppl, pp. 56-61.

Wilson, B. S., Lawson, D. T., Muller, J. M., Tyler, R. S., & Kiefer, J. 2003, "Cochlear implants: Some likely next steps", *Annual Review of Biomedical Engineering*, vol. 5, pp. 207-249.

Wolfe, J and Schafer, E. 2010, " Programming Cochlear Implants". San Diego: Plural Publishing Inc.

Wright, R. (1997). Basic properties of speech. In Speech Audiometry, M. Martin, ed. London: Whurr Publishing.

Xu, L. & Pfingst, B. E. 2003, "Relative importance of temporal envelope and fine structure in lexical-tone perception", *Journal of the Acoustical Society of America*, vol. 114, no. 6, pp. 3024-3027.

Xu, L. & Pfingst, B. E. 2008, "Spectral and temporal cues for speech recognition: Implications for auditory prostheses", *Hearing Research*, vol. 242, no. 1-2, pp. 132-140.

Xu, L., Thompson, C. S., & Pfingst, B. E. 2005, "Relative contributions of spectral and temporal cues for phoneme recognition", *Journal of the Acoustical Society of America*, vol. 117, no. 5, pp. 3255-3267.

Xu, L., Tsai, Y. J., & Pfingst, B. E. 2002, "Features of stimulation affecting tonal-speech perception: Implications for cochlear prostheses", *Journal of the Acoustical Society of America*, vol. 112, no. 1, pp. 247-258.

Xu, L., Zwolan, T. A., Thompson, C. S., & Pfingst, B. E. 2005, "Efficacy of a cochlear implant Simultaneous Analog Stimulation strategy coupled with a monopolar electrode configuration", *Annals of Otology Rhinology and Laryngology*, vol. 114, no. 11, pp. 886-893.

Xu, Y. F. & Collins, L. M. 2005, "Predicting dynamic range and intensity discrimination for electrical pulse-train stimuli using a stochastic auditory nerve model: The effects of stimulus noise", *Ieee Transactions on Biomedical Engineering*, vol. 52, no. 6, pp. 1040-1049.

Ye, Q., Tillein, J., Hartmann, R., Gstoettner, W., & Kiefer, J. 2007, "Application of a corticosteroid (Triamcinolon) protects inner ear function after surgical intervention", *Ear Hear.*, vol. 28, no. 3, pp. 361-369.

Yoshida, T., Sugiura, M., Naganawa, S., Teranishi, M., Nakata, S., & Nakashima, T. 2008, "Three-dimensional fluid-attenuated inversion recovery magnetic resonance imaging findings and prognosis in sudden sensorineural hearing loss", *Laryngoscope*, vol. 118, no. 8, pp. 1433-1437.

Yukawa, K., Cohen, L., Blamey, P., Pyman, B., Tungvachirakul, V., & O'Leary, S. 2004, "Effects of insertion depth of cochlear implant electrodes upon speech perception", *Audiol.Neurootol.*, vol. 9, no. 3, pp. 163-172.

Zeng, F. G. 2004, "Trends in cochlear implants", *Trends Amplif.*, vol. 8, no. 1, pp. 1-34.

Zeng, F. G., Grant, G., Niparko, J., Galvin, J., Shannon, R., Opie, J., & Segel, P. 2002, "Speech dynamic range and its effect on cochlear implant performance", *Journal of the Acoustical Society of America*, vol. 111, no. 1, pp. 377-386.

Zeng, F. G., Rebscher, S., Harrison, W. V., Sun, X., & Feng, H. 2008, "Cochlear Implants:System Design, Integration and Evaluation", *IEEE Rev.Biomed.Eng*, vol. 1, pp. 115-142.

Zhou, N. & Pfingst, B. E. 2012, "Psychophysically based site selection coupled with dichotic stimulation improves speech recognition in noise with bilateral cochlear implants", *Journal of the Acoustical Society of America*, vol. 132, no. 2, pp. 994-1008.

Zhu, Z., Tang, Q., Zeng, F.G., Guan, T & Ye, D. 2012, "Cochlear-implant spatial selectivity with monopolar, bipolar and tripolar stimulation", *Journal of Hearing Research*, vol. 283, no. 1-2, pp. 45-58.

Zwolan, T. A., Collins, L. M., & Wakefield, G. H. 1997, "Electrode discrimination and speech recognition in postlingually deafened adult cochlear implant subjects", *J.Acoust.Soc.Am.*, vol. 102, no. 6, pp. 3673-3685.