ENVIRONMENTAL SOUND PERCEPTION FOR COCHLEAR IMPLANT USERS

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by J. M. Arnephy

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

Figures:

Tables:

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ABSTRACT

This study compared adult cochlear implant (CI) users to normally hearing (NH) listeners in their ability to identify various environmental sounds. It also assessed the impact of cochlear implantation on speech perception as well as the ability to identify environmental sounds. A comprehensive Environmental Sounds Perception Test (EST) was developed for this study. It was hypothesised that: (i) the NH participants would score higher than the experienced CI users on the EST; (ii) for the pre-to-post CI group, scores on the EST would be higher post-surgery than pre-surgery, and (iii) for the pre-to-post CI surgery group, scores on speech perception tests would be higher post-surgery than pre-surgery.

10 experienced adult *Nucleus* CI users and 24 similarly-aged NH subjects were compared on the EST. The study also tested four adults pre-surgery (with HAs), and subsequently post-surgery with the CI on speech perception tests as well as the EST. The closed-set EST consisted of 45 different sounds selected to be representative of everyday stimuli, classified into 9 groups; transport, nature, arriving home, bathroom, kitchen, household appliances, human, office and other. Each sound was represented by two different tokens, ranging in lengths from 2.5 to 12.5 seconds.

The results showed that NH participants scored significantly higher than the experienced CI users on the EST ($p < 0.001$). For the participants tested pre- and post- surgery, the higher scores with the CI than with HAs was approaching significance ($p = 0.068$) for both the EST and the speech perception measures. No significant correlations were found between scores on the EST and a range of participant factors such as age or speech perception scores for any group. Overall these results suggest that CI users are poorer than NH participants, but better than HA users with severe-to-profound hearing losses, in recognizing environmental sounds.

CHAPTER 1

Introduction

Currently, most adult cochlear implant (CI) patients are post-lingually deafened with moderately-severe to profound hearing losses bilaterally. For these people, CIs can often provide better outcomes than what they may achieve with hearing aids (HAs) (Zhao, Stephens, Sim, & Meredith, 1997). For the audiologist to recommend implantation, they must be confident that the patient could obtain improved outcomes with a CI, and for this reason, research investigating the clinical outcomes for CIs is important.

The introductory part of this thesis consists of three chapters. Chapter 2 looks at the background behind the purpose and function of a CI. This is achieved through a description of both the normal hearing mechanism and the changes within it that cause a sensorineural hearing loss (section 2.1), a description of the CI and its components (section 2.2), an overview of CI speech processing strategies (section 2.3), and a discussion of the current CI assessment and selection criteria (section 2.4). Chapter 3 reviews current cochlear implant literature, focusing on studies involved with quality of life, speech perception, and environmental sound perception. This leads to chapter 4 which discusses the rationale behind the current study, and the aims and hypotheses of this research.

The methods section of this thesis is presented in chapter 5. This chapter details selection criteria (section 5.1) and recruitment (section 5.2) of participants, followed by details of the materials (section 5.3), equipment (section 5.4) and procedures (section 5.5) used for this study.

The results section of this thesis is presented in chapter 6. This chapter is divided up into a description of the data analysis carried out (section 6.1), and details of the results obtained for the NH group (section 6.2), the experienced CI group (section 6.3), the comparison between the NH and experienced CI group (section 6.4), and the pre-to-post CI group (section 6.5).

The discussion section of this thesis is addressed in chapter 7. First there is a discussion on the comparison of the NH group to the experienced CI group (section 7.1), followed by a discussion of the pre-to-post surgery comparisons. Section 7.3 is a general discussion that considers the development and use of the EST, how the results of this study compare to that of a recent similar study by Reed and Delhorne, 2005 (section 7.3.2), as well as other considerations including limitations of this study (section 7.3.4) and further research possibilities (section 7.3.5).

The final section of this thesis, chapter 8 summarises the conclusions of this study and the clinical implications of these findings.

CHAPTER 2

The Cochlear Implant

2.1 The hearing mechanism

In the auditory system, perceptual quantities such as pitch and loudness usually relate to the properties of the acoustic stimulus, such as frequency and amplitude. This is the case for normally hearing (NH) individuals as well as for users of conventional hearing aids (HAs). However, when the auditory system is electrically stimulated with a cochlear implant (CI), such perceptual quantities are only in part related to the physical properties of the electrical stimulus.

A HA user uses the same pathways and mechanical mechanisms as a NH person to transmit sound from the environment to the brain (refer to Figure 1). The outer ear picks up acoustic pressure waves that are converted to mechanical vibrations by the small bones of the middle ear. In the inner ear (the cochlea), these mechanical vibrations are transmitted to pressure variations within the cochlear fluids, which result in displacement of the basilar membrane in the cochlea (refer to Figure 2). Attached to the basilar membrane are hair cells that are bent according to the membrane's displacement. The bending of the hair cells results in the release of a neurotransmitter that causes the auditory neurons to fire. This allows for information about the acoustic stimulus to be conveyed the brain (Loizou, 1998).

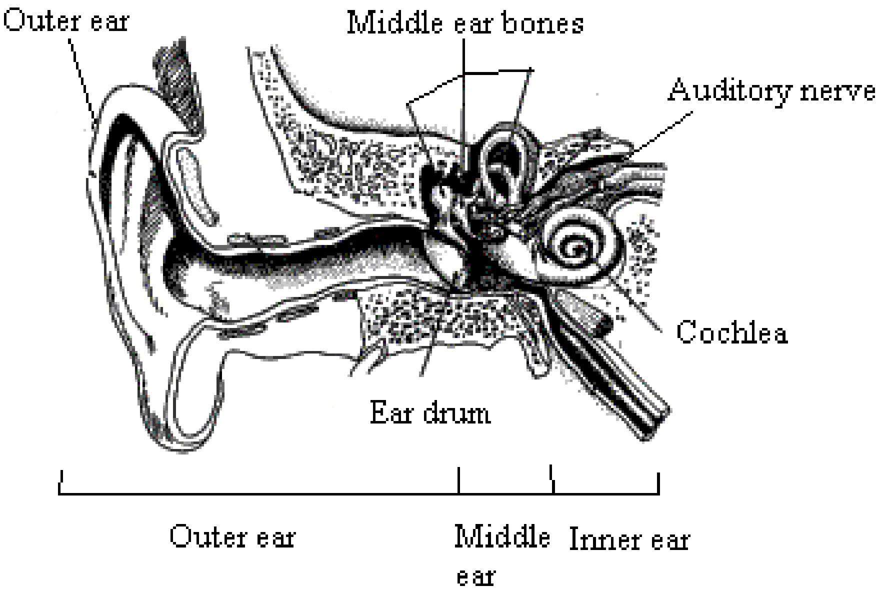

Figure 1: Anatomy of the ear
Cardinal Health. (n.d). *Product manuals - Tympanometry in just seconds.* Adapted.

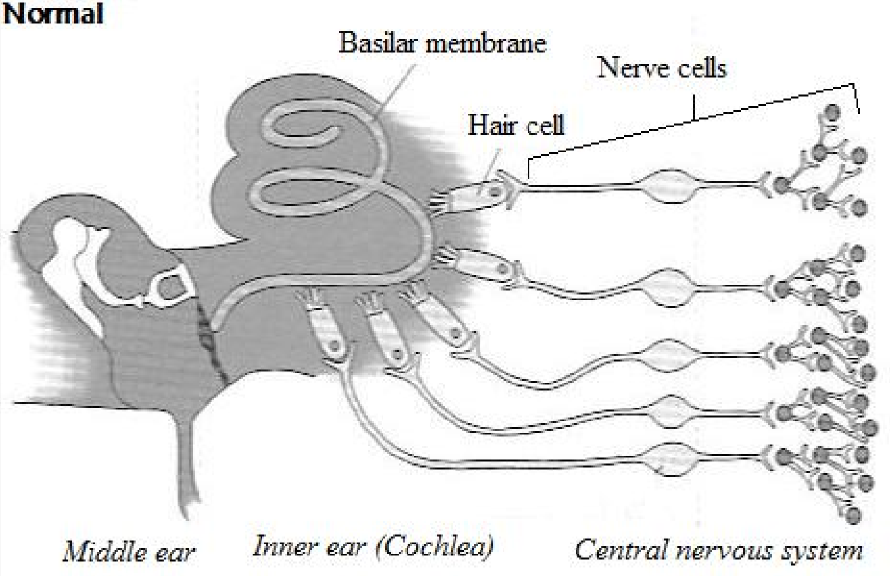

Figure 2: The anatomical structures of the normal ear
Modified from Dorman & Wilson (2004)

Damaged hair cell receptors in the cochlea are a primary cause of sensorineural hearing loss. In individuals with sensorineural hearing loss, the hair cells in the cochlear are damaged or fewer in number (refer to Figure 3).

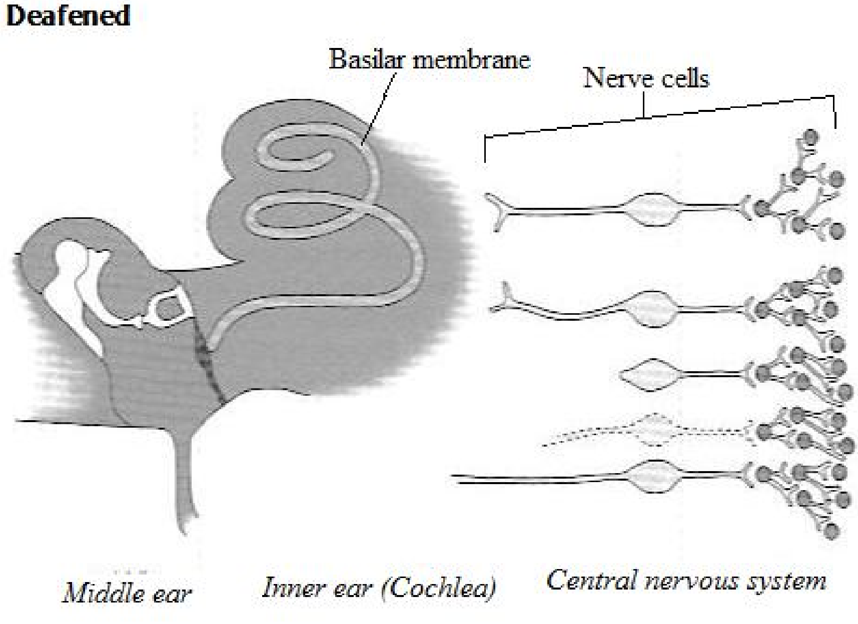

Figure 3: The anatomical structures in an ear with sensorineural hearing loss.
Note the absence of sensory hair cells and the reduced nerve cell survival in the deafened ear.
Modified from Dorman & Wilson (2004)

An audiogram is a graph that is used to show the extent of a person's hearing loss. The level at which they can first hear a sound is plotted against the frequency of that sound. A hearing loss can be described as mild, moderate, moderately-severe, severe or profound (figure 4). A sensorineural hearing loss usually results in thresholds which are worse at the higher frequencies than for lower frequencies. When a sensorineural hearing loss becomes so severe that amplified speech via a HA is no longer effective, a CI is often considered. CIs are usually considered to be a rehabilitative measure for those with severe-to-profound hearing losses.

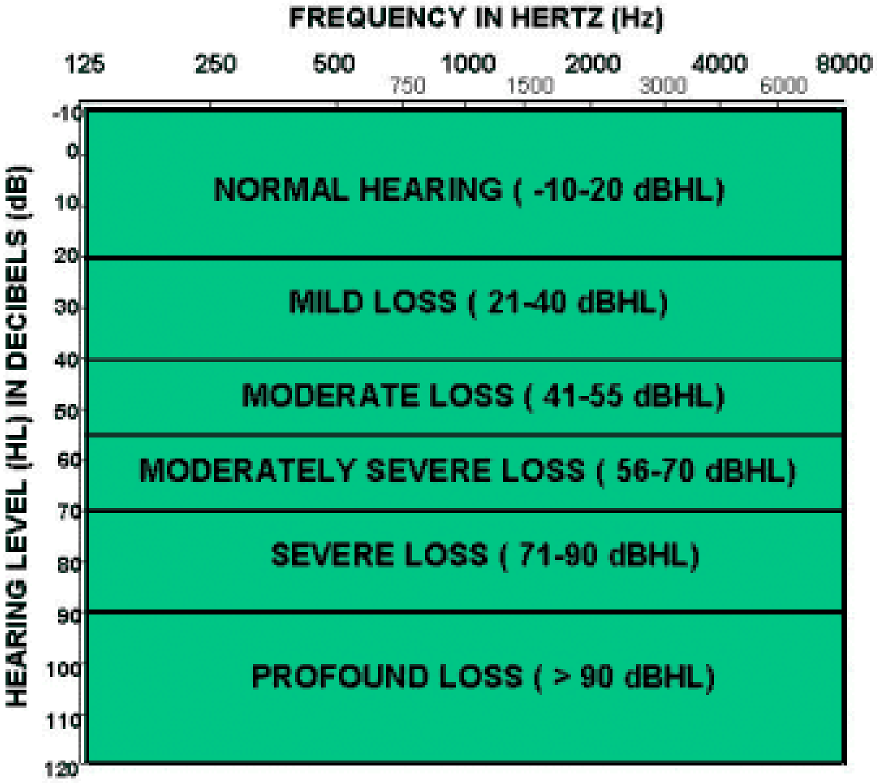

Figure 4: Audiogram showing boundaries used to describe different hearing levels

2.2 Cochlear Implant design

A CI is an electronic device that aims to restore hearing to a person who is profoundly deaf or severely hard of hearing. Unlike HAs, the CI does not amplify sound, but works by directly stimulating any functioning auditory nerves inside the cochlea with electrical impulses. The electrodes are placed inside the cochlea and bypass the damaged or missing hair cells which would usually code sound, and stimulate the auditory nerve directly. Electrical currents from the implant then initiate action potentials in the auditory nerve, which travel to the brain.

A CI has internal and external components. The external components include a microphone, a speech processor, connecting cables, and a transmitting coil (refer to figures 5 and 6). The microphone detects the sound signal which is sent to the speech processor. The speech processor creates a set of coded electrical stimuli that represent the frequency and temporal content of the input sound. This information is then sent to the transmitter located on the outside of the implant user’s head which is aligned with the internal receiving coil by magnets. The signal is then delivered via transcutaneous transmission (i.e. delivered across intact skin using a radio frequency link) to the internal components of the CI (Zwolan, 2002).

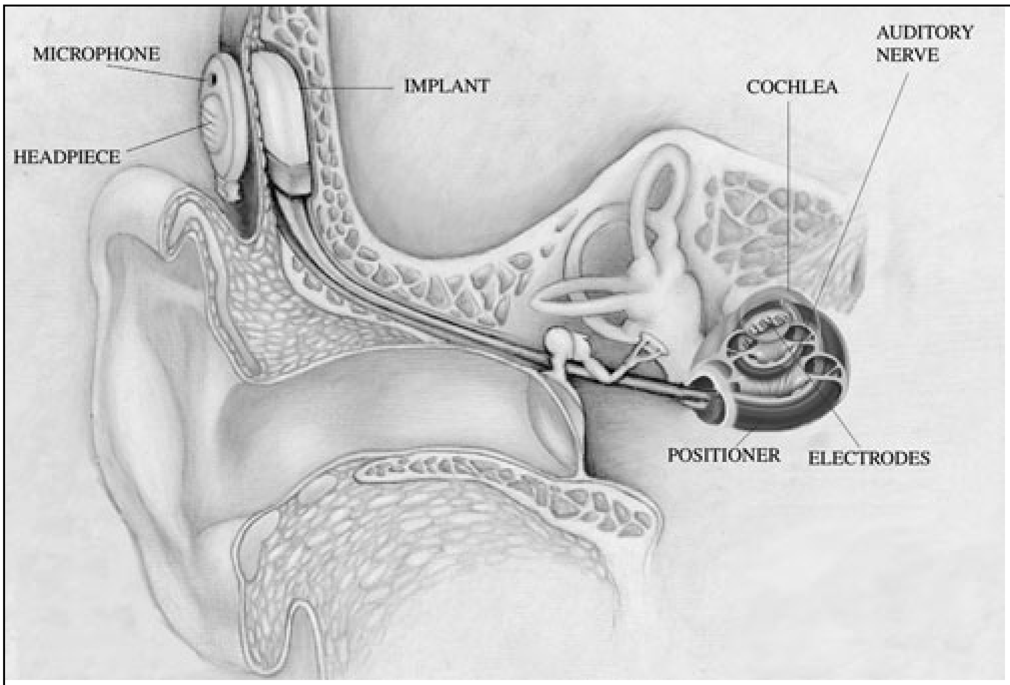

Figure 5: Placement of a Cochlear Implant

Sound picked up by the microphone is converted to an electrical signal that is sent to the speech processor. Both of these components are located in the head piece behind the ear. The speech processor converts the signal into an electrical code. The coded signal is then transmitted via a radio-frequency link to the internal part of the device beneath the skin (labeled 'implant' in the above diagram) called a receiver-stimulator (RS) package. The RS package decodes the signal and uses it to activate the electrodes in the cochlea, which then stimulate the auditory nerve creating the perception of sound.

RAND Health. (2002). Research highlights – low levels of insurance impede access to cochlear implants – how a cochlear implant works.

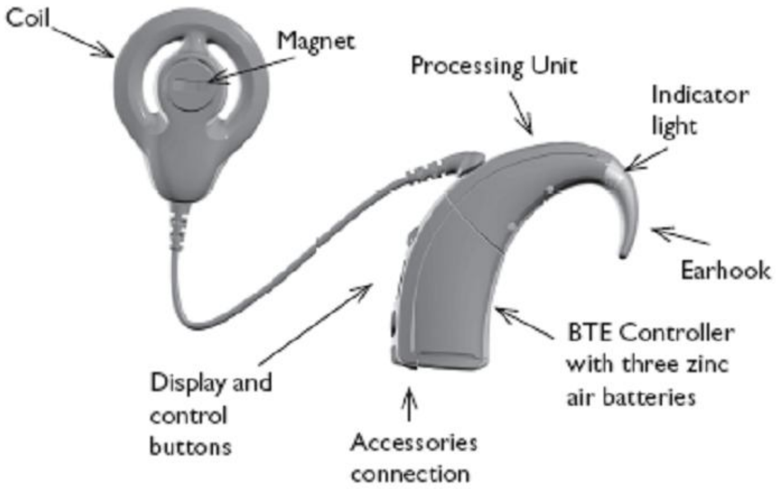

Figure 6: The external part of the Cochlear Nucleus Freedom Implant

The behind-the-ear speech processor is shown. This implant also has the option of a body-worn speech processor

BrownBioMed. (n.d.). Understanding the Cochlear implant –Current model information, Fig 1.

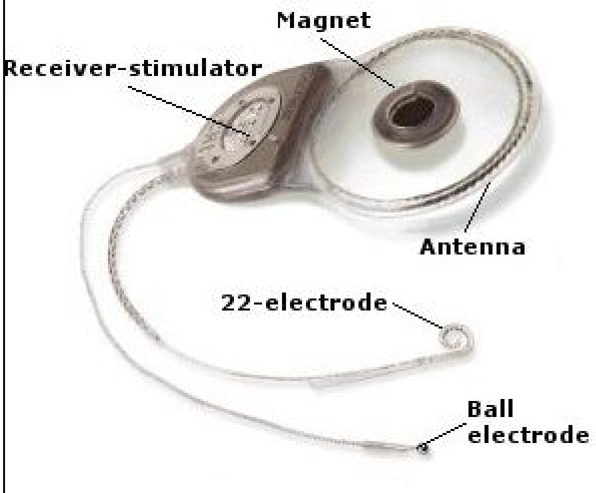

Figure 7: The internal portion of a Cochlear Nucleus Freedom Implant
The Melbourne Hearing Group, The Cochlear implant Clinic. (2004). *What is a Cochlear implant?* Adapted.

The internal components of the implant comprise a receiver-stimulator (RS) package and an electrode array (Figure 7). The RS is implanted in the mastoid bone and comprises a magnet (for attachment of the external headset) and an antenna. For all Nucleus 24 systems, as used by the participants in this study, the RS is encased in titanium. The antenna receives power and information for controlling electrical stimulation from the transmission coil. This information is then used to stimulate the electrodes. The RS controls the electrical current passed to each electrode and the order of stimulation of electrodes based on the information it receives from the speech processor. Most current CIs utilize both extracochlear and intracochlear electrodes. Extracochlear electrodes are located outside the cochlea, such as on the plate of the RS package or under the temporalis muscle (shown as ‘ball electrode’ in figure 7). These extracochlear electrodes are to ground the device for some types of electrical stimulation modes. Intracochlear electrodes are housed along an electrode array which is surgically placed inside the cochlea (shown as ‘22-electrode’ in figure 7). The electrode array extends into the cochlea and the electrical signals transmitted from each electrode stimulate residual auditory nerve fibers. Multichannel CIs, which use multiple intracochlear electrodes, take advantage of the tonotopic organization of the cochlea. “Tonotopic organization” refers to the frequency-to-place mapping of the basilar membrane in the cochlea (refer to figure 8). In a normal ear, sound vibrations in the ear lead to resonant vibrations of the basilar membrane inside the cochlea. The higher the frequency (pitch) of the sound, the less distance it travels along the membrane. In the NH cochlea, hair cells along the length of the basilar membrane are excited by the membrane movement and cause firing of the surrounding nerve cells.

The brain interprets the nerve activity to determine which area of the basilar membrane is resonating, and therefore which sound is being heard.

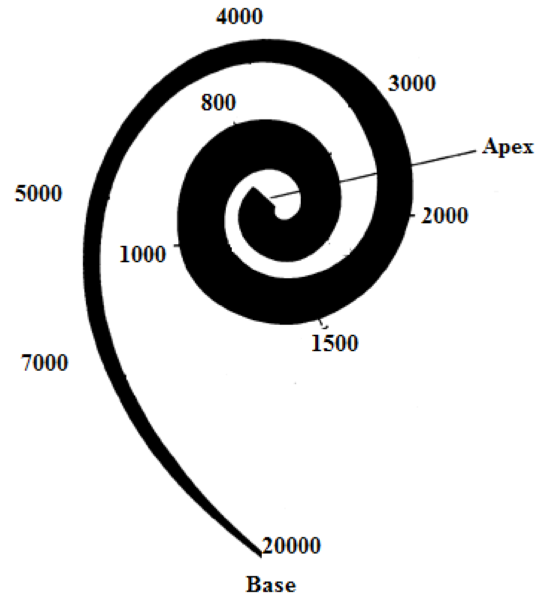

Figure 8: Diagram showing the tonotopicity of the cochlea.
The numbers represent the approximate frequency that causes excitation of that particular part of the basilar membrane.
Cullen, K. (n.d.). *Special Senses.* Adapted.

Although there are several different CI manufacturers, all participants in this study used Cochlear Ltd implants. Their current device is the Freedom implant system which incorporates the Nucleus CI24 implant, as well as the Freedom behind-the-ear, or the Freedom body-worn speech processor (refer to figures 6 and 7). The Nucleus CI24 implant has 22 intracochlear, and 2 extracochlear electrodes, that enables up to 22 channels of stimulation. The Contour array, used by participants for this thesis, is pre-curved, designed to hug the modiolus (the central conical bony pillar of the cochlea). It is thought that this will provide improved sound quality, speech recognition and power efficiency. For patients whom the contour array is contra-indicated there is an option of a Straight array which sits near the lateral (outside) wall of the cochlea.

The benefit provided by a CI depends on both patient-related and device-related factors. Patient-related factors include the cochlea's integrity, the patient's pattern of nerve survival in the implanted cochlea and the condition of the patient's central auditory system (Wilson, 2004; 2006). Device-related factors include the type of electrode array used, its position with respect to the surviving neurons, the mode of stimulation and particularly the speech processing strategy implemented in the processor.

2.3 Speech Processing Strategies

A CI Speech processing strategy (SPS) determines how information about the original speech signal is encoded into electrical pulses that stimulate the auditory nerve. This involves the encoding of information in both a place code (i.e., which electrodes will be activated in which order) and a temporal code (i.e., the rate and amplitude of the stimulation pulses). CI SPSs filter incoming sound using a filter bank, with one filter usually allocated to each electrode of the implant (refer to figure 9). The amplitude of the envelope of the stimuli at the output of the filter bank is used to determine the amount of stimulation applied to each electrode. Amplitude compression is used to ensure that the relatively wide dynamic range of the signal is compressed onto the narrow dynamic range of electrically evoked hearing (Wilson, 2004; 2006). That is, that stimulation remains within an individual patient's 'most comfortable' (C-levels) and 'threshold' (T-levels) (Loizou, 1998). The electrodes are then stimulated sequentially with current pulses using a fixed rate of stimulation. Thus the place information is conveyed by which electrode is stimulated and envelope temporal information is provided by the pattern of stimulation across electrodes, and the amplitude of each electrical pulse. Theoretically, high stimulation rates provide more temporal information and more channels available for stimulation provide more spectral information. Whether all of this extra information is conveyed to and/ or perceived by the CI user is a separate matter, and varies from one individual to the next. Cochlear implant technology is limited in the amount of channels that can be provided in the limited space within the cochlea without interference. This means that the spectral information provided by the CI is comparatively crude, and not nearly as detailed or refined as that provided by the normal hearing mechanism.

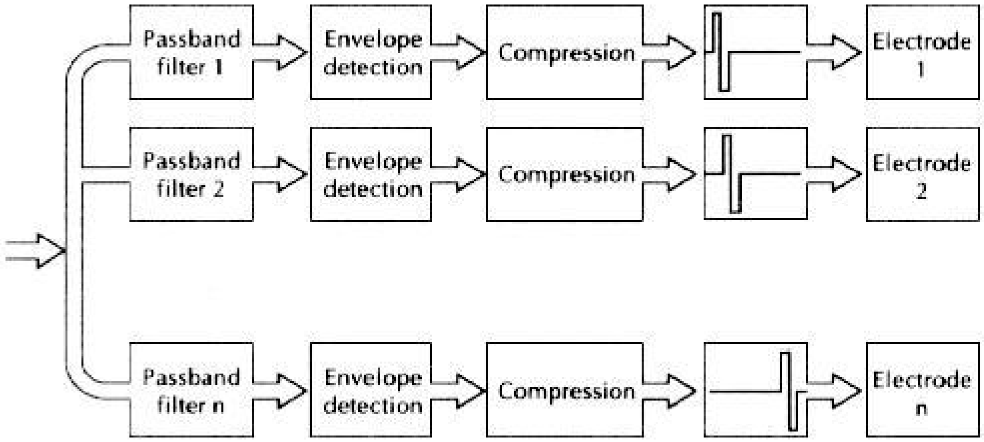

Figure 9: Diagram showing Filter Bank speech processing
From Montandon (1995)

The Nucleus Freedom system allows the implementation of 3 SPS – the CIS, SPEAK, and ACE strategies. The ACE strategy was used by all of the CI users in this research. The ACE strategy is based on some of the concepts of the CIS and SPEAK strategies.

The CIS strategy was developed by researchers at the Research Triangle Institute (Wilson et al., 1991). The primary purpose of this strategy was to represent the timing characteristics of speech. This was achieved by stimulating a fixed number of channels (e.g. six) at a high stimulation rate (e.g. 14400 Hz). The rationale behind this was that higher rates are more accurately represent the response of the normal auditory system (Wilson, Finley, Lawson, & Zerbi, 1997).

The SPEAK strategy was originally described by Skinner et al. (1994). SPEAK aims to provide the listener with the spectral information that is important for speech understanding by utilizing more channels of stimulation than CIS, but at lower stimulation rates. The filter band envelopes with the greatest amplitude in each cycle of stimulation are selected. These are known as ‘maxima’ (refer to figure 10). With each filter band corresponding to a different stimulation channel, only the stimulation channels corresponding to the maxima are stimulated in each cycle. However, the actual channels stimulated change in each stimulation cycle. For example, whereas CIS would stimulate all available channels (e.g. 6) in each cycle, SPEAK would select the maxima from a large number of channels (e.g. 22). Thus, only the channels with the most acoustic energy are stimulated. This theoretically should enhance the perception of consonants and other spectral details (Moore & Teagle, 2002).

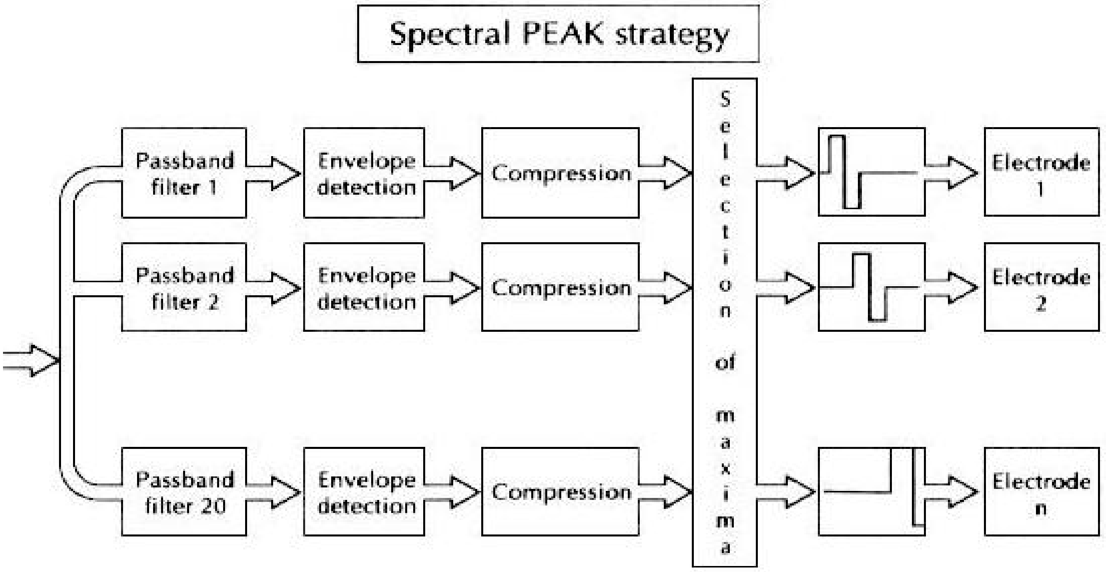

Figure 10: Diagram of SPEAK processing
From (Montandon, 1995)

SPEAK was the precursor to the ACE strategy, which is currently used by most Nucleus device recipients. The ACE strategy was originally described by Vandali et al. (2000). This strategy combines the timing and spectral advantages of the SPEAK and CIS strategies. Like SPEAK, ACE selects the largest filter band envelopes (maxima) from 22 possible channels, and stimulates the corresponding channel. The number of maxima selected for each cycle of stimulation is constant and depends on the value specified in the speech processor program. Usually there are between 6 and 16 maxima (Wilson, 2004; 2006). Similar to CIS, the stimulation rate is relatively high compared to SPEAK with the default switch-on SPS for the Nucleus CI24 device being ACE at a rate of 900 pulses per second per channel.

2.4 Assessment and selection criteria

Previously, cochlear implantation was reserved for those with profound losses who received no benefit from HAs. With the improvement of implant technology and improved outcomes of CI users, selection criteria have expanded to include those with more residual hearing. Expansion of the selection criteria affects the risk-to-benefit ratio for the patient as there is a significant possibility that they could lose their residual hearing in the implanted ear.

A recent study by Dowell et al. (2003) retrospectively analysed speech perception data of postlingually deafened adults to determine the selection criteria that would provide a candidate with a 75% chance of obtaining better speech perception scores following implantation. They determined that pre-implant speech performance could be as good as 70% in the best-aided condition, and up to 40% in the ear to be implanted for open-set sentence stimuli. That is, using that criterion, 75% of adult CI recipients in their study obtained post-implant speech scores higher than their pre-implant scores.

The general audiometric selection criteria for the SCIP in New Zealand for adults is having pure-tone thresholds of greater than 90 dB HL at 1 kHz and above, as well as aided auditory-alone sentence perception scores of less than 40% in the poorer ear and less than 60% in the better ear. Often a binaural score of less than 50% is taken to be adequate for implantation. It is also important that HAs have been optimized for the candidate prior to assessment for cochlear implantation to ensure that the best HA outcomes have been exhausted. In addition to audiologic criteria, medical (e.g. general health for surgery and suitable anatomy as deduced from cochlear imaging), psychological (e.g. psychological issues and reasonability of expectations), and social factors (e.g. level of social support) are also assessed.

CHAPTER 3

Literature Review

3.1 Speech perception and the cochlear implant

Many patients with severe-to-profound sensorineural hearing losses receive little auditory-alone open-set speech recognition from their HAs. In contrast, most patients with these levels of hearing loss can attain significant open-set speech recognition with a CI.

A study by Flynn et al. (1998) described the performance of a group of 34 adult HA users with a severe, or a severe-to-profound hearing impairment, on a range of speech recognition measures. Comparisons were made between this group of participants and the participants from another study by Skinner et al. Skinner et al. (1994) which used a similar design and speech perception materials. The study by Skinner et al. (1994) included a group of 63 adult participants who used the Nucleus-22 CI. For both studies, speech recognition measures included the CNC (Consonant-Nucleus-Consonant) word test (described in more detail later on in the methodology section) (Lehiste & Peterson, 1959) and the CUNY (City University of New York) sentence test (Boothroyd, Hanin, & Hnath, 1985). The CUNY sentence lists comprised 12 sentences and were scored as the number of words correct out of 102 words per list. A percentage-correct score was obtained. The Analysis of Variance showed that the CI users in Skinner et al.'s (1994) study recognized word stimuli significantly poorer than adults with severe hearing losses in Flynn et al.'s (1998) study ($p < 0.001$), but that there were no significant differences when the CI users were compared with the adults with severe-to-profound hearing losses using hearing aids. ($p = 0.34$). For the open-set sentence stimuli there were no significant differences found between the CI users and adults with severe hearing losses in quiet ($p = 0.707$) or in background noise ($p = 0.287$). However, the CI users were significantly better than the adults with severe-to-profound losses for sentences in quiet ($p<0.0001$) and in noise ($p<0.0001$). Therefore according to Flynn et al. (1998), word perception with a CI was equivalent to that of HA users with severe-to-profound losses while sentence perception was equivalent to that of HA users with severe hearing losses.

A study by Proops et al. (1999) investigated the outcomes of the first 100 postlingually deafened adults implanted under the Midland CI Programme. Sentence perception in a quiet, audition-only listening condition gave percentage-correct scores of 0%-100% (mean = 47%, SD =36) at 9 months post-implantation, and from 0%-94% (mean = 43%, SD = 35.2) at 18 months post-implantation. These findings suggested that speech recognition scores are relatively stable from 9 months post-implantation.

Open-set speech recognition is detrimentally affected by background noise. A study by Hamzavi et al. (2001) compared 22 postlingually deafened adults implanted with the Med-El Combi 40/40+ implant to 15 HA users with severe-to-profound sensorineural hearing losses in their ability to recognise speech in quiet and in noise. Patients were tested using the Hochmaier, Schultz, and Moser Speech Discrimination Test (Hochmair-Desoyer, Schulz, Moser & Schmidt, 1997). This test is composed of 30 lists with 20 sentences each. Patients with HAs were tested once after 3 years of HA use. CI users were assessed three times, after 1, 2 and 3 years of CI use. Statistical analysis revealed that CI users from 2 years post-implant had significantly better speech recognition in both quiet and noise compared with the HA users who had 3 years of experience with their device ($p = 0.03$ for 2 years post-implant, and $p = 0.003$ for 3 years post-implant). This study suggests that the sentence perception benefits obtained from a CI exceed that of a HA in the medium to long-term.

A study by Tye-Murray, Tyler, Woodworth, & Gantz (1992) investigated whether the speech recognition of 24 postlingually deafened CI users varied over time since switch-on of their CI. Participants were assessed at 1, 9, and 18 months post switch-on. Sentence perception scores from a sentence perception test and a word perception test presented in a quiet auditory-alone condition, were averaged to provide a composite speech perception score. Composite word scores (n = 22) ranged from 0%-51% (mean = 17%) at 1 month post-implantation, 0%-71% (mean = 27%) at 9 months post–implantation, and 0%-76% (mean = 31%) at 18 months post-implantation. Testing in noise (SNR = 10dB) was also performed. Percent-correct scores (n = 24) ranged from 5%-95% (mean = 60%) at 1 month, 20%-95% (mean = 80%) at 9 months, and 30%-100% (mean = 85%) at 18 months post-implantation. These results suggested that, on average, the CI users in this study improved in their speech perception ability over the 18 months post-implantation.

The results of these studies show that most postlingually deafened adults with severe-to-profound hearing losses can obtain significantly greater open-set sentence perception in quiet than individuals with a similar loss with HAs. They also suggest that improvement in speech perception abilities in CI users' plateaus between 9 and 18 months post switch-on.

3.2 Environmental sound perception and the cochlear implant

Although the CI is largely meeting its aim of enabling open-set speech perception for most postlingually deafened CI users, factors other than speech perception contribute to the outcomes and benefit a patient can obtain from their CI, and the impact of implantation on their quality of life. Surveys of the attitudes of CI recipients indicate that the reception of environmental sounds (e.g. nature sounds or warning signals) is another major benefit they obtain from a CI (Tyler & Kelsay, 1990; Zhao, Stephens, Sim, & Meredith, 1997). For example, for many patients, among the first things they report noticing after their processor is switched on are background sounds like running water and computers humming (Tyler & Lowder, 1992). Current research into the environmental sound perception of CI users is summarised in table 1.

Zhao et al., (1997), administered a benefits/problems questionnaire for 26 patients with a CI at 9 months post-implantation. They found that environmental sound awareness was reported by the respondents as the main benefit they obtained from a CI (77%), followed by general ease of conversation (62%). In a study by Tyler & Kelsay (1990) involving 53 high-performing CI users, participants were asked to list the advantages they perceived from their CI, in order of importance. The main reported advantages of cochlear implantation were improved speech and environmental sound perception. The authors subsequently discussed how these benefits might then affect quality of life. For example, participants reported feeling safer and more at ease in their environment. Tyler & Kelsay (1990) suggested this might have been a result of increased environmental predictability due to the ability to perceive sounds around them.

Several other studies have included closed-set tests of environmental sound perception in their test battery (Proops et al., 1999; Reed & Delhorne, 2005; Tye-Murray, Tyler, Woodworth, & Gantz, 1992; Tyler & Lowder, 1992). Reed & Delhorne (2005) measured the closed-set environmental sound perception performance of 11 postlingually deafened adult CI patients. The test they designed used environmental sounds excerpts classified into four groups – General Home, Kitchen, Office, and Outside. Each group had 10 environmental sounds, with each sound being presented 3 times. A different token was used for each of these 3 presentations. A 10-alternative, forced-choice procedure was used. The mean percentage-correct scores across participants ranged from 45% – 94% (mean= 79.2%) correct across the four groups of sounds.

The study by Proops et al. (1999) discussed earlier with regard to speech perception also included an open-set test of environmental sound recognition. The test consisted of 20 sounds presented a single time at 70 dB(A) in the sound-field. Participants were asked to report what they thought the sound was. Responses were scored as completely correct (1 point), partially correct (1/2 a point) or incorrect/ omitted (0 points). The mean percentage-correct score for this test in the implant-only mode was 57% at both 9 and 18 months post-implantation suggesting that environmental sound recognition scores were relatively stable from 9 months post-implant. The study by Tye-Murray et al. (1992) included both speech and environmental sounds tests. The Iowa Environmental Sounds Test was administered to 21 postlingually deafened CI users, at 1, 9 and 18 months post switch-on.

Table 1: Existing environmental sound research for cochlear implant users

Reference	Details of the environmental sounds test	Participant details	Results
Mo et al. (2004)	Questionnaire: The Performance Inventory for Profound and Severe Loss – Environmental sounds category of the questionnaire - ability to identify familiar sounds when the source cannot be seen.	75 Postlingually deafened monaural CI users (Nucleus, Ineraid, Med-El implants) 59 HA users (PTA > 60 dB HL).	CI users mean score on environmental sounds category was not significantly different to that of HA users.
Proops et al. (1999)	20 pre-recorded common environmental sounds. Open-set. Presented at 70 dB(A) in the sound field. Scoring: correct (1 pt), partially correct (1/2 pt), incorrect/omitted (0 pt). Summed and expressed as a percentage.	100 Postlingually deafened monaural CI users (3x Nucleus 20 + 2 device, 1x Med-El single channel device, remainder Nucleus 22 device).	Mean score at 9 months post-implant was 56.7% (range: 7.5%-95%). This result was not significantly different at 18 months post-implant.
Reed & Delhorne (2005)	Closed-set of 10 sounds (of 3 tokens each) in each of four different settings (general home, kitchen, office, and outside).	11 monaural CI users (9 Ineraid devices & 2 Clarion Advanced Bionics devices). All used CIS speech processing strategy. 10 postlingually deafened.	Mean scores ranged from 45.3%-93.8% (mean = 79.2%) correct. Performance was roughly related to NU-6 word recognition ability. Signals with distinct temporal envelope characteristics were easily perceived by all participants, and confused items tended to share similar overall durations and temporal envelopes.
Tye-Murray et al. (1992)	Iowa Environmental Sounds Test: 2 lists of 18 sounds (closed–set for each list). Presented in the sound field at 73 dB SPL at the participants ear.	11 Nucleus (F0F1F2 speech processing strategy) & 10 Ineraid Postlingually deafened monaural CI users tested at 1, 9 & 18 mo.	Environmental sound recognition improved gradually; significant improvement from the 1 month scores (mean=30%, range=11-64%) was not noted until 18 months (mean=37%, range=19-88%).
Tyler & Lowder (1992)	Iowa Environmental Sounds Test: 2 lists of 18 sounds (closed–set for each list). Presented at 65 dB SPL.	65 postlingually deafened monaural users (10x House single-channel device, 30x Nucleus 22 device, 25x Ineraid 4 channel device). Range of strategies	House device (mean=24%, range=3-41%), Nucleus device (mean=35%, range=5-69%), Ineraid device (mean=47%, range-8-86%).
Tyler & Kelsay (1990)	Questionnaire: asked to list advantages & disadvantages of their implant in order of importance.	53 good monaural CI performers :5x Chorimac device, 9x 3M Vienna device, 19x Nucleus device, 10x Duren/ Cologne device, 10x Symbion device.	‘Environmental sound perception’ was rated as the 2nd most reported advantage (75%) secondary to ‘speech perception with speech reading’ (85%). ‘Environmental sound perception’ was also rated as the 2nd most reported disadvantage (47%) secondary to ‘use of equipment’ (79%).
Zhao et al. (1997)	‘The Open Ended Hearing Questionnaire’ (Barcham & Stephens, 1980) – lists difficulties in order of importance. ‘The benefits/ problems questionnaire for patients with a cochlear implant’ (Stephens & Meredith, 1991) – lists benefits and shortcomings of device in order of importance.	13 postlingually deafened monaural CI users	‘Environmental sound awareness’ listed as a difficulty by 71% of respondents. ‘Environmental sound awareness’ most-common benefit reported (77%) followed by ‘general conversation easier’ (62%).

This test consists of two different lists of 18 sounds presented in a closed-set format. Both lists were presented consecutively at each test session. Mean scores across both lists were 30% at 1 month, 35% at 9 months, and 37% at 18 months post-implantation. On average, environmental sound recognition improved gradually over the 18 month period. There was a significant difference between the 1 and 18 month scores. The possibility that scores improved due to the learning effect was not investigated in either the Tye-Murray et al. (1992) or the Proops et al. (1999) study.

Overall the results of these studies indicate the importance of environmental sound perception and the ability of the current generation of CI's to provide significant environmental sound perception for the implantee.

3.3 Quality of life outcomes

In addition to speech and environmental sound perception, the benefits of cochlear implantation can be considered holistically by looking at the overall benefit to quality of life that is obtained. A recent study by Damen et al. (Damen, Beynon, Krabbe, Mulder, & Mylanus, 2007) followed up 59 postlingually deafened participants from a previous study by Hinderink et al. (Hinderink, Krabbe, & Van Den Broek, 2000). Three health-related quality-of-life assessments were used to obtain data for both studies. Quality-of-life benefits of cochlear implantation were seen in the areas of sound perception, speech production, self-esteem, activity, social interactions, hearing, emotions and mental health, and these benefits were maintained over a period of 6 years.

Other studies that have looked at the effect of cochlear implantation on quality of life include Knutson et al (Knutson et al., 1991) and Spitzer et al. (Spitzer, Kessler, & Bromberg, 1992) who both reported positive outcomes in the areas of depression and anxiety. Faber and Grontved (Faber & Grontved, 2000) reported improved scores on the indices for communication and family functioning, with Binzer (Binzer, 2000) reporting significant improvements in the 'personal adjustment scale' of the Communication Profile for the Hearing Impaired after three months of implant use. The participants in a study by Tyler and Kelsay (1990) reported feeling more comfortable in social situations, which the authors suggested could have been due to improved speech perception, and consequently improved communication.

These studies show that the more specific benefits of cochlear implantation such as improved speech and environmental sound perception carry over to more general quality of life measures.

3.4 Chapter summary

The main aim of cochlear implantation is to provide significantly better speech perception for those with severe-to-profound hearing losses, compared with what they can achieve with HAs. These studies show that this aim is largely being achieved. However, these studies also indicate that factors other than speech perception contribute to the improved quality of life reported by CI users. The importance of environmental sound perception for CI users is highlighted. This summary of the literature also highlights the lack of a standardized environmental sound assessment measure and the paucity of environmental sound research that compares the performance of CI users to both NH participants and HA users.

CHAPTER 4

Overview of the current study

4.1 Rationale

A review of the literature as covered in chapter 3 identified several areas related to CI outcomes for postlingually deafened adults which are still inadequately addressed. Firstly, there is little published research assessing the ability of CI users to identify environmental sounds, which is, as discussed in chapter 3, an important skill which impacts on quality of life for the CI user.

Secondly, existing environmental sound perception studies have involved either subjective responses via surveys (Tyler & Kelsay, 1990; Zhao, Stephens, Sim, & Meredith, 1997) or environmental sounds tests involving experienced CI users (Reed & Delhorne, 2005; Tyler & Lowder, 1992). There has been no attempt to compare the performance of CI users with that of other populations, in particular normal hearing listeners.

Thirdly, the environmental sounds tests used in previous studies have a number of limitations. Most of the previous environmental sounds tests have been closed-set tests with small set sizes. The largest closed set test is the Iowa environmental sounds test with 18 sounds per closed-set list. This provides a high chance-performance rate of 6%. The only open-set test developed so far is the test by Proops et al. (1999), incorporating only 20 sounds, and subjective marking criteria of correct, partially correct, or incorrect. In the previous studies CI users were able to achieve close to 100% on the environmental sounds tests. This indicates that ceiling effects may become a problem particularly if comparisons with other groups such as normal hearing participants are to be made. Another potential advantage to the development of a new environmental sounds test as part of this project is that it may be useful in the clinical setting for pre- and/or post- implantation assessments.

Fourthly, there is no published research investigating the ability of newly-implanted recipients to identify environmental sounds, nor any research comparing the same subject pre-to-post surgery on such tests. The current study adds to knowledge about the changes in auditory perceptual skills (such as those required to identify environmental sounds) pre- to post-surgery.

In addition, there is currently no published research of pre-to-post CI surgery speech perception outcomes for patients from New Zealand. The only comparable research has been of speech perception outcomes from international clinical programs such as ‘The Nucleus Freedom North American clinical trial’ (Balkany et al., 2007), ‘The Cochlear Implant Clinic of the Royal Victorian

Eye and Ear Hospital' in Melbourne Australia (Dowell, Hollow, & Winton, 2003; Flynn, Dowell, & Clark, 1998); 'The Midland Cochlear Implant Programme' in the UK (Proops et al., 1999); 'The Vienna Cochlear Implant Programme' in Austria (Hamzavi, Franz, Baumgartner, & Gstoettner, 2001); 'The University of Iowa CI Program' in the US (Tyler, Parkinson, Woodworth, Lowder, & Gantz, 1997); and 'The CI centre' in Nijmegen in the Netherlands (van Dijk et al., 1999). This current study provides results for adult CI recipients from the Southern Cochlear Implant Programme (SCIP), New Zealand, for the perception of speech in both quiet and noise. These results will give clinicians baseline data from which future outcomes, and the rate of development of speech perceptual skills post-implantation, can be predicted.

The results of this study, in combination with results from further studies, may also have implications for the current implantation criteria in NZ. Implantation criteria are derived by looking at how levels of pre-operative HA performance compare to the post-operative performance of a large group of CI users (Dowell, Hollow, & Winton, 2003). Implantation should be considered if there is a high probability that post-operative outcomes will exceed pre-operative levels of performance. Comparison of an individual's performance with HAs to the post-operative performance of a large group of CI users can be used to determine the likelihood of the individual obtaining benefit from a CI (Tyler & Lowder, 1992). Collecting pre- and post- implantation data allows for future adaptation of the existing CI criteria in New Zealand, based on the outcomes obtained by current CI recipients.

Changes to the implantation criteria would affect any adults with a significant hearing impairment considering a CI. The results may be used to lobby the Government for increased funding for the CI program, in view of the improved post-surgery outcomes for speech perception, and improved quality of life that a CI potentially provides to most recipients. Currently there is a long waiting list for adults in New Zealand to receive a CI. Many more adults may be able to benefit from a CI but are unable to be considered due to the lack of Government funding. Increased Government funding would mean that more adults with a significant hearing loss might be able to obtain improved speech perception, socialisation and quality of life that the CI has been shown to provide to most recipients.

4.2 Aims and hypotheses

The main aims of this study were to develop an environmental sounds test (EST) to investigate the effect of cochlear implantation on environmental sound perception in postlingually deafened adults with a moderately-severe to profound hearing loss, and to then compare their performance with that of normal hearing listeners. To achieve this aim NH participants and experienced CI users were assessed using the developed EST.

A secondary aim was to look at the early benefit of cochlear implantation on speech and environmental sound perception, by assessing participants with hearing aids prior to CI surgery, and then following up these same participants 3 months post switch-on of their CI. To achieve this, hearing thresholds, as well as scores on speech and the EST were obtained for participants' pre- and post- CI surgery.

It was hypothesised that: (i) the NH participants would score higher than the experienced CI users on the EST; (ii) for the pre-to-post CI group, scores on the EST would be higher post-surgery than pre-surgery, and (iii) for the pre-to-post surgery group, scores on speech perception tests would be higher post-surgery than pre-surgery.

CHAPTER 5

Methods

Ethical approval for this study was obtained from The University of Canterbury Human Research Ethics Committee and from the Upper South Health and Disability Ethics Committee. All procedures were undertaken in accordance with this approval.

5.1 *Participants:*

In order to address the hypotheses mentioned in the previous chapter, three groups of participants were recruited for this study:

1) Experienced CI group: 10 postlingually-deafened adult CI users
    a. Age (years): Range: 29-77, mean = 57.6, SD = 16.4
    b. Experience with CI (months): Range:10-58, mean = 27.3, SD = 13.5
    (More detail about this group is provided in table 2)

2) Pre-to-post CI group: 4 postlingually deafened adult HA users who subsequently received a CI in 2007 through the Southern Cochlear Implant Program.
    Age (years): Range: 43-66, mean = 54.8
    (More detail about this group is provided in table 3)

All CI users in this study used Cochlear Ltd. devices – either the ‘Nucleus’ C124R, or the C124RE implant, with either the Esprit 3G or the Freedom speech processor. All participants used the ACE speech processing strategy with a stimulation rate of either 900 or 1200 Hz.

It should be noted that the exact onset of a person's hearing loss is often hard to define. Therefore the term postlingually deafened has been used to indicate adults who developed normal speech and language skills prior to having a significant hearing loss.

3) Normal-Hearing (NH) group: 24 adults with hearing thresholds $\leq$ 25 dB HL in the speech frequency range (250 Hz - 4000 Hz)
    Age (years): Range: 23-72, mean = 47.0, SD = 16.6
    There was no significant difference ($p > 0.05$) between the age of the NH and Experienced CI users (t-test) (more detail about this group is provided in table 4).

Table 2: Descriptive statistics for the Experienced CI group

Participant	Sex	Age	Duration of hearing loss pre-CI (years)	Ear with CI	LFA non-implanted ear (dB HL) *	Time since switch on (months)	Type of CI	CI speech processing strategy	Speech perception score post-CI			
									HINT quiet	**HINT noise**	**CNC words**	**CNC phonemes**
1	M	77	77	R	100	22	Freedom C124RE(CA)	ACE 1200 Hz/channel	100	83	75	86
2	F	74	42	R	55	23	Freedom C124RE(CA)	ACE 1200 Hz/channel	77.35	20.03	40	63.33
3	M	58	38	L	82.5	29	Esprit 3G C124R(CA)	ACE 900 Hz/channel	43.1	0	3.5	35.65
4	F	71	22	R	77	10	Freedom C124RE(CA)	ACE 900 Hz/channel	98	74	77	89.5
5	F	46	44	L	98.5	25	Esprit 3G C124R(CA)	ACE1200 Hz/channel	46.2	19.6	18	43
6	F	45	45	R	93.5	29	Esprit 3G C124R(CA)	ACE 900 Hz/channel	78.4	38.5	29	58.3
7	F	67	67	L	120	11	Freedom C124RE(CA)	ACE 1200 Hz/channel	96.2	83.7	63	82.3
8	F	29	15	R	77.5	36	Esprit 3G C124R(CA)	ACE 900 Hz/channel	96	84	80.5	90.5
9	F	68	48	R	105.5	30	Esprit 3G C124R(CA)	ACE 900 Hz/channel	100	53	64	86
10	F	41	26	R	66	58	Esprit 3G C124R(CA)	ACE 900 Hz/channel	100	#	#	#
Mean		57.6	42.4		87.5	27.3			83.5	50.7	50	70.5

**The low frequency average (LFA) was obtained from the mean of the 250 and 500 Hz thresholds in the non-implanted ear. This was calculated to represent the amount of residual hearing remaining in the non-implanted ear of each participant. These frequencies were chosen as CI candidates would be expected to have severe-to-profound hearing losses at 1 kHz and above.*

#Most Speech perception data was unable to be obtained for participant 10 as the nature of her job meant that she knew the speech materials off by heart.

Table 3: Descriptive statistics for the Pre-to-post CI group

Participant	Sex	Age	Duration of hearing loss pre-CI (years)	Time with hearing aids (years)	Hearing aid type	Ear with CI	Type of CI	CI speech processing strategy	Speech perception score (%) pre-CI (with bilateral hearing aids)				Speech perception score (%) post-CI (with unilateral CI –monaural)			
									HINT quiet	HINT noise	CNC words	CNC phonemes	HINT quiet	HINT noise	CNC words	CNC phonemes
1	M	55	15	11	Phonak Sonoforte	R	Freedom C124RE(CA)	ACE 900 Hz/channel	69.5	10	34	56	100	98.5	79	91.5
2	M	55	28	23	Phonak Claro	L	Freedom C124RE(CA)	ACE 900 Hz/channel	4	9	0	0	95	88.5	86	93.5
3	F	43	41.5	41.5	Phonak Perseo	R	Freedom C124RE(CA)	ACE 900 Hz/channel	4	4	1	11.5	39	20.5	9	34
4	M	66	30	12	Phonak Perseo	R	Freedom C124RE(CA)	ACE 900 Hz/channel	69.5	10	8	34	83.5	79.5	52	77
Mean		54.8	28.6	87.5					36.8	8.3	10.8	25.4	79.4	71.8	56.5	74

Table 4: Descriptive statistics for the Normal Hearing group

Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Mean
Sex	M	F	F	F	F	F	M	M	M	F	F	M	F	F	F	F	F	F	F	M	F	F	F	F	
Age	50	45	45	67	48	27	35	30	32	35	23	27	23	24	61	71	72	64	54	57	56	53	66	64	47.0

5.1.1 *Inclusion criteria*

For the experienced CI users the inclusion criteria were that they were over 18 years of age, had had their implant for at least 10 months, were implanted through the SCIP, had no other impairments, and spoke English as their first language.

For the pre-to post CI group, the selection criteria were similar, but without implantation having taken place. Pre-to post CI group participants also needed to be regular HA users, and scheduled to be implanted through the SCIP in 2007, and be part of the SCIP.

NH participants were included if they were over 18 years of age and if they had thresholds less than or equal to 25 dB HL at the octave frequencies between 0.5 and 4 kHz. Normal hearing participants were recruited so that there was no significant difference between the ages of the experienced CI and NH subject groups (t- test).

5.2 *Recruitment of Participants*

Participants for the experienced CI group were recruited via an information sheet and consent form provided to them when they came to the University of Canterbury for participation in another project (Looi et al. 2008). These participants were required to attend two appointments. The total number of experienced CI users that were recruited for this study was 13. Of the 13 participants, 10 returned 3-4 months following the initial appointment for the follow-up session. Of those who did not return, two were from out of town and one participant declined to take part in follow-up testing. Consequently, the results presented in this thesis are those of the 10 who attended both appointments.

Recruitment of the participants for the pre-to-post surgery group was via a mailed-out invitation letter with an information sheet and consent form attached. Letters were sent out to all of the adults on the waiting list to receive a CI through the SCIP in 2007. Patients were asked to post back the consent form to the researchers should they be able to participate in the study. Based on records for the previous years, approximately 15-20 adults received a CI each year through the SCIP. However due to a change-over in program management and the consequent settling-in period, there was some disruption to the program and difficulty with contacting participants pre-surgery. Further, many of the potential participants were from out of town, and stated that they could not make the necessary travel arrangements to participate in this study. Five participants were tested pre-surgery, however one participant's CI failed soon after surgery, and he was subsequently re-implanted several months later. Therefore only the results of the 4 participants, who completed all of the testing, are presented in the results section of this thesis.

NH participants were initially recruited via friends and colleagues, who provided the names and contact details to the researchers. The researchers then contacted the potential participants to provide further information. All participants signed the consent form.

5.3 Materials

5.3.1 The Environmental Sounds Test (EST)

A closed-set test of environmental sound perception was developed for this study. The aim was to develop a more-difficult and comprehensive test than those used in previous research to avoid ceiling effects.

The initial version of the EST included 50 different sounds, with two tokens for each sound (Table 5). The sounds were selected to be representative of stimuli that may be encountered in everyday life. Effort was made to select a variety of sounds, with some easier to identify, or more obvious than others. The test sounds were chosen with consideration given to the frequency that these sounds occur in everyday life. Out of the 50 sounds selected, 28 appear on the list of environmental sounds reported in the ecological frequency survey conducted by Ballas (1993). Twelve of the sounds incorporated into the EST that were not included on Ballas' list, consist of human sounds, speech, music, and general sound environments (e.g. a general office environment). These sounds were not included in the ecological study by Ballas (1993). The other 10 sounds included in this EST were less common, but they either had distinctive or unique acoustic characteristics (e.g. breaking glass), were considered important warning signals (e.g. a fire siren), or were animal sounds or sounds from nature (e.g. a dog barking, or thunder). The sounds chosen for this test were classified into the following groups for later analysis: traffic noise, nature sounds, arriving home, bathroom sounds, kitchen sounds, household appliance sounds, human sounds, office sounds, and other sound (see table 5).

All stimuli were obtained from commercially-available sound databases that were recorded onto compact discs. Phonak, the British Broadcasting Corporation (BBC), and Gateway produced the specific databases used (details of where each sound token came from is listed in table 7). The stimuli for the test were then created using the computer software program 'Adobe Audition'. Each sound type was represented by two separate tokens; that is, the pilot version of test comprised 100

Table 5: The sounds included in the initial Environmental Sounds Test

Arriving Home	Bathroom	Household Appliances	Human	Kitchen	Nature	Office	Traffic	Other
Door bell Door opening/ closing Keys jangling Knock on door	Running water Toilet flushing Water Dripping	Alarm clock Clock ticking Hairdryer Lawnmower Telephone ringing *Vacuum cleaner*	Baby crying Laughter Footsteps Many males & females talking at the same time 1 male & 1 female talking at the same time Single female voice Single male voice Snoring	Doing dishes Food frying *Fridge hum* Whistling kettle	Bird(s) chirping Cat(s) meowing Dog(s) barking *Ocean* *Rain* River/ stream babbling Thunder Wind blowing	Drawers opening and closing Office environment Paper rustling Typing on the computer	Aeroplane Car horn *Car starting* Fire/ ambulance siren Helicopter Traffic on a busy road Train	Breaking glass Construction site Hand saw Classical music Modern music Restaurant

Italicized items were removed for the final version of the test

separate sound files. The two different tokens were derived either from separate recordings or files (e.g. two different birds singing), or by sampling different sections of a single waveform (e.g. two separate samples from a long extract of traffic noise). The length of each sound token ranged from 2.5 seconds for breaking glass to 12.5 seconds for the fire siren. The length of the tokens were different for the different sound types in order to ensure that the extract was realistic and provided adequate acoustic information, representative of the information available in the normal listening environment, without unnecessarily prolonging the test. For example, a single footstep may not provide adequate information for identification, with four or more footsteps in succession possibly required. However, the sound of a door closing is relatively brief, and prolonging its duration may result in an unrepresentative and unrealistic sound token. Continuous waveforms (e.g. continuous traffic noise or excerpts of different environments such as an office) had a 30 ms onset and offset ramp applied to minimise any distortion caused by a rapid on-set and/or off-set of the sound. For discrete waveforms (e.g. footsteps, door knocks, or glass breaking), tokens of the waveform commenced and ceased at natural silence breaks in the waveform. The speech stimuli incorporated into the EST allowed the assessment of the ability of subjects to identify male and female voices, and to differentiate between a single speaker and many speakers. As the purpose of the stimuli was not for subjects to identify the actual words and/or understand what the talker was saying, these speech extracts were spoken in a foreign language (i.e. German).

The EST was originally piloted on 5 normally hearing adults. These adults were recruited solely to undertake pilot testing of the EST. The total confusion matrix for this testing is shown in table 6.

A total of 49 confusions were made by the 5 pilot adults. Removal of the ‘vacuum cleaner’ from the list of sounds eliminated 10 confusions. Removal of the ‘rain’ sound eliminated 9 confusions. Removal of ‘car starting’ eliminated 5 confusions, and removal of ‘fridge hum’ and ‘ocean’ each eliminated 4 confusions. In total 32 of the 49 confusions were eliminated, by these changes to the test. Accordingly, these 5 sounds were eliminated with the final version of the EST consisting of 45 sounds with 2 tokens each – i.e. 90 sound files. This provided a chance performance rate of 2.2%.

For calibration purposes a calibration tone (white noise) was generated at the average RMS level across the remaining 90 sound files.

5.3.2 Speech tests:

The open-set speech perception tests included in this study were the Consonant Nucleus Consonant (CNC) words test and the Hearing In Noise Test (HINT) sentences test. These were the same speech tests used by the SCIP for adult assessments both pre- and post- surgery. The recordings of these tests used by the SCIP were made by a female speaker with a New Zealand English accent.

The Hearing In Noise Test (HINT) was initially developed by Nilsson et al. (1994). The HINT is composed of 25 lists, each with ten sentences. It uses sentence material from the Bamford-Kowal-Bench (BKB) sentence test (1979). The BKB sentence test consists of over 300 sentences, and was originally developed for use with children in the United Kingdom. For the HINT, these sentences were altered to represent normal American English, and the sentences were equated in terms of length, difficulty, and phonemic content. The lists are rated at a first-grade reading level and therefore should be comprehensible by adults, including the postlingually deafened adults in this study (Nilsson, Soli, & Sullivan, 1994). Target words in each sentence are scored right or wrong.

Consonant Nucleus Consonant (CNC) words test lists were developed by Lehiste and Peterson in 1959. The monosyllabic words used were derived from the word lists developed by Thorndike

Table 6: Total confusion matrix for five normally hearing adults who pilot tested the Environmental Sounds Test

The stimulus is indicated by the column while the response is given by the row. The letters representing the stimuli correspond to the letters in the response column. The number within each square represents the number of times a given response was provided for a given stimulus. The shaded squares indicate the number of sound tokens correctly identified, and the white squares indicate confusions. For the EST each sound stimulus has two different tokens that are presented during the test. Therefore the total number of responses for each stimulus is 2nx (where n = number of participants in the group and x =number of times each participant was assessed). The bottom row shows the % correct identification score for each stimulus.

n=5	**STIMULI**																																																		
RESPONSE	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**n**	**o**	**p**	**q**	**r**	**s**	**t**	**u**	**v**	**w**	**x**	**y**	**z**	**aa**	**bb**	**cc**	**dd**	**ee**	**ff**	**gg**	**hh**	**ii**	**jj**	**kk**	**ll**	**mm**	**nn**	**oo**	**pp**	**qq**	**rr**	**ss**	**tt**	**uu**	**vv**	**ww**	**xx**	
a) aeroplane	**9**	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13
b) car horn	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
c) car starting	0	0	**5**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
d) siren	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
e) helicopter	0	0	0	0	**8**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
f) traffic	0	0	4	0	0	**10**	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
g) train	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
h) birds	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
i) cats	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
j) dogs	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
k) ocean	0	0	0	0	0	0	0	0	0	0	**6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
l) rain	0	0	0	0	0	0	0	0	0	0	0	**4**	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
m) river	0	0	0	0	0	0	0	0	0	0	4	0	**10**	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
n) thunder	0	0	0	0	0	0	0	0	0	0	0	0	0	**7**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
o) wind	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**9**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
p) door bell	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**9**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
q) door	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
r) keys	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
s) knock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**9**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
t) tap run	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	**9**	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
u) toilet flush	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
v) tap drip	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
w) dishes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
x) food fry	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	**6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
y) fridge hum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
z) kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**9**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
aa) alarm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
bb) clock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
cc) hairdryer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**7**	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
dd) mower	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**8**	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13
ee) phone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
ff) vacuum	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	0	**4**	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	11
gg) baby	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
hh) laughter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
ii) footsteps	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
jj) many	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
kk) both	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	0	10
ll) female	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	0	10
mm) male	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	0	10
nn) snoring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	0	10
oo) drawers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	0	0	10
pp) office	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**9**	0	0	0	0	0	0	0	0	9
qq) paper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	0	10
rr) typing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	0	10
ss) glass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	0	0	10
tt) construction	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**8**	0	0	0	0	12
uu) saw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	0	0	0	10
vv) classical	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**10**	1	0	11
ww) modern	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**9**	0	9
xx) restaurant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**10**	11
Total responses	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	
% Correct	**90**	**100**	**50**	**100**	**80**	**100**	**100**	**100**	**100**	**100**	**60**	**40**	**100**	**70**	**90**	**90**	**100**	**100**	**90**	**90**	**100**	**100**	**100**	**60**	**60**	**90**	**100**	**100**	**70**	**80**	**100**	**40**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**90**	**100**	**100**	**100**	**80**	**100**	**100**	**90**	**100**	

Total Mean 90.2%

Table 7: Details of the sounds used for the Environmental Sounds Test

Stimuli	Database 1	Length 1 (s)	Database 2	Length 2 (s)
1 male & 1 female simultaneously	Phonak 2, Nos 17.4	5	Phonak 2, Nos17.3	5
aeroplane	BBC, # 42	10	Phonak 2, Nos 17.21	10
alarm clock	Phonak 1, Ala 17.4	5	Phonak 1, Ala 17.5	5
baby crying	Phonak 2, Nos17.4	5	Phonak 2, Nos 17.4	5
bird(s) chirping	BBC-06, #40	5	BBC-06, # 42	5
breaking glass	BBC-01, # 35	2.5	BBC-01, # 33 + # 32	2.5
car horn	Phonak 1, Ala 17.21	5.17	Phonak, Ala 17.23	5.17
car starting	BBC-05, # 14	10	BBC-02, # 8	10
cat(s) meowing	BBC-06, # 1	5	BBC-06, # 2	5
classical music	Phonak 2, Mus 17.8	5	Phonak 2, Mus 17.12	5
clock ticking	Phonak 2, Nos 17.1	5	BBC-3 , # 8	5
construction site	Phonak 2, Nos 17.5	10	Gateway 1/2, # 66	10
dog(s) barking	BBC-06, # 7	5	BBC-06, # 9	5
doing dishes	BBC-03, # 22	10	BBC-03, # 22	10
door open/ close	Gateway 1/2, # 29	3.8	BBC-3, # 13	3.8
doorbell	Phonak 1, Ala 17.15	7.35	Phonak 1, Ala 17.17	7.3
fire/ ambulance siren	Phonak 1, Ala 17.18	12.5	Phonak 1, Ala 17.18	12.5
food frying	Phonak 2, Nos 17.17	6	BBC-3, # 30	6
footsteps	BBC-07, # 43	5	Gateway 3/4, # 26	5
fridge hum	BBC-03, # 19	5	BBC-03, # 19	5
hair dryer	BBC-03, # 41	7	BBC-03, # 41	7
hand saw	BBC-03, # 44	6	Gateway 3/4, #	6
helicopter	BBC-05, # 36	5	BBC-05, # 35	5
keys jangling	Phonak 2, Nos 17.23	5	Phonak 2, Nos 17.23	5
knock on the door	Gateway 3/4, # 11	4	Gateway 1/2, # 37	4
laughter	Gateway 3/4, # 71	5	Gateway 3/4, # 71	5
lawnmower	Phonak 2, Nos 17.16	11	Gateway 1/2, # 16	11
many males & female simultaneously	Phonak 2, Nos 17.14	5	Phonak 2, Nos 17.17	5
metal drawers (open/ close)	Gateway 3/4, # 39	3.5	Gateway 3/4, # 39	3.5
modern music	Phonak 2, Mus 17.12	5	Phonak 2, Mus 17.39	5
ocean	BBC-02, # 3	10	BBC-01, # 1	10
office environment	Phonak 2, Nos 17.24	10	Gateway 3/4, # 54	10
paper rustling	Phonak 2, Nos 17.25	5	Phonak 2, Nos 17.26	5
rain	Phonak 2, Nos 17.29	5	Gateway 1/2, # 5	5
restaurant	Phonak 2, Nos 17.47	10	Gateway 3/4, # 70	10
river or stream babbling	BBC-01, # 3	5	Gateway 1/2, # 9	5
running water	BBC-03, # 36	5	BBC-03, # 38	5
single female voice	Phonak 1, Spe 17.18	5	Phonak 1, Spe 17.1	5
single male voice	Phonak 1, Spe 17.23	5	Phonak 1, Spe 17.19	5
snoring	BBC-08, # 22	10	BBC-08, # 22	10
telephone ringing	Phonak 1, Ala 17.37	7.5	Phonak 1, Ala 17.45	7.5
thunder	Gateway 1/2, # 13	6.7	Gateway 1/2, # 12	6.7
toilet flushing	BBC-03, # 35	6	BBC-03, # 35	6
traffic on a busy road	Phonak 2, Nos 17.25	10	Phonak 2, Nos 17.26	10
train	Phonak 2, Nos 17.29	5	Phonak 2, Nos 17.3	5
typing on computer	BBC-10, #30	5	BBC-10, # 30	5
vacuum cleaner	Phonak 2, Nos 17.46	6	Phonak 2, Nos 17.47	6
water dripping	BBC_03, # 23	5	BBC-03, # 23	5
wind blowing	BBC_02, #13	5	BBC-02, # 13	5
whistling kettle (boiling)	BBC-03, # 27	10	BBC-03, # 27	10

and Lorge (1944). The CNC lists developed by Lehiste and Peterson (1959) provided more-precise phonemic balancing and list equivalency, with each initial consonant, vowel, and final consonant appearing with the same frequency of occurrence within each list. The Lehiste & Peterson version of the CNC words test consists of 10 lists, each with 50 words.

5.4 *Equipment*

Pure-tone audiometry testing was conducted with a calibrated Interacoustics Diagnostic AD229e audiometer (Interacoustics A/S, Assens, Denmark) with Telephonics TDH-39P supraaural headphones (Telephonics Corporation, NY, USA). The speech and environmental sound testing was carried out via an HP Compaq PC (Hewlett-Packard, CA, USA), connected to a Crown D75 amplifier (Crown Audio Inc, CA, USA), a DBX 231 graphic equalizer (dbx Professional Products, UT, USA), and a Diamond Studiomaster Compact 4-2X audiomixer (Recording Studio Design Ltd., Bedfordshire, UK). These were connected to a JBL Ti 100 Center sound field speaker (JBL, CA, USA). Stimuli and background noise levels were measured with a Rion model NA24 sound level meter (Rion, Tokyo, Japan) on a fast setting.

5.5 Procedures

All of the testing was undertaken in a quiet, sound-treated room at University of Canterbury Speech and Hearing Clinic. Ambient noise levels in the room prior to testing measured less than 32 dB(A). This is within the guidelines recommended by the ANSI standards (ANSI S3.1-1999).

Participants for the two experimental groups (pre-to-post surgery group, and the experienced CI group) were asked to attend two test sessions at The University of Canterbury Speech and Hearing Clinic. Total testing time for the initial appointment for both experimental groups lasted about 1.5 hours. For the Experienced CI users' group, pure-tone-audiometry and speech perception data was collected by another researcher on the same day as the EST was administered. Testing with the other researcher took about one hour with the following environmental sound testing taking approximately a further 30 minutes. The pre-surgery session for the pre-to-post CI group was in the month prior to implantation.

The second session for both experimental groups was approximately 3-4 months following their first appointment. For the pre-to-post CI group this meant that follow-up was approximately 3 months following switch-on of the participants new CI. The Experienced CI users were asked to return approximately 3-4 months later for a retest in order to assess for the potential of a learning effect biasing the within-group comparisons for the pre-to-post surgery participant group.

For the Experienced CI users, the second session consisted only of a repeat of the EST and therefore the re-test time was approximately 30 minutes. For the pre-to-post surgery group, the second session lasted approximately 1 hour. This session was shorter than the pre-surgery session as hearing thresholds were only obtained for the implanted ear, and the speech perception tests were only administered in a CI-only listening condition.

For the pre-surgery session for the pre-to-post surgery group, participants were assessed whilst using their own HAs. For the Experienced CI users and for the post-surgery assessment for the pre-to-post surgery group, participants were assessed while using their own CI in the monaural implant-only listening condition. The decision to test in a CI-only condition (i.e. no HA on the other ear) is due to the fact that clinicians in the SCIP recommend to patients that they use only their CI in the first 3 months post-implantation in order to allow their brain to adjust to the new sound. For all testing, participants were asked to use the settings they usually use for everyday listening. Participants were able to adjust the settings of their CI or HA (i.e. program, volume and or sensitivity controls) to their preferred level.

Normal hearing participants attended one test session. They were firstly screened to confirm that they had hearing thresholds at the octave frequencies between 0.5 and 4 kHz $\leq$ 25 dB HL. If the participant met the normal hearing criteria, they then undertook the EST which took approximately 20 minutes.

To assess the hearing thresholds for the experimental groups, air-conduction pure-tone audiometry testing using supra-aural headphones was carried out. Firstly, un-aided pure-tone audiometry testing was carried out in 2 dB steps at octave intervals in the speech frequency range 250 Hz - 8000 Hz for both ears. The order of test frequencies was 1000, 2000, 4000, 8000, 500 and 250 Hz. The modified Hughson-Westlake procedure (Carhart & Jerger, 1959) was used as per routine audiological practice, except in 2 dB, instead of 5 dB, steps to provide greater accuracy.

For the speech and environmental sounds tests, stimuli were presented via a loudspeaker placed at 0 degrees azimuth, 1 meter from the listener’s ear. Presentation levels, for both the calibration tone and the stimuli, were calibrated to be 65 dB (A) at the position of the participant’s ear, using a sound level meter. This is the same level used by the SCIP for their clinical testing.

The stimuli for the EST were delivered via a computer, connected to an amplifier, a graphic equalizer, an audiomixer and a sound field speaker. Test items were stored on the computer as .WAV files, and a computer program ('UC_ID')[1] presented the stimuli in random order. The program allowed the experimenter to have control over the timing of the presentations, and the responses were entered directly into the program for later analysis. The participant had a list of the environmental sounds, and they were asked to select the sound that they thought was played. Participants were given as long as necessary to make their decision, and no feedback was given regarding the accuracy of their answers during the test itself. Stimuli were not replayed. The final version of the test had 45 different sounds with two tokens each, and therefore a score out of 90 was obtained. Scores were converted to a percentage-correct form.

Following the EST, speech perception tests were conducted. For this study, the following HINT sentence lists were used: 3, 4, 7, 8, 11, 12, 15, 16, 19, 20, 23, and 24. It should be pointed out that lists 3 and 4 were excluded in the pre-surgery session for the pre-to-post CI users as participants were tested with these lists at their SCIP appointment around the same time as their appointments for this study. All ten lists of CNC words were included in the pool from which the test lists were selected.

The speech lists chosen were randomly selected from the 10 CNC word lists, and the 12 HINT sentence lists available. HINT sentences were carried out in both quiet and in noise (SNR +10dB). No feedback was given to subjects regarding the accuracy of their answers during the test, and stimuli were not repeated. The HINT was marked according to the number of target words correctly repeated, with a percentage-correct score being obtained. The CNC word lists were marked according to both the number of words (out of 50) and phonemes (out of 150) correct per list. These scores were then converted to give percentage-correct scores for both phonemes and words. Speech perception testing included 2 lists of HINT sentences in quiet, 2 lists of HINT sentences in noise, and 2 lists of CNC words. The scores from the two lists presented for each test were averaged for subsequent data analysis.

For the experienced CI users and for the post-surgery session of the pre-to-post CI group, speech and EST assessment was carried out in the implant-only listening condition. The non-implanted

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[1] The UC_ID program was developed by Dr Greg O'Beirne, a lecturer at the University of Canterbury. Designed for psychoacoustic research, the software enables selected sound files on the computer to be presented to listeners at a controlled presentation level. Although various options are available in the set-up of the program, for this study, the files were presented in a random order, and the responses were entered directly into the program by the researcher. Upon conclusion of the test, an output file was generated containing details of the sound file presented, the corresponding response made by the subject, and a percentage-correct score.

ear was not blocked or masked. A correlation between the score on the EST and the low-frequency average of hearing thresholds was carried out for the experienced CI group to confirm that residual hearing did not contribute to their performance. For the pre-to-post CI group's pre-surgery session, assessment was carried out in the binaural listening condition (i.e. with bilateral HAs). It should be noted that all of the experimental participants had been fitted with individually optimised HAs/ CI as part of the SCIP process. Therefore the HA/ CI settings used by the patient in these sessions should have been the most appropriate settings for the patient to obtain the greatest listening benefit from their HAs/ CI.

CHAPTER 6

Results

6.1 Data Analysis

The statistical software used for analysis of the results of this study was SPSS 15.0 (SPSS Inc., IL, USA). Two-tailed statistical tests (t-tests) were used with a significance value of $p \leq 0.05$. Correlation analysis was undertaken using non-parametric Spearman's rho.

For the EST results, confusion matrices were constructed to provide information on participants' responses and error patterns for each test administration. For the experienced CI group, a paired t-test showed no significant difference between the two test administrations ($p > 0.05$). Therefore their data was combined for comparison to the NH group (section 6.4).

For all of the confusion matrices that follow, the stimulus is indicated by the column while the response is indicated by the row. The letters representing the stimuli correspond to the sound indicated with those same letters in the response column. The number within each square represents the number of times a given response was provided for a given stimulus. The shaded squares indicate the number of sound tokens correctly identified, and the white squares indicate confusions. For example, in Table 9 for the stimulus "aeroplane" the correct response of "aeroplane" was provided 37 times. Other responses (confusions) that were provided for the stimulus "aeroplane" included "helicopter", "hairdryer" and "construction site" 3 times each, and "alarm" and "train" a single time each. For the EST each sound stimulus has two different tokens that are presented during the test. Therefore the total number of responses for each stimulus is 2nx (where n = number of participants in the group and x = the number of times each participant was assessed). This number is therefore included for each column in the row entitled "total responses". For example in Table 9, the total number of responses for each stimulus is 2 x 24 participants x 1 assessment, i.e. a total of 48 responses. The bottom row of each confusion matrix indicates the percentage that each sound stimulus that was correctly identified. The total in the right bottom corner of the matrix indicates the mean percentage-correct for the entire EST for the relevant group of participants. For example, Table 9 shows that the mean percentage-correct for the NH group on the entire EST was 92.9%.

6.2 Normal Hearing Participants

The mean total percentage-correct score on the EST was 92.92% (SD = 4.28). For the 24 participants the total number of errors (confusions) made were 89. Table 8 shows the data for each participant, subdivided into the 9 different categories. The confusion matrix for the 24 NH participants on the EST is shown in Table 9. Seventy percent of the errors were accounted for by the 12 most-common confusions, as shown in Table 10.

A one-way repeated measures ANOVA showed a significant difference between the categories (p = 0.013). Post hoc analysis using Bonferroni corrections showed significant differences between the most-accurately recognized category (human) and the two least-accurately recognized categories of household (p = 0.007) and office (p = 0.020). There was no significant correlation between overall participants' score on the EST and their age (p = 0.703; Spearman's rho).

Table 8: Percentage-correct score for each Normal Hearing participant for each category of the Environmental Sounds Test

Participant	**Category (% correct)**									**Total**
	Transport	**Nature**	**Arriving Home**	**Bathroom**	**Kitchen**	**Household Appliances**	**Human**	**Office**	**Other**	
1	91.67	83.33	100	83.33	83.33	80	100	87.5	91.67	90
2	100	91.67	100	100	83.33	90	100	75	91.67	93.33
3	91.67	100	87.5	100	100	100	100	100	91.67	96.67
4	83.33	100	100	100	83.33	90	100	87.5	91.67	93.33
5	75	83.33	87.5	83.33	83.33	80	100	87.5	83.33	85.56
6	83.33	91.67	75	66.67	100	80	100	100	100	90
7	91.67	91.67	100	100	83.33	100	100	87.5	91.67	94.44
8	100	91.67	75	100	83.33	80	93.75	75	100	90
9	91.67	83.33	87.5	100	100	100	100	62.5	100	92.22
10	91.67	100	87.5	100	100	80	100	100	83.33	93.33
11	100	100	100	100	100	100	100	100	91.67	98.89
12	83.33	83.33	100	100	100	80	93.75	87.5	100	91.11
13	100	91.67	87.5	83.33	83.33	100	93.75	62.5	91.67	90
14	100	100	100	100	100	80	100	87.5	91.67	95.56
15	91.67	100	87.5	83.33	83.33	90	87.5	87.5	83.33	88.89
16	66.67	75	100	83.33	83.33	60	100	100	100	85.56
17	100	100	100	83.33	100	90	100	100	100	97.78
18	100	91.67	100	100	100	100	100	100	100	98.89
19	91.67	100	100	100	83.33	100	93.75	87.5	100	95.56
20	91.67	100	100	100	100	100	100	100	100	98.89
21	100	75	87.5	66.67	83.33	70	93.75	87.5	83.33	84.44
22	100	100	100	100	100	90	100	100	91.67	97.78
23	100	83.33	100	100	100	90	100	87.5	91.67	94.44
24	66.67	100	100	100	100	90	100	87.5	100	93.33
Mean	91.32	92.36	94.27	93.06	92.36	88.33	98.18	89.06	93.75	92.92
SD	10.27	8.48	8.22	10.9	8.48	10.90	3.44	11.25	6.14	4.28

Table 9: Total confusion matrix for the Normal Hearing group

The stimulus is indicated by the column while the response given is indicated by the row. The letters representing the stimuli correspond to the letters in the response column. The number within each square represents the number of times a given response was provided for a given stimulus. The shaded squares indicate the number of sound tokens correctly identified, and the white squares indicate confusions. For the EST each sound stimulus has two different tokens that are presented during the test. Therefore the total number of responses for each stimulus is 2nx (where n = number of participants in the group and x =number of times each participant was assessed). The bottom row shows the % correct identification score for each stimulus.

n=24	**STIMULI**																																												
RESPONSE	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**n**	**o**	**p**	**q**	**r**	**s**	**t**	**u**	**v**	**w**	**x**	**y**	**z**	**aa**	**bb**	**cc**	**dd**	**ee**	**ff**	**gg**	**hh**	**ii**	**jj**	**kk**	**ll**	**mm**	**nn**	**oo**	**pp**	**qq**	**rr**	**ss**
a) aeroplane	**37**	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
b) car horn	0	**47**	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
c) siren	0	0	**47**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d) helicopter	3	0	0	**37**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
e) traffic	0	0	0	0	**48**	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
f) train	1	0	0	1	0	**47**	0	0	0	0	1	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
g) birds	0	0	0	0	0	0	**48**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
h) cat	0	0	0	0	0	0	0	**48**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
i) dog	0	0	0	0	0	0	0	0	**48**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
j) river	0	0	0	0	0	0	0	0	0	**45**	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
k) thunder	0	0	0	0	0	0	0	0	0	0	**40**	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
l) wind	0	0	0	0	0	0	0	0	0	0	4	**37**	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
m) doorbell	0	0	0	0	0	0	0	0	0	0	1	0	**45**	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n) door	0	0	0	0	0	0	0	0	0	0	0	0	0	**46**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0	0	0	0	0	0	0	0	0
o) keys	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**46**	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
p) knock	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**44**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
q) tap run	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	**39**	0	0	0	5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
r) toilet	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	3	**47**	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s) tap drip	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**48**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
t) dishes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**47**	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
u) food fry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**39**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
v) kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**47**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w) alarm	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	**45**	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x) clock	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**48**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
y) hairdryer	3	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**32**	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
z) mower	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**41**	0	0	0	0	0	0	0	0	0	1	0	0	0	0	4	0	0	0	0
aa) phone	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**46**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
bb) baby	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**48**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
cc) laughter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**48**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dd) footstep	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**47**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
ee) many	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**45**	1	0	0	0	0	0	0	0	0	0	0	0	0	5
ff) both	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	**47**	0	0	0	0	0	0	0	0	0	0	0	0	0
gg) female	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**47**	0	0	0	0	0	0	0	0	0	0	0	0
hh) male	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**47**	0	0	0	0	0	0	0	0	0	0	0
ii) snoring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**48**	0	0	0	0	0	0	0	0	0	0
jj) drawers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**43**	0	0	0	0	1	0	0	0	0
kk) office	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**35**	0	0	0	5	0	0	0	0
ll) paper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**45**	0	0	0	0	0	0	0
mm) typing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	**48**	0	0	0	0	0	0
nn) glass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**48**	0	0	0	0	0
oo) construction	3	0	0	0	0	1	0	0	0	0	0	0	1	0	0	4	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	**37**	0	0	0	1
pp) saw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	**48**	0	0	0
qq) classic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**47**	0	0
rr) modern	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**48**	0
ss) restaurant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	**42**
Total responses	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
% Correct	**77**	**98**	**98**	**77**	**100**	**98**	**100**	**100**	**100**	**94**	**83**	**77**	**94**	**96**	**96**	**92**	**81**	**98**	**100**	**98**	**81**	**98**	**94**	**100**	**67**	**85**	**96**	**100**	**100**	**98**	**94**	**98**	**98**	**98**	**100**	**90**	**73**	**94**	**100**	**100**	**77**	**100**	**98**	**100**	**88**

Total Mean **92.92 %**

Table 10: The 12 most-common confusions made by the Normal Hearing group on the Environmental Sounds Test

The column headed "Total number of confusions" indicates the number of time each error was made. For this group the total number of errors made was 89. The total row shows the total number of errors accounted for by the listed "most-common" confusions. For example one of the most common errors was mistaking the "helicopter" stimulus for an "aeroplane".

Stimulus	Response	Total number of confusions (out of 89)
Helicopter	Aeroplane	7
Wind	Train	7
Office	Restaurant	7
Tap running	River/ stream babbling	6
Hairdryer	Wind	6
Food frying	Tap running	5
Restaurant	Many males and females talking at the same time	5
Construction site	Office environment	4
Lawn mower	Aeroplane	4
Thunder	Wind	4
Construction site	Lawn mower	4
Knock on the door	Construction site	4
Total		63

6.3 Experienced CI users

6.3.1 Hearing Thresholds

The hearing thresholds of each of the 10 experienced CI users are shown in Table 11.

Table 11: Pure-tone thresholds for the Experienced CI group

The pure-tone frequencies (Hz) tested are in bold font in the heading (i.e. 250-8000Hz). Thresholds are given in dB HL. 'NR' = no response at the limits of the audiometer. The limit of the audiometer was 110 dB HL for 250 and 8000 Hz, and 120 dB HL for the other octave frequencies 500-4000 Hz.

Participant	Un-Implanted Ear						Implanted Ear					
	250	**500**	**1000**	**2000**	**4000**	**8000**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
1	90	110	107	125	125	115	94	NR	NR	NR	NR	NR
2	48	62	82	115	125	115	NR	NR	NR	NR	NR	NR
3	66	99	100	115	116	115	NR	NR	NR	NR	NR	NR
4	66	88	86	108	108	115	NR	NR	NR	NR	NR	NR
5	93	104	108	120	125	115	104	115	NR	NR	NR	NR
6	90	97	110	114	125	115	65	65	84	80	114	NR
7	115	125	125	125	125	115	NR	NR	NR	NR	NR	NR
8	65	90	100	115	120	115	110	NR	NR	NR	NR	NR
9	101	110	106	108	125	115	NR	NR	NR	113	NR	NR
10	58	74	84	100	104	115	98	120	NR	114	120	NR

6.3.2 Speech Perception

The speech perception scores for each of the 10 experienced CI users for both the HINT sentences and the CNC words are shown in Table 12.

Table 12: Speech perception scores for the Experienced CI group
Percentage- correct scores for the HINT sentences presented in quiet and in noise (+10 dB SNR), as well as results of CNC words (words and phonemes) are presented.

Participant	**HINT**		**CNC**	
	Quiet	**Noise**	**Words**	**Phonemes**
1	100	83	75	86
2	77.35	20.03	40	63.33
3	43.1	0	3.5	35.65
4	98	74	77	89.5
5	46.2	19.6	18	43
6	78.4	38.5	29	58.3
7	96.2	83.7	63	82.3
8	96	84	80.5	90.5
9	100	53	64	86
10	100	#	#	#
Mean	83.53	50.65	50	70.51
SD	22.19	32.44	28.23	21.07

 # Participant 10 was not tested as she was overly familiar with the testing materials, as she worked at a CI clinic doing these speech perception assessments.

6.3.3 EST

The experienced CI group was assessed twice. The Pearson's correlation coefficient (r = 0.891) suggests strong test-retest reliability for this test. The mean score and SD for each category for the initial and follow-up tests are shown in Table 14. A 2-way repeated measures ANOVA was conducted in order to see if there was any significant difference between initial and follow-up administrations of the EST. This showed no significant difference for test block (p = 0.78). Therefore the following analyses use the combined results for both test blocks of the EST.

The mean total percentage-correct score on the EST was 59.28% (SD = 11.48). For the 10 participants, the total number of errors made was 733. The confusion matrix for the 10 experienced CI users is shown in Table 15. The error pattern exhibited by this group was more diffuse than the NH group with the 28 most-common confusions only accounting for 31% of the errors. These confusions are shown in Table 13.

The 2-way repeated measures ANOVA referred to earlier also showed differences between different sound categories in addition to the different test administrations. A significant difference between the categories was found (p = 0.004). There was no significant interaction between the factors of test block and category (p = 0.454). Post-hoc analysis using Bonferroni corrections showed that the two most-accurately recognized categories (human, and arriving home) were recognized significantly better than the least-accurately recognized category of transport (Human & transport p = 0.01; Arriving home & transport p = 0.028). Table 16 shows the mean percentage-correct score for each participant, for each category; combined for the two test runs.

Table 16 shows the mean percentage-correct score for each participant, for each category; combined for the two test runs.

Table 13: The most-common confusions made by the Experienced CI group on the Environmental Sounds Test

This table shows the 12 most- common errors made by the experienced CI group. The column headed "Total number of confusions" indicates the number of time each error was made. For this group the total number of errors made was 733. The total row shows the total number of errors accounted for by the listed "most-common" confusions.

Stimulus	**Response**	**Total number of confusions (out of 733)**
Many males and females talking at the same time	One male and one female talking at the same time	18
River/ stream babbling	Running tap	13
Construction site	Traffic	13
One male and one female talking at the same time	Single male voice	13
Glass breaking	Keys jangling	12
Food frying	Running tap	11
Helicopter	Train	10
Thunder	Traffic	9
Doing dishes	Office environment	7
Wind	Traffic	7
Toilet flushing	Running tap	7
Footsteps	Construction site	7
Restaurant	Traffic	7
Running tap	River/stream babbling	7
Traffic	Wind	7
Office environment	Restaurant	7
Aeroplane	Traffic	7
Train	Construction site	7
Keys jangling	Food frying	7
Thunder	Wind	6
Aeroplane	Hair dryer	6
Hairdryer	River/stream babbling	6
Siren	Classical music	6
Traffic	Aeroplane	6
Wind	Train	6
Dripping tap	Footstep	6
Office environment	Dishes	6
Many males and females talking at the same time	Male voice	6
Total		230

Table 14: Category mean and standard deviation scores for the initial and follow-up tests for the experienced CI group

Category	**Transport**	**Nature**	**Arriving Home**	**Bathroom**	**Kitchen**	**Household Appliances**	**Human**	**Office**	**Other**	**Total**
Initial	41.67 (12.4)	55.83 (18.5)	70 (24.4)	60 (31.6)	45 (28.4)	71 (16.6)	67.4 (18.2)	59.75 (19.4)	61.94 (16.4)	59.2 (22.7)
Follow-up	40 (15.1)	59.17 (9.2)	67.5 (17.9)	66.67 (22.2)	46.67 (35.8)	60 (17.0)	75 (14.7)	57.5 (12.1)	55 (15.3)	58.6 (20.9)
Combined	41.67 (12.7)	55 (8.3)	68.75 (17.9)	61.67 (23.0)	43.33 (24.8)	65.5 (14.2)	72.5 (15.1)	58.13 (15.0)	59.58 (12.1)	59.3 (11.5)

Table 15: Total confusion matrix for the Experienced CI group

The stimulus is indicated by the column while the response is indicated by the row. The letters representing the stimuli correspond to the letters in the response column. The number within each square represents the number of times a given response was provided for a given stimulus. The shaded squares indicate the number of sound tokens correctly identified, and the white squares indicate confusions. For the EST each sound stimulus has two different tokens that are presented during the test. Therefore the total number of responses for each stimulus is 2nx (where n = number of participants in the group and x= number of test administrations for each participant). The bottom row shows the % correct identification score for each stimulus.

n=20	**STIMULI**																																												
RESPONSE	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**n**	**o**	**p**	**q**	**r**	**s**	**t**	**u**	**v**	**w**	**x**	**y**	**z**	**aa**	**bb**	**cc**	**dd**	**ee**	**ff**	**gg**	**hh**	**ii**	**jj**	**kk**	**ll**	**mm**	**nn**	**oo**	**pp**	**qq**	**rr**	**ss**
a) aeroplane	**1**	1	0	3	6	1	0	0	0	0	5	4	0	0	0	0	0	0	0	0	0	0	0	0	2	5	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	5
b) car horn	0	**31**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
c) siren	1	0	**25**	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d) helicopter	1	0	0	**6**	1	1	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	2
e) traffic	7	0	0	4	**18**	3	0	0	0	2	9	7	0	0	0	0	0	1	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	1	0	2	0	0	0	13	0	0	0	7
f) train	2	0	0	10	3	**19**	0	0	0	3	4	6	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	3	1	3	0	2
g) birds	0	0	0	0	0	0	**40**	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
h) cat	0	0	1	0	0	0	0	**33**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
i) dog	0	1	0	0	0	0	0	0	**37**	0	0	0	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
j) river	2	0	0	1	1	0	0	0	0	**11**	0	2	0	0	0	0	7	3	0	0	1	0	0	0	6	1	0	0	0	0	0	0	0	0	0	1	1	2	0	0	1	0	1	0	0
k) thunder	0	0	0	0	0	0	0	0	0	0	**6**	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0
l) wind	5	0	0	0	7	1	0	0	0	2	6	**5**	0	0	0	0	0	0	0	1	1	0	0	0	4	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	1	0	1	0	2
m) doorbell	0	2	0	0	0	0	0	0	0	0	0	0	**25**	0	0	0	0	0	0	0	0	1	1	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
n) door	1	0	0	0	0	0	0	0	0	0	0	0	0	**28**	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
o) keys	0	0	0	0	0	0	0	0	0	0	0	0	2	1	**23**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	12	0	0	0	0	0
p) knock	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	**34**	0	0	1	0	0	0	0	4	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
q) tap run	0	0	0	0	0	0	0	0	0	13	0	0	0	0	4	0	**24**	7	0	0	11	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	1	0	0
r) toilet	2	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	1	**25**	0	1	3	3	0	0	4	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0
s) tap drip	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**25**	0	1	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	4	1	0	0	0	0	1
t) dishes	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**15**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	1	0	2	1	0	0	0	0
u) food fry	0	0	0	0	0	0	0	0	0	2	0	0	0	0	7	0	4	1	0	2	**15**	4	0	0	4	0	0	0	0	0	0	0	0	0	0	0	2	2	0	1	0	0	0	0	0
v) kettle	2	0	0	0	0	1	0	0	0	0	0	0	0	0	3	0	1	0	0	0	5	**22**	4	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w) alarm	0	1	0	0	0	0	0	1	0	1	0	0	1	0	1	0	0	0	0	0	1	3	**29**	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x) clock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	**32**	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
y) hairdryer	6	0	0	5	0	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	**11**	1	0	0	0	0	1	0	0	0	3	0	1	0	0	0	0	0	0	0	0
z) mower	0	0	0	3	1	2	0	0	0	1	0	1	0	0	0	0	1	1	0	0	0	0	0	0	1	**25**	0	0	0	0	0	0	0	0	3	1	0	0	0	0	1	0	0	0	0
aa) phone	0	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	2	0	0	0	**34**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
bb) baby	1	0	5	0	0	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**32**	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
cc) laughter	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**35**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dd) footstep	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	5	1	0	0	1	0	0	0	0	0	**29**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ee) many	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**13**	2	0	0	1	0	1	0	0	0	0	0	0	0	5
ff) both	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	**23**	1	0	0	0	0	0	0	0	0	0	0	0	0
gg) female	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	**38**	0	0	0	0	0	0	0	0	0	0	0	0
hh) male	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13	1	**39**	0	0	0	0	0	0	0	0	0	0	0
ii) snoring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**23**	1	0	0	0	0	0	0	0	0	0
jj) drawers	0	0	0	0	0	1	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**24**	0	0	1	0	0	0	0	0	0
kk) office	2	0	1	1	0	1	0	0	0	0	0	2	0	1	0	0	0	0	0	7	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	4	**10**	1	0	0	1	0	1	0	1
ll) paper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**25**	0	0	0	0	0	0	0
mm) typing	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	**34**	0	0	0	0	0	0
nn) glass	0	0	1	0	0	0	0	1	0	0	0	0	3	0	1	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**18**	0	0	0	0	0
oo) construction	5	1	1	4	3	7	0	0	0	1	4	5	1	2	0	4	1	1	4	2	0	2	1	3	2	1	0	0	0	7	0	0	0	0	2	0	4	1	0	0	**13**	0	2	0	5
pp) saw	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	**38**	0	0	0
qq) classic	0	1	6	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	2	0	0	0	1	0	**28**	0	2
rr) modern	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**40**	2
ss) restaurant	1	0	0	0	0	1	0	0	0	0	2	2	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	1	0	0	1	0	0	0	**6**
Total responses	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
% Correct	**3**	**78**	**63**	**15**	**45**	**48**	**100**	**83**	**93**	**28**	**15**	**13**	**63**	**70**	**58**	**85**	**60**	**63**	**63**	**38**	**38**	**55**	**73**	**80**	**28**	**63**	**85**	**80**	**88**	**73**	**33**	**58**	**95**	**98**	**58**	**60**	**25**	**63**	**85**	**45**	**33**	**95**	**70**	**100**	**15**

Total Mean 59.8%

Table 16: Percentage correct score for each Experienced CI participant for each category of the Environmental Sounds Test

Participant	Group (% correct)									Total
	Transport	Nature	Arriving Home	Bathroom	Kitchen	Household Appliances	Human	Office	Other	
1	54.17	58.33	56.25	50	16.67	45	78.13	43.75	66.67	56.11
2	33.33	54.17	62.5	66.67	8.33	60	59.38	43.75	50	50
3	16.67	41.67	43.75	8.33	25	60	40.63	31.25	33.33	35
4	58.33	62.5	75	58.33	50	65	87.5	62.5	62.5	66.67
5	41.67	58.33	75	58.33	41.67	65	75	75	62.5	62.22
6	50	50	62.5	50	50	80	62.5	62.5	50	57.78
7	33.33	45.83	68.75	83.33	58.33	50	68.75	62.5	58.33	57.22
8	37.5	54.17	93.75	83.33	75	65	87.5	56.25	70.83	68.33
9	37.5	54.17	50	75	25	70	78.13	81.25	70.83	61.67
10	54.17	70.83	100	83.33	83.33	95	87.5	62.5	70.83	77.78
Mean	41.67	55	68.75	61.67	43.33	65.5	72.5	58.13	59.58	59.28
SD	12.73	8.29	17.92	22.97	24.78	14.23	15.08	15.04	12.12	11.48

6.3.4 Correlations

Spearman’s rho analyses showed no significant correlation between the overall score on the EST and the participant-factors of age (p = 0.082), duration of hearing loss pre-implantation (p = 0.128), duration of CI use (p = 0.243), degree of residual hearing (LFA; p = 0.533), or any of the speech tests [HINT in quiet (p = 0.223) and in noise (p = 0.205), CNC words (p = 0.099), or CNC phonemes (p = 0.081)]. The other participant factors were reported in Table 2, Chapter 5.

6.4 Comparison of NH participants and Experienced CI users

As discussed in the previous section, there was no significant difference between the initial and follow-up results for the experienced CI group. In view of this, the scores for each participant from the two runs were averaged, and used for the analyses in this section.

In order to see if there was any significant difference between the performance of the NH and the experienced CI groups, a 2-way repeated measures ANOVA was conducted using the between-subject factor of group and the within-subject factor of category. This analysis showed a significant difference between groups (p < 0.001) and between categories (p < 0.001), as well as a significant interaction between these two factors (p < 0.001).

The differences between the categories for each group have been discussed earlier in sections 7.2 and 7.3.3. Figure 11 shows the mean percentage-correct score for the NH listeners and the CI users for each sound category. Significant differences were found between the average results for the Experienced CI and NH participants for each EST category.

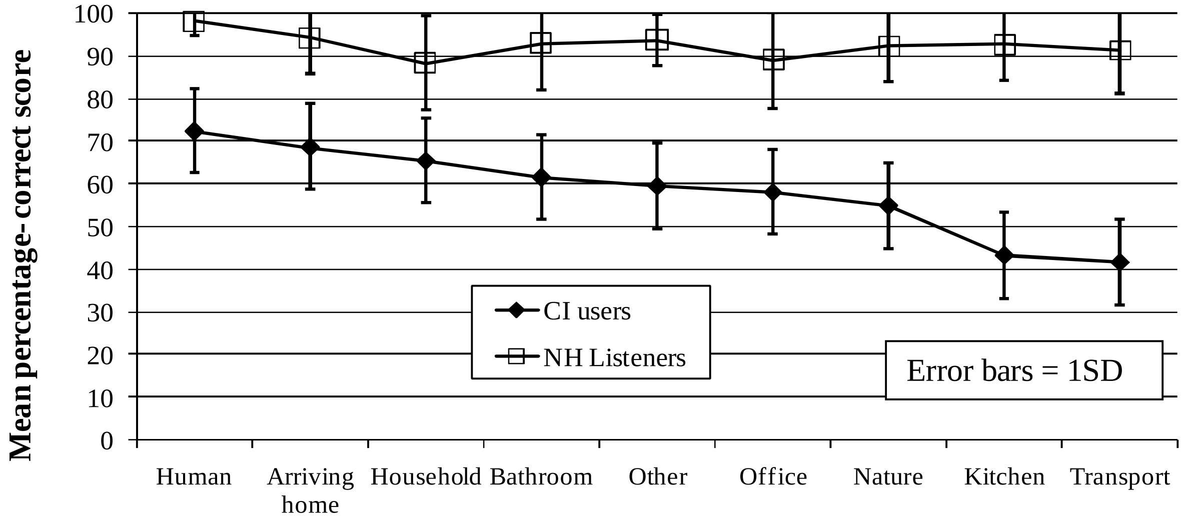

Figure 11: Comparison of category means for the Experienced CI and Normal Hearing groups

6.5 Pre-to-post CI Participant group

6.5.1 Hearing thresholds

The hearing thresholds of each of the pre-to-post CI group participants' are shown in Table 18.

6.5.2 Speech perception

The speech perception scores for each of the pre-to-post CI surgery group pre- and post- surgery are shown in Table 17.

In view of the small participant numbers (n = 4), a non-parametric Wilcoxon Signed Ranks Test was conducted to see if there was any difference between the pre-to-post surgery means for the various speech tests. The difference for all pre-to-post comparisons were approaching significance ($p = 0.068$) with the post-surgery scores being higher than the pre-surgery scores.

6.5.3 *EST*

The mean total percentage-correct score on the EST pre-surgery was 39.72% (SD = 14.27). The mean total percentage-correct score on the EST post-surgery was 57.22% (SD = 21.42). A non-parametric Wilcoxon Signed Ranks Test was conducted to see if there was any difference between the pre-to-post surgery means for the EST. The difference was approaching significance ($p = 0.068$) with the post-surgery score (with CI) being higher than the pre-surgery score (with HAs).

For the four participants the total number of errors was 217 pre-surgery, and 154 post-surgery. The pre-surgery confusion matrix for the 4 pre-to-post CI surgery participants is shown in Table 22, with post-surgery matrix being shown in Table 23. Pre-surgery, 12%, and post-surgery 14% of the errors were accounted for by the 7 most-common confusions, as shown in Tables 20 and 21. A comparison of the pre- and post-surgery percentage-correct scores for each category is shown in Table 19 and Figure 13. For each category, recognition scores were higher post-surgery (with CIs) than pre-surgery.

6.5.4 Correlations

Spearman's rho analyses showed no significant correlation pre- or post-surgery between the overall score on the EST and the participant factors of age at the time of assessment (p = 0.6), duration of hearing loss pre-surgery (p = 0.2), or any of the speech tests [(HINT in quiet (p = 0.2) and in noise (p = 0.2)), CNC words (p = 0.6), or CNC phonemes (p = 0.6)].

6.6 Summary

In summary, the NH group scored significantly better than the experienced CI group on the EST. For the pre-to-post surgery group, scores were higher post-surgery with a CI than pre-surgery with HAs on both the EST and the various speech perception measures. However, the differences for the pre-to-post surgery group were not significant due to the small sample size (n=4). No significant correlations were found for either of the experimental groups between scores on the EST and subject factors of age at the time of assessment, CI duration, speech perception scores, hearing loss duration pre-implantation. There was also no significant correlation found for the Experienced CI group between scores on the EST and residual hearing levels.

Table 17: Speech perception scores for the Pre-to-post CI group

Percentage-correct scores for the HINT sentences presented in quiet and in noise (+10 dB SNR), as well as results of CNC words (words and phonemes) is presented.

Participant	Pre-CI surgery (with HAs)				Post-CI surgery (with CI-only)			
	HINT		CNC		HINT		CNC	
	Quiet	Noise	Words	Phonemes	Quiet	Noise	Words	Phonemes
1	69.5	10	34	56	100	98.5	79	91.5
2	4	9	0	0	95	88.5	86	93.5
3	4	4	1	11.5	39	20.5	9	34
4	55	58	8	34	83.5	79.5	52	77
Mean	33.13	20.25	10.75	25.38	79.38	71.75	56.5	74
SD	34.15	25.30	15.90	24.82	27.79	35.04	34.9	27.66

Table 18: Pure-tone thresholds for the Pre-to-post CI group

The pure-tone frequencies (Hz) tested are in bold font in the heading (i.e. 250-8000 Hz). Thresholds are given in dB HL.
'NR' = no response at the limits of the audiometer. The limit of the audiometer was 110 dB HL for 250 and 8000 Hz, and 120 dB HL for the other octave frequencies 500-4000 Hz.

Participant	**Implanted ear**												**Un-implanted Ear**					
	250		**500**		**1000**		**2000**		**4000**		**8000**		**250**	**500**	**1000**	**2000**	**4000**	**8000**
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post						
1	70	96	86	104	86	120	80	115	68	NR	78	NR	54	82	86	76	72	86
2	40	65	92	115	104	115	110	120	120	NR	NR	NR	46	88	104	116	NR	NR
3	80	100	90	110	95	110	105	110	NR	120	NR	NR	80	95	100	110	NR	NR
4	38	62	63	98	75	94	105	110	95	112	108	110	33	68	81	105	110	NR

Table 19: Percentage-correct scores for each participant pre- and post- cochlear implant surgery for each category of the Environmental Sounds Test

Participant	**Category (% correct)**																		**Total**	
	Transport		**Nature**		**Arriving Home**		**Bathroom**		**Kitchen**		**Household Appliances**		**Human**		**Office**		**Other**			
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
1	33.33	8.33	16.67	33.33	37.5	37.5	0	16.67	16.67	33.33	30	20	68.75	43.75	0	25	8.33	33.33	27.78	28.89
2	16.67	50	33.33	58.33	37.5	75	0	66.67	0	50	30	60	43.75	93.75	37.5	75	41.67	75	30	68.89
3	50	75	50	50	75	100	50	50	50	83.33	40	90	87.5	93.75	75	100	41.67	58.33	58.89	77.78
4	50	50	25	75	37.5	50	50	33.33	16.67	50	30	40	68.75	75	25	62.5	50	25	42.22	53.33
Mean	37.5	45.83	31.25	54.17	46.88	65.63	25	41.67	20.83	54.17	32.5	52.5	67.19	76.56	34.38	65.63	35.42	47.92	39.72	57.22
SD	15.96	27.64	14.23	17.35	18.75	27.72	28.87	21.52	20.97	20.97	5	29.86	17.95	23.59	31.25	31.25	18.48	22.95	14.27	21.42

Table 20: The seven most-common confusions made by the Pre-to-post CI group pre-surgery
The column headed "Total number of confusions" indicates the number of times each error was made. For this group the total number of errors made was 217. The total row shows the total number of errors accounted for by the listed "most-common" confusions.

Stimulus	**Response**	**Total number of confusions (out of 217)**
Restaurant	Office	4
Hairdryer	Wind	4
Siren	Classical music	3
Doing dishes	Office	3
Alarm clock	Whistling kettle	3
Clock ticking	Knock on the door	3
Cat(s) meowing	Bird(s) chirping	3
Hairdryer	Traffic	3
Total		26

Table 21: The seven most-common confusions made by the Pre-to-post CI group post-surgery
The column headed "Total number of confusions" indicates the number of times each error was made. For this group the total number of errors made was 154. The total row shows the total number of errors accounted for by the listed "most-common" confusions.

Stimulus	**Response**	**Total number of confusions (out of 154)**
Aeroplane	Traffic	3
Thunder	Wind	3
Glass breaking	Keys jangling	3
Keys jangling	Running tap	3
Tap dripping	Clock ticking	3
Tap dripping	Footsteps	3
One male and one female talking at the same time	Many males and females talking at the same time	3
Total		21

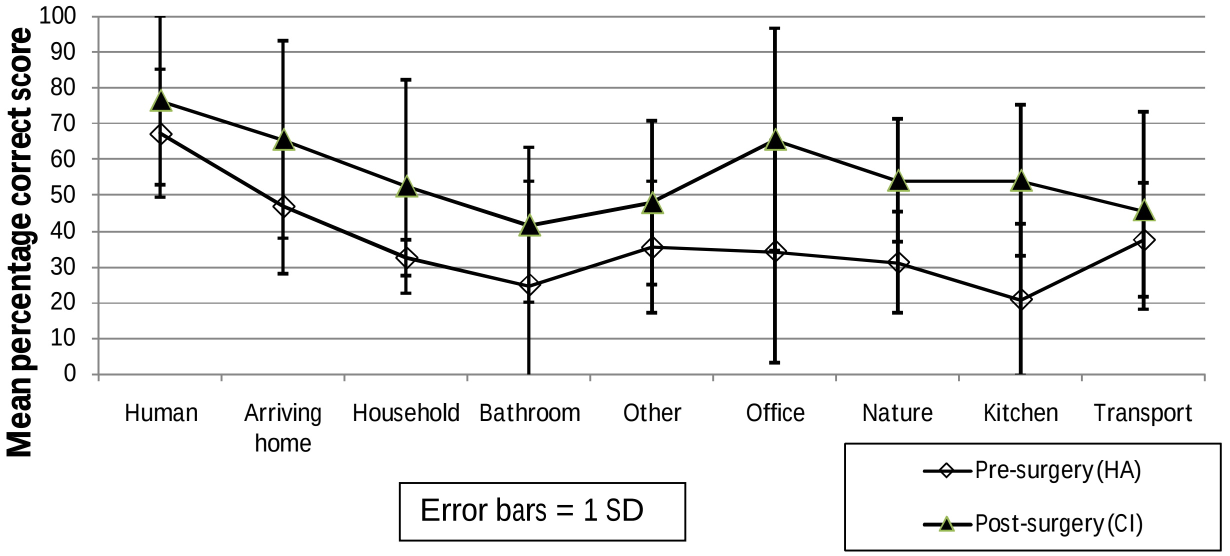

Figure 12: Comparison of category means pre- and post- cochlear implant surgery, for the Pre-to-post CI group

Table 22: Total confusion matrix for the Pre-to-post CI group pre-surgery

The stimulus is indicated by the column while the response given is indicated by the row. The letters representing the stimuli correspond to the letters in the response column. The number within each square represents the number of times a given response was provided for a given stimulus. The shaded squares indicate the number of sound tokens correctly identified, and the white squares indicate confusions. For the EST each sound stimulus has two different tokens that are presented during the test. Therefore the total number of responses for each stimulus is 2nx (where n = number of participants in the group and x = number of times each participant was assessed).The bottom row shows the % correct identification score for each stimulus.

n = 4	STIMULI																																												
RESPONSE	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	aa	bb	cc	dd	ee	ff	gg	hh	ii	jj	kk	ll	mm	nn	oo	pp	qq	rr	ss
a) aeroplane	**1**	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
b) car horn	0	**7**	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
c) siren	0	0	**1**	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0
d) helicopter	0	0	0	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
e) traffic	1	0	0	2	**6**	2	0	1	0	0	0	1	0	0	1	0	1	0	0	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	2	0	0	0	0
f) train	0	0	0	0	0	**3**	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0
g) birds	0	0	0	0	0	0	**2**	3	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
h) cat	0	0	0	0	0	0	0	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
i) dog	0	0	0	0	0	0	0	0	**8**	0	0	0	1	0	0	0	0	0	2	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
j) river	0	0	0	0	0	1	0	0	0	**2**	0	2	0	0	0	0	1	1	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
k) thunder	0	0	0	0	0	1	0	0	0	0	**2**	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
l) wind	1	0	0	1	0	0	0	0	0	0	2	**1**	0	0	0	0	0	2	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	1	0	0	0	0
m) doorbell	0	0	0	0	0	0	0	1	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
n) door	0	0	0	0	0	0	0	0	0	1	0	0	0	**5**	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
o) keys	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
p) knock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**7**	0	0	2	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
q) tap run	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	**2**	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
r) toilet	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**3**	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
s) tap drip	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
t) dishes	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
u) food fry	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**2**	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
v) kettle	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0	2	**3**	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
w) alarm	0	0	0	0	0	0	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0	1	**1**	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x) clock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**3**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
y) hairdryer	2	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
z) mower	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
aa) phone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**5**	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
bb) baby	0	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
cc) laughter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	**5**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dd) footstep	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0	0	**6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ee) many	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**5**	1	0	0	0	0	0	0	0	0	0	0	0	0	1
ff) both	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**5**	0	0	0	0	1	0	0	0	0	0	0	0	0
gg) female	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**8**	0	0	0	0	0	0	0	0	0	0	0	0
hh) male	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**6**	0	0	0	0	1	0	0	0	0	0	0
ii) snoring	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**	0	0	1	0	0	0	0	0	0	0
jj) drawers	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**3**	0	1	0	1	1	0	0	0	0
kk) office	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	**2**	0	0	0	0	0	0	0	4
ll) paper	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**3**	1	0	0	0	0	0	0
mm) typing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**3**	0	0	0	0	0	0
nn) glass	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0
oo) construction	2	0	0	2	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**	0	1	0	0
pp) saw	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**3**	0	0	0
qq) classic	0	0	3	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**4**	1	0
rr) modern	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**6**	1
ss) restaurant	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	1	0	1	2	1	0	0	0	1	0	0	**1**
Total Responses	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
% Correct	**13**	**88**	**13**	**0**	**75**	**38**	**25**	**0**	**100**	**25**	**25**	**13**	**13**	**63**	**25**	**88**	**25**	**38**	**13**	**0**	**25**	**38**	**13**	**38**	**13**	**38**	**63**	**75**	**63**	**75**	**63**	**63**	**100**	**75**	**25**	**38**	**25**	**38**	**38**	**13**	**25**	**38**	**50**	**75**	**13**

Total Mean **39.72%**

Table 23: Total confusion matrix for Pre-to-post CI group post-surgery

The stimulus is indicated by the column while the response given is indicated by the row. The letters representing the stimuli correspond to the letters in the response column. The number within each square represents the number of times a given response was provided for a given stimulus. The shaded squares indicate the number of sound tokens correctly identified, and the white squares indicate confusions. For the EST each sound stimulus has two different tokens that are presented during the test. Therefore the total number of responses for each stimulus is 2nx (where n = number of participants in the group and x = number of times each participant was assessed).The bottom row shows the % correct identification score for each stimulus.

n = 4	**STIMULI**																																												
RESPONSE	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**n**	**o**	**p**	**q**	**r**	**s**	**t**	**u**	**v**	**w**	**x**	**y**	**z**	**aa**	**bb**	**cc**	**dd**	**ee**	**ff**	**gg**	**hh**	**ii**	**jj**	**kk**	**ll**	**mm**	**nn**	**oo**	**pp**	**qq**	**rr**	**ss**
a) aeroplane	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b) car horn	0	**6**	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
c) siren	0	0	**5**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d) helicopter	0	0	0	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
e) traffic	3	0	0	2	**4**	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0
f) train	0	0	0	0	1	**4**	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2
g) birds	0	0	0	0	0	0	**7**	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
h) cat	0	0	0	0	0	0	0	**6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
i) dog	0	0	0	0	0	0	0	0	**7**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
j) river	0	0	0	0	0	0	0	0	0	**3**	0	1	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
k) thunder	0	0	0	0	0	0	0	0	0	0	**2**	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
l) wind	1	0	1	0	2	0	0	0	0	0	3	**1**	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
m) doorbell	0	2	0	0	0	0	0	0	0	0	0	0	**4**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
n) door	0	0	0	0	0	0	0	0	0	0	0	0	0	**6**	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
o) keys	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0
p) knock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**8**	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
q) tap run	0	0	0	0	0	0	0	0	0	2	0	0	0	0	3	0	**4**	2	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
r) toilet	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	**5**	0	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
s) tap drip	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
t) dishes	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0
u) food fry	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**6**	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
v) kettle	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	**5**	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
w) alarm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**5**	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x) clock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	**6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
y) hairdryer	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
z) mower	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	**3**	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
aa) phone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
bb) baby	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**7**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
cc) laughter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**8**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dd) footstep	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	1	0	0	0	**6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ee) many	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**6**	3	0	0	0	0	1	0	0	0	0	0	0	0	1
ff) both	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**	0	0	0	0	1	0	0	0	0	0	0	0	0
gg) female	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**8**	0	0	0	0	0	0	0	0	0	0	0	0
hh) male	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	**7**	0	0	0	0	0	0	0	0	0	0	0
ii) snoring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**4**	0	0	0	0	0	0	0	0	0	0
jj) drawers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**5**	0	0	0	0	0	0	0	0	0
kk) office	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	**3**	0	0	0	1	0	0	0	1
ll) paper	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**7**	0	0	0	0	0	0	0
mm) typing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**6**	0	0	0	0	0	0
nn) glass	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**	0	0	0	0	0
oo) construction	2	0	0	1	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	**2**	0	0	0	1
pp) saw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**7**	0	0	0
qq) classic	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**5**	2	0
rr) modern	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	**6**	0
ss) restaurant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	**1**
Total Responses	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
% Correct	**13**	**75**	**63**	**25**	**50**	**50**	**88**	**75**	**88**	**38**	**25**	**13**	**50**	**75**	**38**	**100**	**50**	**63**	**13**	**25**	**75**	**63**	**63**	**75**	**13**	**38**	**75**	**88**	**100**	**75**	**75**	**38**	**100**	**88**	**50**	**63**	**38**	**88**	**75**	**25**	**25**	**88**	**63**	**75**	**13**

Total Mean **57.22%**

CHAPTER 7

Discussion

The main aim of this study was to develop an EST to investigate the effect of cochlear implantation on environmental sound perception in postlingually deafened adults with a moderately-severe to profound hearing loss, and to compare their performance with that of age-equivalent normal hearing listeners. It was hypothesised that: (i) the NH participants would score higher than the experienced CI users on the EST; (ii) for the pre-to-post CI group, scores on the EST would be higher post-surgery than pre-surgery, and (iii) for the pre-to-post surgery group, scores on speech perception tests would be higher post-surgery than pre-surgery. The results of this study supported the first hypothesis, and suggested that with larger participant numbers the other two hypotheses may also have been supported. This will be discussed in more detail in this chapter.

7.1 NH group vs. Experienced CI group comparisons

The results of the current study support the first hypothesis, with the NH group scoring significantly better than the experienced CI group on the EST. As there was no significant difference in the ages of the two groups, age-related factors that may have arisen in some previous studies have been avoided in this study. A significant difference was also found between the sound categories on the EST along with a significant interaction. This indicates that not only were some sound categories better recognized than others, but also that the NH and experienced CI group differed in terms of the relative difficulty experienced in perceiving sounds across the different sound categories. Post hoc analysis showed that the NH group recognized the ‘human’ sound category significantly better than the categories of ‘household’ or ‘office’, while the experienced CI group recognized the sound categories of ‘human’ and ‘arriving home’ significantly better than the category of ‘transport’. It is possible that CI users recognized ‘human’ and ‘arriving home’ sounds better that ‘transport’ sounds because of the differences in the weight of spectral and temporal information in these categories. However, it is also possible that the difference in performance between these sound categories is due to the reality that most of the “human” and “arriving home” sounds occur more frequently in everyday life of a CI user than do most of the “transport” sounds. It is well established that the greater the exposure so particular sounds, the greater the ability to recognize these sounds via the CI.

There was also a difference in the confusion patterns of the 2 groups. The error pattern for the experienced CI group was more diffuse than that of the NH group with the 12 most-common errors accounting for 70% of the NH group's errors, compared with the 28 most-common errors accounting for only 31% of the experienced CI group's errors. All but one of the sounds confused by NH listeners involved continuous waveforms with similar spectral characteristics. This suggests that temporal cues were well perceived, with subtle differences in spectral characteristics being the most common cause of confusions, even for NH listeners. The only common confusion made by NH listeners that did not involve a continuous waveform was the identification of 'knock on the door' as a 'construction' site. This confusion was probably due to the 'knock on the door' being perceived as 'hammering a nail' (i.e. 'construction site'). Common errors that both the NH and experienced CI groups shared were identifying 'wind' as 'train', identifying 'office' as 'restaurant', identifying 'tap running' as 'river/ stream babbling', identifying 'food frying' as 'tap running' and identifying 'thunder' as 'wind'. Again these were continuous waveforms with similar characteristics. Of greater interest is how the two groups performed differently from each other. Most of the additional errors made by the experienced CI group were similar to those made by the NH group in that they were generally continuous waveforms with similar spectral characteristics. The exaggerated difficulty in spectral differentiation displayed by the experienced CI group in comparison to the NH group is not surprising since a CI cannot provide the same degree of spectral resolution that is possible in the NH system.

A few of the common-confusions made by the experienced CI group were very different to those made by the NH group. These confusions can be separated into three groups: confusion of voice stimuli, confusion of high frequency stimuli, and confusion of temporally similar stimuli. Firstly, the most-common confusion for the experienced CI group was identifying the 'many males and females talking at the same time' stimuli as 'one male and one female talking at the same time'. In addition, two of the other common confusions were mistaking either the 'One male and female talking at the same time' or the 'many males and females talking at the same time' stimuli for the 'single male voice' stimulus. Therefore confusions between voice stimuli were common in the experienced CI group, but uncommon for the NH group.

Secondly, it was also common for experienced CI users to be confused between different high-frequency stimuli with similar temporal characteristics. These confusions included identifying 'glass breaking' as 'keys jangling', and identifying 'keys jangling' as 'food frying'. These confusions were uncommon for the NH group. Reasons for these confusions could be the crude spectral analysis performed by the CI, or alternatively it could be related to CI users having been deprived of high frequency sounds for many years because of their hearing loss. For example, it is possible that although the CI enables them to perceive the higher frequencies, their brain is still learning to interpret them in a way that would help them differentiate between such sounds.

Thirdly, it was common for experienced CI users to confuse stimuli with similar temporal characteristics. The ‘Dripping tap’ stimulus was identified as ‘footsteps’, and ‘footsteps’ was often identified as the ‘construction site’ stimulus (i.e. hammering nails). This is probably due to the fact that CI users are more reliant on temporal cues than NH listeners, therefore the differences in the spectral characteristics of these sounds were not sufficient to enable the CI user to differentiate between these stimuli.

For all CI users, (i.e. both the pre-to-post CI participants after surgery and the experienced CI users), testing was carried out in the implant-only condition. However, the opposite ear was not occluded for testing and therefore it should be considered whether residual hearing in the non-implanted ear contributed to their performance. The average pure-tone-audiogram of the non-implanted ear for the experienced CI users is shown in Figure 14.

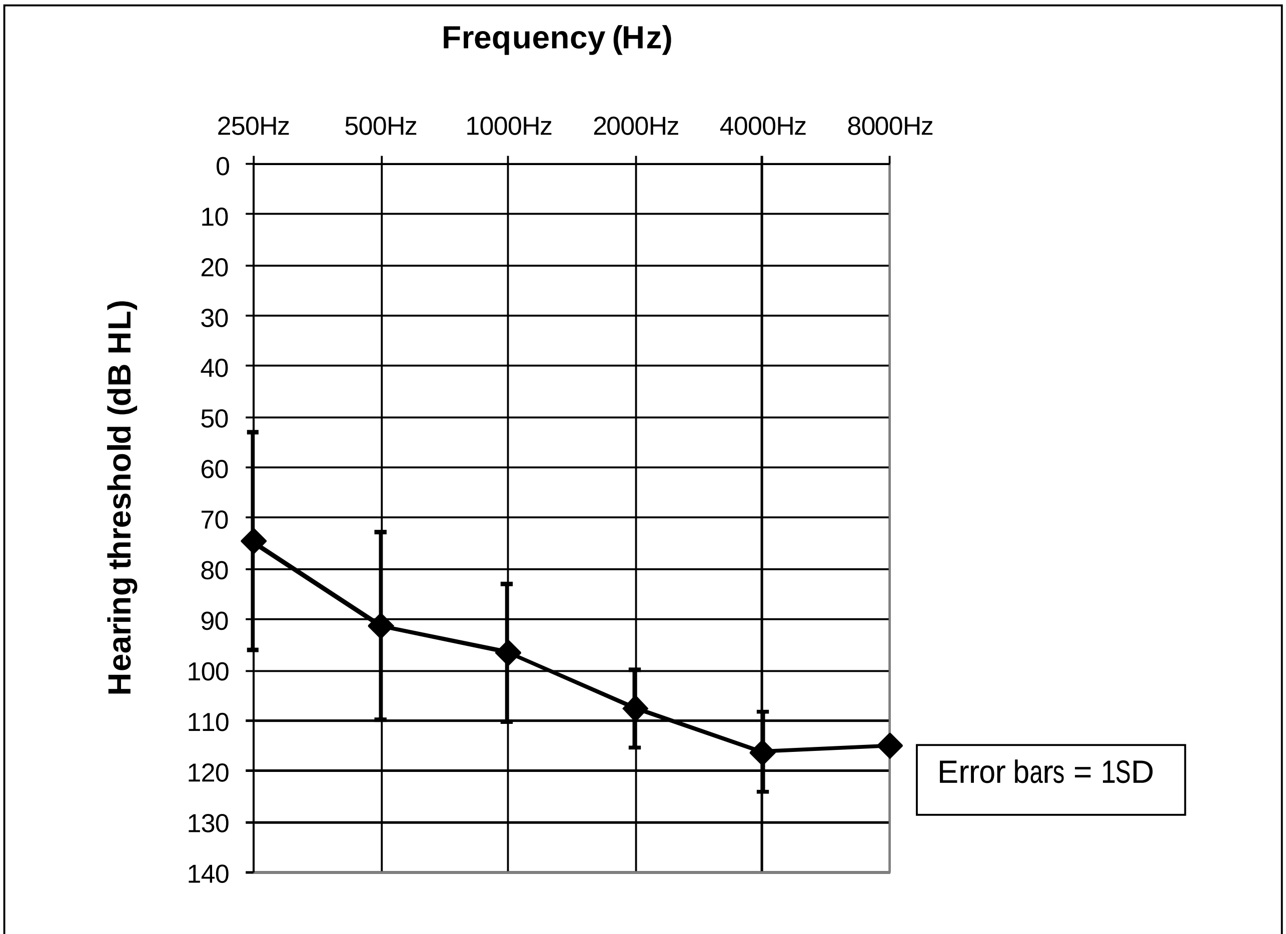

Figure 13: Average audiogram for the non-implanted ear for Experienced CI group

The absence of a correlation between residual hearing (LFA) and performance of the EST for the experienced CI group, suggests that the residual hearing in the un-implanted ear did not contribute to performance on the EST.

The fact that EST scores did not correlate with any of the speech perception measures indicates the importance of environmental sound perception as a separate skill for CI users, and that environmental sound perception is not simply an extension of speech perception. This highlights the importance of environmental sound perception testing in the measurement of CI benefit. In this study, EST scores did not correlate with the participant factors of age, duration of hearing loss, duration of CI use, or degree of residual hearing, suggesting that these were not confounding variables in this study.

In summary, the NH participants were significantly better than the CI users at identifying environmental sounds, although the error patterns of both groups indicate the importance of accurate spectral resolution and differentiation for identifying these stimuli.

7.2 Pre-to-post surgery comparisons

A secondary aim of this study was to look at the initial benefit of cochlear implantation on speech and environmental sound perception, by assessing participants with HAs prior to surgery, and then following up these same participants 3 months post switch-on of their CI. It was hypothesized that the pre-to-post CI group would perform significantly better post-surgery than pre-surgery on both speech tests and the EST.

7.2.1 Speech perception

The mean percentage-correct score on all the speech perception measures increased from the pre-surgery assessment to the post-surgery assessment. These differences were approaching significance. It is possible that the lack of participant numbers been contributed to the lack of a significant statistical result, with the mean percentage-correct improvement being 45.75% for the word stimuli and 46.25% for the sentence stimuli in quiet, and 51.5% for sentence stimuli in noise.

7.2.2 EST

The mean percentage-correct score on the EST also increased from the pre-surgery assessment to the post-surgery assessment. Again this difference approached significance; had there been more participants the difference may have reached statistical significance.

Although all four participants performed better on the EST post-surgery compared with pre-surgery, participants 1 and 4 performed poorer post-implantation in 3 and 2 categories respectively (out of 9). There is generally a large amount of variability in the performance of CI users on perceptual tests and there seemed to be no predominating reason for the drop in scores for these categories. However, it is possible that since switch-on of their CI (3 months), these two participants had less exposure to the sounds in the categories where they performed poorer, and were therefore unable to recognize them.

As was found for the NH and experienced CI users, most of the sounds confused for the pre-to-post surgery group both pre- and post- surgery involved continuous waveforms with similar spectral characteristics. Like the NH group, the pre-surgery group also identified ‘hairdryer’ as ‘wind’. In common with the experienced CI group, the pre-surgery confusion matrix showed common confusions to be the ‘siren’ being identified as ‘classical music’ and ‘doing dishes’ as being identified as ‘office’. These confusions are likely to be due to the importance of higher frequency spectral clues for their differentiation. These participants, pre-surgery whilst wearing their HA(s) would have had very little high frequency hearing. It was common for the participants when tested pre-surgery to be completely unaware of some of the higher frequency sounds such as the ‘whistling kettle’. They would often comment that if they could not hear a sound adequately, it must be a ‘high sound’ and they would then make a guess accordingly. Assuming that the following sounds were considered to be high-frequency sounds by the participant: keys jangling, breaking glass, whistling kettle, doorbell, telephone ringing, birds chirping and fire/ambulance siren, it can be seen from table 21 that 18.9% of the errors could have been due to this consideration.

Common confusions that were unique to the pre-surgery HA group was identifying ‘clock ticking’ as ‘knock on the door’, ‘cat(s) meowing’ as ‘birds chirping’, and ‘alarm clock’ as ‘whistling kettle’. Some of these confusions could also be due in part to the lack of high frequency spectral information received by these participants.

As would be expected, the post-surgery CI group made confusions that were similar to those of the experienced CI group than any of the other groups. As with the experienced CI group most of these confusions could be separated into three groups: confusion of voice stimuli, confusion of high frequency stimuli, and confusion of temporally similar stimuli. The most-common voice stimuli confusion made by the post-surgery CI group was identifying ‘one male and female talking at the same time’ as ‘many males and females talking at the same time’. Similar to the experienced CI users, the post-surgery CI users, identified ‘Aeroplane’ as ‘traffic’, ‘glass breaking’ as ‘keys jangling’, and ‘tap dripping’ as ‘footsteps’. These sounds are temporally very similar and differ spectrally. Two confusions that were unique to the post-surgery CI group were the identification of ‘keys jangling’ as a ‘running tap’ and ‘tap dripping’ as a ‘clock ticking’. Again these confused sounds were similar both temporally and spectrally.

As mentioned earlier, factors related to the reduced spectral resolution and/or deprivation for high frequency sounds may in part account for the difficulty with differentiating sounds based on their high frequency spectral content. The results highlighted the necessary reliance, of cochlear implant users, on temporal information for the identification of environmental sounds.

7.2.3 Learning effect

The finding that there was no significant change in performance on the EST between test sessions for the experienced CI group suggests the absence of a task-related ‘learning effect’ for this task. This is a relevant consideration in this study as the absence of a ‘learning effect’ suggests that any significant difference in the performance on the EST for the pre-to-post surgery group may be largely attributable to the different devices (i.e. HAs vs. CI).

However, it may also be possible that other non-device factors contributed to the improvements observed. For example the possibility of degree of concentration or attention could have been a factor. The possibility of a ‘halo effect’ must be considered – i.e. the expectation that the new device (the CI) would perform better than the old device (the HA). A lot of time, pain, and money is involved in cochlear implantation. Patients considering a CI are usually very keen for an improvement in their ability to hear. Consequently, there is a lot of emotional investment made by these patients getting a CI. Although ensuring that patients have realistic expectations for the CI is part of the assessment and counseling process, it would not be unreasonable for the patient to expect some degree of benefit from the CI. These factors could result in an increased level of concentration or effort displayed by the patient post-surgery with a CI, compared to pre-surgery with HAs, in a subconscious effort to maximise the benefit they have received. This could be further confounded by the feeling pre-surgery that “I get nothing from my HAs”, or that “the HAs are not doing anything so why bother trying?”

7.3 General discussion

7.3.1 Development and use of the EST

The main aim in the development of the EST for this study was to develop a more-difficult and more-comprehensive test than those used in previous research to avoid the possibility of ceiling effects impacting on the results obtained. This study had the largest closed-set size of all ESTs published in the literature thus far. This reduced the chance performance rate from the previously lowest rate of 6% for the Iowa EST to 2.2% for the EST in the current study. The results of the current EST suggest reduced potential ceiling or floor effects for any of the experimental groups. The best NH listeners were only able to perform up to scores of 99% (there were no scores of 100%), while the poorest performers, the HA users, achieved scores of greater than 25%, (which is significantly larger than the chance performance rate). There was also quite a wide range of scores for each participant group. The current EST also had strong test-retest reliability and was successful at being able to show significant benefits between the groups, when reasonable numbers of participants were involved.

7.3.2 Comparison to Reed and Delhorne’s (2005) study

Despite the use of different speech and EST materials (differences in the actual sound categories and the number of stimuli in each of the categories), and the inclusion of participants with different types of CI, it is worthwhile comparing the findings from the experienced CI group in this study to those from the study by Reed and Delhorne (2005). Similar to Reed and Delhorne (2005) this study also found no correlation between speech perception scores and scores on ESTs. Also error pattern analyses in both studies showed the importance of temporal characteristics in the identification of environmental sounds for CI users. For both studies, stimuli with distinct temporal characteristics were more accurately recognised by CI users, with confused sounds usually having similar temporal characteristics. Reed and Delhorne (2005) suggested that better performance with a CI may be related to better ability to resolve temporal differences and to use gross spectral cues.

A finding from the current study that differed to that of the study by Reed and Delhorne was the performance of CI participants across sound categories. Reed and Delhorne found similar performance across all ‘stimulus sets’ in their study, while in the current study a significant difference was found between sound categories. It should be noted though, that unlike Reed and Delhorne (2005) who had 10 sounds in each of their 4 categories, this study had 9 categories with differing numbers of stimuli in each category.

7.3.3 Speech perception

The results obtained in the current study can be used as a gauge to assess the suitability of the current implantation criteria at the SCIP. All of the pre-to-post CI surgery participants in this study performed better post-surgery than pre-surgery. This suggests that the current implantation criteria (i.e. having pre-surgery speech scores less than 60% correct in the best-aided condition and less than 40% correct in the ear to be implanted) ensure that most CI users obtain better speech and environmental sound perception post-surgery with a CI compared to pre-surgery with HAs. The significant improvement in speech perception outcomes for the participants of our study from pre- to post-implant indicates that this speech candidacy criterion is not too lenient.

7.3.4 Limitations

A few considerations are worth noting in interpreting the findings of the current study. Firstly, pre-surgery, HA users were tested in a bilateral HA condition, which was then compared to the (unilateral) implant-only condition. This means that any benefit shown by this comparison is possibly underestimated as CI users may perform even better with binaural hearing through the use of a HA on the other ear. The current protocols of the SCIP encourage newly implanted patients to only use their CI for the first few months while their brain acclimatizes to the ‘new sound’ of the implant. Therefore it is possible that the addition of a HA as the implantee becomes more experienced may result in even better results. Pre-surgery all participants had been fitted with and utilized bilateral HAs.

A second limitation of this study is that environmental sound perception in real life situations has many contextual cues. It is therefore quite unnatural to have only the auditory clues available for determining a sound. This could explain why even normally hearing adults are unable to achieve 100% correct on the EST. This reality indicates that any score on this EST will probably underestimate performance in real-life contexts. However, the score of this test does provide information on the differences in this task between normal hearing individuals and that of experienced CI users.

If this EST were to be revised, a review of the categories used may be considered. A few participants found some classifications confusing, and may have missed seeing sounds listed in other categories as a possible alternative answer. Also, a few of the sounds may need to be excluded from the test to further eliminate confusions that were not the fault of the participants. For example, confusions between the stimuli “river” and” running tap” or “office” and “restaurant” were still common for NH listeners, and is probably not unexpected considering the similarities between these sounds. It may also be necessary given the time constraints in the clinical setting to try and reduce the time necessary for the test. Following the revisions mentioned above, time to administer the test should be less of an issue.

Finally, the lack of participant numbers, particularly for the pre-to-post CI group, probably impacted on the lack of statistical significance in the results for that group. However, issues beyond the control of the researchers (e.g. participants living out of the city, a mid-year halt for the CI program due to external issues and the short time-frame for the research) precluded more participants from being included in the pre-to-post CI group.

7.3.5 Further research

Firstly, although the results of the four pre-to-post CI participants suggests benefit in environmental sound perception pre-to-post CI surgery, due to the issues discussed above, further research needs to be done to determine the significance of this benefit.

Secondly, more specialized testing is required in order to more-clearly address the relative contribution and importance of spectral and temporal cues for environmental sound perception.

Finally, extending the time-frame for the pre-to-post CI group follow-up, so that assessments could be carried out at 3, 6 and 12 months would be useful to see if further improvements in environmental sound perception are obtained over the first year post-implant. These results could be also compared with the performance of NH individuals.

CHAPTER 8

Conclusions and Clinical Implications

The results of this study support the hypotheses: NH participants scored higher than experienced CI users on the EST, and both EST and speech perception scores were higher post-surgery (with a CI) than pre-surgery (with HAs).

This study highlights the importance of temporal cues in the absence of spectral information for the perception of environmental sounds. Subtle differences in spectral characteristics for temporally similar sounds were the most-common cause of confusions, even for NH listeners. The results of this study suggest that the better performance of the NH participants was largely due to their more-accurate spectral resolution and differentiation. It is possible that because a CI is unable to provide the same degree of spectral resolution as the NH system, temporal cues are even more important for CI users. This highlights the need for explanation and consideration of the importance of temporal cues when counseling patients on the limitations of a CI.

Another counseling issue that this study raises is that context is an important part of environmental sound recognition. Environmental sound testing with a focus on auditory-alone perception does not allow context to be used by the CI user. CI users need to be aware that their performance on such a test does not mirror their performance in everyday environments. CI users can be counseled how to better use context cues to help with identification of environmental sounds in the natural environment.

Environmental sound perception has been shown by previous studies to be important for quality of life outcomes for CI users. The EST scores did not correlate with any of the speech perception measures used in this study. This suggests that environmental sound perception may be a separate skill for CI users unrelated to speech perception. This implies that it is important for an environmental sound test to be included in any comprehensive assessment CI benefit.

The EST developed as part of this study was more-difficult and more-comprehensive that those used in previous research. It was shown to have strong test-retest reliability and provide a high range of scores while minimizing ceiling and floor effects. The EST was also successful at showing significant benefit between groups when reasonable numbers of participants were involved. This suggests that, following a few minor modifications to make sure that potential responses in the closed set were unambiguous, it would be reasonable to use the EST developed as part of this study for assessment of CI benefit clinically.

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