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BILATERAL PROCESSING BENEFIT IN SEQUENTIALLY IMPLANTED ADULT COCHLEAR IMPLANT USERS

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LIST OF ABBREVIATIONS

It should be noted that the following abbreviations are used throughout the text:

BiCI: Bilateral cochlear implants
CI 1: First cochlear implant
CI 2: Second cochlear implant
CID: Central Institute for the Deaf (CID) Everyday Speech Sentences
dB: Decibel
EABR: Evoked auditory brainstem response
FDA: Food and Drug Administration Regulatory Body
HL: Hearing level
Hz: Hertz
ILD: Interaural level difference
ITD: Interaural time difference
NF: Noise directed from the front
NHS: National Health Services
NIH: United States National Institutes of Health
NL: Noise directed to the left ear
NR: Noise directed to the right ear
MSO: Medial superior olivary
n: Population
PCIP: Pretoria Cochlear Implant Programme
SNR: Signal-to-noise ratio
SPIN: Speech perception in noise
SPL: Sound pressure level
SR: Speech reception
SRM: Spatial release of masking
SRT: Speech reception threshold
SWN: Speech-weighted noise

GLOSSARY

Better cochlear implant: The cochlear implant considered as the better functioning implant or the superior cochlear implant, may be due to the fact that it is the ear with better residual hearing[1] and/or improved technology used in that specific implant (Litovsky, Cochlear Corporation, 2008b; Van Wieringen, 2010). Thus, a comparison between the first cochlear implant (CI 1) and the second cochlear implant (CI 2) is considered to determine the implant demonstrating the best performance. For sound localisation, the better performing implant represents the implant with which the participant could correctly localise the most speech weighted noise signals. For speech in noise perception, the better performing implant represents the implant with which the participant could correctly perceive the speech material at the lowest signal to noise ratio. The term "superior cochlear implant" will however be used.

Bilateral benefit: It is the benefit provided by two implants relative to only one implant (whichever implant had been shown to be the superior implant). The bilateral benefit was determined by comparing the results of the *cochlear implant demonstrating the best performance* to the results of *both implants* in tests of sound localisation and speech perception in noise (with speech and noise spatially separated and coincident).

Bilateral cochlear implantation: Two separate internal and external hardware systems, placed during separate surgeries (that is, sequential implantation) or during the same surgical procedure (simultaneous implantation) (Lustig & Wackym, 2005:126).

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[1] The more residual hearing in the ear implanted and stimulated effectively by the implant, the less auditory deprivation is present, consequently leading to better outcomes with the cochlear implant (Sharma et al., 2002:532-539).

Bilateral hearing/processing/benefit/abilities: Bilateral input occurs when both ears are presented with sound. Unlike binaural hearing, integration of sounds presented to the two ears may not occur in bilateral hearing (Litovsky, Cochlear Corporation, 2008b).

Bilateral spatial benefits: Bilateral spatial benefits include the head shadow effect, summation, squelch, and spatial release of masking (SRM), and are calculated to furthermore quantify the extent of bilateral/binaural benefit (Eapen et al., 2009:153; Van Deun, Van Wieringen & Wouters, 2010:702-713).

Binaural hearing/processing/benefit/abilities: Binaural refers to the integration of input along the auditory pathway after both ears have received sound, as happens in the normal auditory system (Litovsky, Cochlear Corporation, 2008b).

Dichotic listening condition: Listening condition where the speech and noise signals are spatially separated, i.e. speech is presented from the front (0°) and noise are presented from a different location (e.g. an angular difference of 45° or 90° between the loudspeakers that present the speech and noise) (Ramsden et al., 2005:989).

Diotic listening condition: Listening condition where the speech and noise signals are spatially coincident, i.e. both the speech and noise signals are presented from the same location (Ramsden et al., 2005:988).

Head shadow effect: The head shadow effect arises in the bilateral listening condition when the ear with the more favourable SNR is added in the bilateral listening condition (Litovsky et al., 2009:420). Thus, the head shadow effect is evident in spatially separated speech and noise conditions.

Sequential cochlear implantation: Two separate internal and external hardware systems, placed during separate surgeries (Lustig & Wackym, 2005:126).

Signal-to-noise ratio: This refers to the relationship wherein the overall level of the signal and the overall level of the background noise are compared. Thus, it is the relationship between the speech level as a function of frequency and the noise level as a function of frequency (Crandell & Smaldino, 2002: 608).

Simultaneous cochlear implantation: Two separate internal and external hardware systems, placed during the same surgical procedure (Lustig & Wackym, 2005:126).

Sound localisation: Localisation is the term referring to the ability to know the location of a sound-producing object and depends on two types of hearing, namely directional hearing and distance hearing (Flamme, 2002:10). Sound localisation facilitates the detection and identification of sound by means of binaural hearing (Tollin, 2007).

Spatial release of masking (SRM): This effect is defined as the improvement in speech perception as a result of spatial separation of speech and noise when listening with both ears.

Speech discrimination/recognition abilities: The ability of a person the identify words at a particular suprathreshold level, expressed in percentage of words correct in each list (Brandy, 2002:100-101).

Speech weighted noise (SWN) (speech spectrum noise): This is a white noise that is filtered to simulate the long-term average spectrum of conversational speech. It is filtered above 1000 Hz at a rate of 12dB per octave, thereby providing relatively more energy in the low-frequencies to approximate the frequency-energy distribution of speech. This reduction in the high frequencies produces a more limited bandwidth than white noise, making speech-weighted noise more efficient masker during speech perception testing (Katz & Lezynski, 2002:130).

Squelch: The enhancement in speech perception due to the addition of an ear with a poorer signal to noise ratio is known as the squelch effect (Cochlear Corporation Limited, 2005:1). The squelch effect utilises the advantage of a spatial separation between a primary signal source and a noise source, and is the result of the neural ability of the brainstem to make use of the distinct temporal and/or intensity differences at the two ears, as produced by each of the sources (Dunn & Ou, 2008:1-8; Müller et al., 2002:198-206; Schön et al., 2002:710). In the case of bilateral cochlear implantation, this effect is termed *binaural squelch*, which is defined as the additional advantage above the first stated head-shadow benefit and the contribution of the ear with the poorer SNR (Cochlear Corporation Limited, 2005:1).

Summation: The advantage of bilateral hearing with identical signals with the same auditory characteristics arriving at the two ears (Müller et al., 2002:198-206). This effect is produced by binaural redundancy (also known as diotic summation, that is, the difference between bilateral performance and better ear performance in spatially coincident speech and noise) and binaural loudness summation (Cochlear Corporation Limited, 2005:1; Schön et al., 2002:710).

Superior cochlear implant: The cochlear implant considered as the superior cochlear implant, may be due to the fact that it is the ear with better residual hearing[2] and/or improved technology used in that specific implant (Litovsky, Cochlear Corporation, 2008b; Van Wieringen, 2010). Thus, a comparison between the first cochlear implant (CI 1) and the second cochlear implant (CI 2)

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[2] The more residual hearing in the ear implanted and stimulated effectively by the implant, the less auditory deprivation is present, consequently leading to better outcomes with the cochlear implant (Sharma et al., 2002:532-539).

is considered to determine the implant demonstrating the superior performance. For sound localisation, the superior performing implant represents the implant with which the participant could correctly localise the most speech weighted noise signals. For speech in noise perception, the superior performing implant represents the implant with which the participant could correctly perceive the speech material at the lowest signal to noise ratio. The term “superior cochlear implant” will however be used, although the term “better implant” is also a recognized term in the field of cochlear implants.

ABSTRACT

Title: Bilateral processing benefit in sequentially implanted adult cochlear implant users
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Supervisor: Prof. De Wet Swanepoel
Co-supervisor: Dr. Catherine van Dijk
Department: Communication Pathology
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Bilateral cochlear implantation is accepted medical practice since 2008 in clinically suitable adults and children to enhance bilateral processing benefits. Bilateral implantation may lead to the restoration of some bilateral hearing advantages, such as improved speech recognition in noise, localisation, head shadow effect, summation, and squelch. The majority of the advantages stated in literature, though, are characteristic of the simultaneously implanted cochlear implant population. Simultaneous implantation is not yet a reality in South Africa due to funding constraints, therefore determining the bilateral processing abilities in sequentially implanted adults is essential. Determining bilateral processing benefits achievable with sequential implantation could result in evidence-based recommendations in terms of candidacy considerations, surgery protocols, motivations for medical aid funding for simultaneous cochlear implantation, and relevant measures to determine the bilateral processing benefit attainable. Furthermore, it might enhance audiologists' insight regarding post-implantation performance of sequentially implanted patients and enable them to counsel prospective candidates realistically. The aim of this study was to determine the bilateral benefit attained by sequentially implanted adults. A quantitative, cross-sectional research approach was followed in a one group post-test-only exploratory research design. A purposive convenient sampling method with specified selection criteria was used to select 11 adult clients of an established cochlear implant programme in Pretoria. Tests of sound localisation in the horizontal plane and speech perception in noise were performed. During the test of sound localisation, performance with only the first or only the second implant was found to be very similar. For the majority of participants the second cochlear implant (CI 2) was the superior performing implant during speech perception in noise testing, in spatially separated speech and noise conditions where noise was directed to the first implant, as well as in spatially coincident speech and noise. A statistical significant bilateral benefit ($p < 0.05$) was attained by sequentially implanted adults for sound localisation. A bilateral benefit for speech perception in noise was observed when noise was directed to the first implant and in the diotic listening condition with average benefits of 1.69 dB and 0.78 dB, respectively. It was not statistically significant ($p > 0.05$), however, and was smaller than bilateral benefit values achieved by simultaneously implanted adults in previous studies. The head shadow effect at 180° was found to be the strongest and most robust bilateral spatial benefit. Squelch and summation benefit values ranged from negative values to 2 dB and 6 dB, respectively. This corresponded with values found in previous studies. The improvement in speech perception in spatially distinct speech and noise from adding the ear with a better SNR (signal to noise ratio) indicated that the contribution of CI 2 seems to be greater than that of CI 1 for bilateral spatial benefit. It can be concluded that adults with sequential implants may achieve some extent of bilateral benefit even with many years of unilateral implant use, when speech processors differ, when the second implant is done ≥ 10 years after the first implant, and in cases of prelingual deafness. A key benefit of sequential implantation appears to be related to the advantage of having hearing on both sides so that the ear with the more favourable environmental signal-to-noise ratio is always available.

Key words: *bilateral benefit, bilateral implantation, bilateral processing, cochlear implant, head shadow effect, sequential implantation, simultaneous implantation, sound localisation, speech-perception-in-noise, squelch, summation, superior performing cochlear implant*

OPSOMMING

Titel: Bilaterale prosesseringsvoordeel in opeenvolgend-geïnplanteerde volwasse kogleêre inplantingsgebruikers
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Graad: M. Kommunikasiepatologie

Bilaterale kogleêre inplanting is sedert 2008 aanvaarde mediese praktyk vir klinies geskikte volwassenes en kinders, ten einde bilaterale prosesseringsvoordeel te verhoog. Bilaterale inplanting kan lei tot die herstel van sommige van die voordele van bilaterale gehoor, soos verbeterde spraakherkenning in lawaai, klanklokalisering, die kopskadu-effek, sommering en selektiewe onderdrukking (“squelch”). Die meeste van die voordele wat in die literatuur bespreek word, is egter kenmerkend van dié persone by wie twee kogleêre inplantings gelyktydig gedoen is. Gelyktydige inplanting is as gevolg van beperkte befondsing nog nie in Suid-Afrika ‘n werklikheid nie, daarom is dit noodsaaklik om te bepaal watter bilaterale prosesseringsvoordele by opeenvolgend-geïnplanteerde volwassenes voorkom. Die bepaling van watter bilaterale prosesseringsvoordele met opeenvolgende inplanting bereik kan word, sou kon lei tot getuienis-gebaseerde aanbevelings met betrekking tot besluite oor die geskiktheid van kandidate, protokol vir sjirurgie, motiverings vir die befondsing van gelyktydige kogleêre inplantings deur mediese voorsorgfondse, en toepaslike maatstawwe om te bepaal watter mate van bilaterale prosesseringsvoordeel haalbaar sou wees. Dit sou verder oudioloë se insig kon verbreed met betrekking tot die na-operatiewe prestasie van opeenvolgend-geïnplanteerde persone en hulle sodoende in staat stel om voornemende kandidate van realistiese raad te bedien. Die doel van hierdie studie was om te bepaal wat die bilaterale prosesseringsvoordele is wat deur opeenvolgend-geïnplanteerde volwassenes verkry kan word. ‘n Kwantitatiewe navorsingsbenadering met ‘n dwarsprofiel van ‘n enkelgroep is gevolg, met ‘n post-toets verkennende navorsingsontwerp. ‘n Doelgerigte gerieflikheidssteekproef met gespesifiseerde seleksiekriteria is gebruik om 11 volwasse kliënte van ‘n gevestigde kogleêre inplantprogram in Pretoria te selekteer. Klanklokalisering in die horisontale vlak en die waarneming van spraak in lawaai is getoets. Tydens die toets vir klanklokalisering is gevind dat prestasie met slegs die eerste of slegs die tweede inplanting soortgelyk was. Vir die meeste deelnemers aan die studie het die tweede kogleêre inplanting (KI 2) die beste prestasie gelewer tydens spraakwaarneming in lawaai, in omstandighede waar spraak en lawaai ruimtelik geskei is en die lawaai op die eerste inplanting gerig is, asook in omstandighede waar spraak en lawaai ruimtelik saamvoorkomend aangebied is. ‘n Statisties beduidende bilaterale voordeel ($p < 0.05$) is deur opeenvolgend-geïnplanteerde volwassenes vir klanklokalisering behaal. ‘n Bilaterale voordeel vir spraakwaarneming in lawaai is waargeneem waar lawaai op die eerste inplanting gerig is en ook in diotiese luistertoestande, met ‘n gemiddelde voordeel van 1.69 dB en 0.78 dB, onderskeidelik. Dit was egter nie statisties beduidend nie en was ook kleiner as die bilaterale voordeelwaardes wat in vorige studies deur gelyktydig-geïnplanteerde volwassenes behaal is. Die kopskadu-effek by 180° was die sterkste en mees robuuste bilaterale ruimtelike voordeel. Voordeelwaardes vir selektiewe onderdrukking en sommering het gewissel van negatiewe waardes tot 2 dB en 6 dB onderskeidelik. Dit stem ooreen met waardes wat in vorige studies gevind is. Die verbetering in spraakwaarneming in ruimtelik geskeide spraak en lawaai wat verkry is deur die oor met ‘n beter STR (sein-tot-ruis ratio) by te voeg, het daarop gedui dat die bydrae van KI 2 tot bilaterale ruimtelike voordeel waarskynlik groter as die bydrae van KI 1 is. Die gevolgtrekking kan gemaak word dat volwassenes met opeenvolgende inplantings ‘n mate van bilaterale voordeel verkry selfs na vele jare van unilaterale inplantingsgebruik, wanneer die spraakprosesseerders in die twee inplantings van mekaar verskil, wanneer die tweede inplanting ≥ 10 jaar na die eerste plaasvind, en in gevalle van prelinguale doofheid. ‘n Sleutelvoordeel van opeenvolgende inplanting hou klaarblyklik verband met die voordeel van gehoor aan albei kante te hê sodat die oor met die gunstigste sein-tot-lawaai ratio altyd beskikbaar is.

Sleutelwoorde: *bilaterale voordeel, bilaterale inplanting, bilaterale prosessering, kogleêre inplanting, kopskadu-effek, opeenvolgende inplantting, gelyktydige inplanting, klanklokalisering, spraakwaarneming in lawaai, selektiewe onderdrukking, sommering,*

kogleêre inplanting met beste prestasie

1. INTRODUCTION AND ORIENTATION

"Of all the changes that have taken place in the last forty years that have impacted upon people with hearing loss… the advent of cochlear implants has to rank as the most portentous" (Ross, n.d.).

AIM OF THE CHAPTER

Chapter one serves as an orientation to the research project. Current research on the topic is evaluated and shortcomings in the literature are described. The rationale for the study as well as the research question is formulated and explained within the context of the study field.

1.1 INTRODUCTION

Cochlear implantation has had a transformative impact on the way in which audiologists, ear nose and throat specialists, and related audiologic professions think about severe and profound hearing loss. Cochlear implants can be viewed as the most recent and effective means to habilitation and rehabilitation that provide useful hearing and improved communication abilities to children and adults with severe-to-profound hearing losses (Zwolan, 2002:740).

Over the last few years bilateral cochlear implantation has become increasingly common in clinical practice. However, this trend has occurred especially in the paediatric population (Sharma, Gilley, Martin, Roland, Bauer & Dorman, 2007:218). *Bilateral cochlear implantation* refers to two separate internal and external hardware systems, placed during separate surgeries (that is, sequential implantation) or during the same surgical procedure (simultaneous implantation) (Lustig & Wackym, 2005:126).

The auditory benefits of bilateral cochlear implants (both simultaneous and sequential) have been thoroughly investigated and reported in international literature. According to Neuman, Haravan, Sislian and Waltman (2007:73), research started in the early 1990's to determine whether bilateral cochlear implantation would provide significant binaural benefit. Recent research on bilateral cochlear implants has yielded important conclusions regarding bilateral advantage, that is, the overall benefit of using bilateral implantation over a single cochlear implant (Cochlear Corporation Limited, 2005:1). Bilateral cochlear implantation may lead to the restoration of some of the advantages of binaural hearing, such as improved listening or speech recognition in noise, localisation, directional hearing, binaural summation and squelch (Litovsky, Parkinson, Arcaroli & Sammeth, 2006b:714-731; Neuman et al., 2007:73-82; Sharma et al., 2007:218; Wolfe, Baker, Caraway, Kasulis, Mears, Smith, Swim & Wood, 2007:589-596). The debate in literature on the use of the term *bilateral* versus *binaural* benefit will be explored in depth in Chapter 2.

Background

Improved speech perception, especially in noise, is acknowledged as a potential benefit of bilateral cochlear implants (Iwaki, Masumura, Yasouka, Okumura & Kubo, 2004:228-229; Litovsky et al., 2004:648; Müller, Schon & Helms, 2002:198-206). According to Laszig et al. (2004:958-968) and Litovsky et al. (2006b:714-731) the strongest and most robust effect demonstrated for spatially separated speech in noise tests is the head-shadow effect that concerns speech perception in noise. This is purely a geometrical effect since the head acts as an acoustic barrier, causing frequency-dependent attenuation of the signal of the far side of the head in relation to the signal on the near side of the head (Schön, Müller & Helms, 2002:710). However, the brain must be able to attend to the ear with the better signal-to-noise-ratio (SNR) in order to take advantage of this physical, geometrical effect (Dunn & Ou, 2008:1-8). Thus, the head-shadow effect results in the user’s attention to the information available from the ear with the most favourable SNR. The head-shadow effect is not regarded as a consequence of binaural sound processing, but as a result of wearing two cochlear implant devices, which permits the person to take advantage of the presence of two different SNRs (Laszig et al., 2004:958-968). The result of the *bilateral head-shadow effect* (Laszig et al., 2004:958-968) is improved speech perception. This effect can be beneficial, for example, if the listener (user) listens to a speaker in a room with background noise. The barrier between the voice and the noise that is produced by the head and shoulders may enable the listener to hear the intended signal, specifically speech, more distinctly (Dunn & Ou, 2008:1-8).

Furthermore, improved speech perception in noise can be attributed to a second effect, namely the *binaural summation effect*. This is defined by Müller et al. (2002:198-206) as the advantage of bilateral hearing with identical signals with the same auditory characteristics arriving at the two ears. According to Schön et al. (2002:710), this effect is produced by binaural redundancy (also known as diotic summation, that is, the difference between bilateral performance and better ear performance in spatially coincident speech and noise) and binaural loudness summation. Binaural summation can improve speech perception scores by up to 19% in quiet environments and up to 16% in noise (Tyler, Gantz, Rubinstein, Wilson, Parkinson, Wolaver, Preece, Witt & Lowder, 2002:80-89; Van Hoesel, Tong, Hollow & Clarke, 1993:3188). Bilateral electrical stimulation provides the binaural auditory processing advantage of improved comprehension of speech as it occurs within a nonstatic environment, thus in everyday listening situations, particularly amid background noise (Laszig et al., 2004:958-968). This is significant since most speech interaction in everyday conditions occurs in the presence of background noise, and since a person's speech-perception-in-noise abilities decline with age and/or as hearing declines (Cainer &Rajan, 2008:155). In addition to the stated objective findings, Müller et al. (2002:198-206) report that most users of bilateral cochlear implants subjectively experience sound to be more natural and clear, in comparison to the experience with unilateral cochlear implantation. In addition, they experienced speech comprehension, especially in the presence of competing noise, as less demanding.

Most acoustical orientation abilities, as well as noise reduction, of the human auditory system depend crucially on a person having access to time, intensity, and spectral differences between sound signals as sensed binaurally (Müller et al., 2002:198-206; Nopp, Schleich & D'Haese, 2004:205-214). In comparison to monaural cochlear implant users as well as users with dual microphone input to a unilateral cochlear implant, Verschuur and Lutman (2003:13) found marked improvement in horizontal localisation abilities of bilateral cochlear implant users for a range of stimuli with different spectral and temporal characteristics. In addition to displaying an average improvement of 30° in accuracy of localisation, users of bilateral cochlear implants tend to be more consistent in their localisation judgments (Nopp et al., 2004:205-214). Simultaneous cochlear implantation was found to enhance the ability to identify the sound source location in both paediatric and adult users (Litovsky et al., 2004:648-655; Neuman et al., 2007:73-82; Sharma et al., 2007:218). This improvement in the accuracy and consistency of localisation may enable the user with bilateral cochlear implants to turn more accurately toward the speaker, allowing access to visual clues for speech reading (Neuman et al., 2007:73-82). Thus, improved sound localisation skills could augment speech perception abilities further. Ultimately, the binaural advantage for localization due to bilateral cochlear implantation could enhance the individual users' sense of well-being in their environment (Laszig et al., 2004:958-968). This is possible because an improvement in bilateral cochlear implant users' ability to orientate themselves in their physical environment can enhance their functioning in social, communicative, and safety facets of daily life.

The advantages of binaural hearing as realized in the use of bilateral cochlear implantation can also be attributed to a third effect known as the *squelch effect* (Müller et al., 2002:198-206; Schön et al., 2002:710). The squelch effect utilises the advantage of a spatial separation between a primary signal source and a noise source, and is the result of the neural ability of the brainstem to make use of the distinct temporal and/or intensity differences at the two ears, as produced by each of the sources (Dunn & Ou, 2008:1-8; Müller et al., 2002:198-206; Schön et al., 2002:710). In the case of bilateral cochlear implantation, this effect is termed *binaural squelch*, which is defined as the additional advantage above the first stated head-shadow benefit and the contribution of the ear with the poorer SNR (Cochlear Corporation Limited, 2005:1).

The squelch effect and the binaural summation effect both require binaural processing by the brain, whereas the head-shadow effect merely entails attending to the ear with the more favourable signal-to-noise ratio (Schön et al., 2002:710). Hence, the head-shadow effect is known as a monaural processing effect as opposed to the binaural processing effects of binaural summation and the squelch effect (Schön et al., 2002:710).

Speech perception in spatially separated and spatially coincident speech and noise, as well as sound localisation are reported in the literature to be the most significant benefits of bilateral cochlear implantation. These can be referred to as binaural hearing abilities and/or the binaural benefit. To determine whether a bilateral cochlear implant user is taking advantage of the binaural benefit, the audiologist should therefore investigate the client's abilities of sound localisation and speech perception in noise, especially in spatially separated and spatially coincident speech and noise. The majority of the advantages stated in the literature, however, were found to be characteristic of the *simultaneous* cochlear implant population (Dunn, Noble, Tyler, Kordus, Gantz & Haihong, 2010:296-298; Eapen, Buss, Adunka, Pillsbury & Buchman, 2009:153-159; Galvin, Mok, Dowell & Briggs, 2008:636-646; Iwaki et al., 2004:228-229; Laszig et al., 2004:958-968; Litovsky, Parkinson, Arcaroli & Arcaroli, 2009:419-431; Litvosky et al., 2006b:714-731; Litovsky et al., 2004:648-655; Manrique, Huarte, Valdivieso & Pérez, 2007:224-231; Neuman et al., 2007:73-82; Sharma et al., 2007:218-223; Schon et al., 2002:710-714).

In individuals with normal hearing abilities, the peripheral and central auditory systems receive externally presented stimuli bilaterally. Interaction between these ipsi- and contralateral auditory pathways provide robust processing of signals. These result in more accurate speech perception performance in binaural listening compared to monaural listening conditions (Manrique et al., 2007:224). Thus, during a period of unbalanced binaural auditory input, which can be found in the sequential implant user population, it can be surmised that the effects discussed above would reduce the effectiveness of the cochlear implant (Sharma, Dorman & Spahr, 2002:532-539) especially in terms of binaural benefits due to the reduced experience of bilateral processing.

Sequential implantation implies a period of monaural auditory stimulation, thus leading to deprived auditory stimulation in the second implanted ear, even in the cases where a hearing aid is worn contralaterally. This increased auditory deprivation can be proportional to a decrease in neuronal plasticity (Litovsky et al., 2004:648-655) and widespread degeneration in the central auditory system (Sharma et al., 2002:532-539). According to Sharma et al. (2002:532-539), these changes include reduction in cell density in the spiral ganglion, anteroventral cochlear nucleus and ventral cochlear nucleus; changes in neural projections between brainstem nuclei; reduced cortical synaptic activity in cortico-cortical and cortico-thalamic connections; a reduced number of primary dendrites in cortical pyramidal cells; and a recruitment of auditory cortical areas by visual function. The extent of cross-modal recruitment of the auditory cortex increases as the duration of deafness increases. This deters the restoration of auditory processing in the auditory cortex of long-term deafened individuals, thus the adult population, after cochlear implantation (Lee, Lee, Oh, Kim, Kim, Lee & Kim, 2001:150). Teoh, Pisoni and Miyamoto (2004b:1714) suggest that this colonization of the auditory cortex by other sensory modalities is the main limiting factor in post-implantation performance, especially post-implantation performance of complex speech perception.

A study by Manrique et al. (2007:228) reported elevated auditory thresholds for the second implanted ear relative to the first implanted ear for the first two years after implantation. These elevated thresholds may reflect long-term consequences of auditory deprivation on the later-implanted ear that are not ameliorated by early or simultaneous implantation in the opposite ear. Furthermore, the second implanted ear often exhibits a poorer performance in bilateral speech perception tasks (Cochlear Corporation Limited 2005:3,4). Consequently, superior performance in the first implanted ear for sound perception on word/sentence level may be expected, resulting in a more limited experience of binaural processing than would typically be expected with sequentially implanted users. In addition, the extent of auditory deprivation may be considered a determining factor in cochlear implant users' sound localisation performance, as acclimatisation to bilateral cochlear implant use is necessary for the binaural ability of sound localisation (Neuman et al., 2007:73-82).

Rationale

The first published report on bilateral cochlear implantation dates back to 1993 (Van Hoesel, Tong, Hollow & Clarke, 1993: 3178-3189). Of the more than 70 000 patients universally who have received cochlear implants, approximately 3500 patients have undergone a second implantation (Lustig & Wackym, 2005:126). Müller et al. (2002:198-206) state that before 1995, bilateral cochlear implantation was not intended as primary treatment for restoration of binaural hearing abilities. It was mainly the result of a technology upgrade, where the second ear was implanted with newer technology, rather than replacing the older, first implanted device; a result of insufficient functioning of or inadequate performance of the device in the first ear, or at the request and discretion of the patient and surgeon in the pursuit of further improved hearing abilities in everyday listening situations (Laszig et al., 2004:958-968; Müller et al., 2002:198-206). Thus, the majority of these first bilateral cochlear implants were done in the adult population and by means of sequential surgical procedures. Recent international literature indicates an extension of the bilateral cochlear implant population as more paediatric cases of bilateral implantation are evident in reports on cochlear implantation research (Litovsky et al., 2004:648-655; Manrique et al., 2007:224; Sharma et al., 2007:218; Wolfe et al., 2007:589-596). In the South African context, of the total of 321 patients of the Pretoria Cochlear Implant Programme (PCIP) only 43 patients (approximately 13%) received bilateral cochlear implants, all of which were sequentially implanted. The cochlear implant programmes of Johannesburg, Tygerberg, and Port Elizabeth have 49, 72, and five patients respectively, all with sequential implants. To date, the Johannesburg and Tygerberg programmes are the only programmes known to have one and 14 simultaneously implanted users, respectively (Müller, 2010).

There are currently six cochlear implant programmes in South Africa, with Tygerberg and PCIP as the two largest implant programmes. It is clear that simultaneous implantation is not yet widely employed in South Africa as South African cochlear implant teams, specifically the PCIP, mainly implant bilateral implants sequentially (Cass, 2010). There are several reasons why patients in the South African context receive sequential cochlear implants, amongst others limited reimbursement or financial resources to fund simultaneous implantation surgery; limited state funding; additional risk and difficulty of extended surgical procedures; the practice of preserving one ear for future technologies; difficulty in obtaining collaboration from medical insurance providers/medical aid funds for simultaneous bilateral implantation; extended time needed for mapping two implants at the same time, which could lead to fatigue, especially in young children; and possibly the exchange rate and import tax costs as the major cochlear implant companies are located in the United States of America, France, Austria, and Australia (Laszig et al., 2004:958-968; Litovsky et al., 2006b:714-731; Sharma et al., 2007:218).

As stated earlier, the international trend is to implant children bilaterally, rather than adults (Peters, Wyss & Manrique, 2010:S21). This strong focus and increasing trend to provide bilateral implantation for children as opposed to adults is related at least in part to funding priorities. The National Health Services (NHS) in the most of the non-United State countries (e.g. Belgium, Canada) and the United Kingdom exclusively approve funding for bilateral implantation in *children* considering their developmental needs and life expectancy as well as cost-effectiveness of bilateral implantation, compared to that of adults (NHS, 2009; Peters et al., 2010:S25-26). The PCIP has a limited client base of bilaterally implanted adults, namely 4.36% (14) of a total of 321 clients, all of whom are sequential cochlear implant users (Cass, 2010). The total number of children who received bilateral implants is 29. Thus, more bilateral implants are evident in the paediatric population of the PCIP than in the adult population. Also, in previous research studies bilateral implantation in adults is less prevalent, with smaller sample sizes, compared to studies on the paediatric population. In general, studies on the adult population have used an average of eight to ten subjects (Eapen et al., 2009:153; Galvin, Hughes & Mok, 2010:368; Litovsky et al., 2004:648-655; Müller et al., 2002:198-206; Neuman et al., 2007:73-82; Schön et al., 2002:710-714; Verschuur & Lutman, 2003:13) while paediatric studies' sample sizes mostly range from 20 to more than a 100 participants (Manrique et al., 2007:224-231; Sharma et al., 2002:532-539; Sharma et al., 2007:218-223).

According to published literature, improvement in bilateral performance outcomes may be negatively influenced if the first implant is not received relatively early in life (on or before two to three years of age) and when the second implant is not done within five years of the first implant (Manrique et al., 2007:230-231; Sharma et al., 2002:532-539). However, Manrique et al., (2007:230-231) argues that these findings may not be applicable to cochlear implant users with a late initial implantation or with longer periods between the first and second implants. Wolfe et al., (2007:589-596) similarly reports that if a child receives his/her first implant by the age of three and the second implant not later than 10 years of age, improvement in the bilateral benefit of speech recognition in noise is evident. Improved localisation abilities for children who received their first implant at an early age and the second implant as late as 12 years of age can also be expected (Litovsky, Johnstone & Godar, 2006a:43-59). Thus, for children there seem to be a critical period for sequential implantation. The majority of international studies have focused on the benefit provided to children who received their second implant before 10 years of age with few published studies involving adolescents or adults (Galvin et al., 2010:369; Manrique et al., 2007:224-231; Wolfe et al., 2007:589-596). Yet, the study of Galvin et al., (2010:368-377), concluded that a second implant up to the age of 19 and an interval period of ≤ 16 years, may gain some bilateral benefit.

According to these findings, a patient can be considered as late implanted if the first implant is not done by the age of three and the second implant by the age of 19. Hence, from the literature a general conclusion can be drawn that the younger a person is at the time of the second implant and the shorter the duration between sequential implants, the greater benefit can be expected (Galvin et al., 2010:369). It is imperative, therefore, to consider the plasticity of the auditory nervous system, as it plays a significant part in the usability of binaural cues (Litovsky et al., 2004:648-655). It would appear that sequential cochlear implantation could affect the extent of the experience of binaural processing in terms of sound localisation, as well as speech perception in noise, especially spatially coincident speech and noise signals.

Limited experience of binaural processing in terms of sound localisation and speech perception in noise in the sequentially implanted adult cochlear implant population could prevent users from gaining optimal and functional use of bilateral cochlear implantation. Literature findings seem to point to the increased auditory deprivation in the later implanted ear as cause (Sharma et al., 2002:532-539; Wolfe et al., 2007:589-596). The research by Sharma et al. (2002:532-539) revealed that the human central auditory system’s maximal plasticity (the ability of neurons to change in response to experience, stimulus, or injury) has a sensitive developmental period of three and a half years and decreases to a great extent after seven years where after auditory cortex recruitment is often irreversible (Lee et al., 2001:149,150). Furthermore, according to Wolfe et al. (2007:589-596), up to a year of bilateral experience may be necessary to develop localisation abilities and improved speech perception in noise. This could impact on candidacy consideration, expectations, and surgery protocol considerations, as bilateral implantation at an early age or minimal time interlude between implantations may potentially serve to enhance each ear’s speech perception capacity (Wolfe et al., 2007:589-596). Thus, sequential cochlear implantation can influence the bilateral processing benefit experienced by sequentially implanted adult cochlear implant users. This is important because sound localisation has essential practical advantages as revealed in the ability to identify the location of a sound source successfully and also to use speech reading in addition to speech (Neuman et al., 2007:73-82). Improved sound localisation ability may thus further enhance speech perception in noise. As a result, improved quality of life might be experienced by sequentially implanted adult cochlear implant users when the extent of binaural processing is ensured.

Problem statement

Enhanced performance in binaural hearing tasks may improve the stated benefits of bilateral cochlear implantation. It is clearly essential to determine the bilateral processing benefits in sequentially implanted adult cochlear implant users. Data on this aspect is limited, however, especially in the South African context where sequential cochlear implantation is more commonly performed than simultaneous implantation at most centres. Furthermore, Litovsky et al. (2006b:714-731) urged more research to be conducted in the adult population implanted with sequential surgeries. In the current South African context determining the bilateral processing benefit abilities of sequentially implanted adult cochlear implant users could result in evidence-based recommendations. These recommendations may assist team members in the following: candidacy considerations, surgery protocols, motivations for medical aid funds to fund simultaneous cochlear implantation, and relevant measures to determine the bilateral processing benefit. Furthermore, it might enhance audiologists' insight in post-implantation performance of sequentially implanted patients in order to counsel prospective candidates realistically. Determining the outcomes may help to ensure service delivery that is accountable and optimise bilateral cochlear implant clients' performance and satisfaction. The question to be addressed by this research project therefore is:

"What is the bilateral processing benefit in sequentially implanted adult cochlear implant users?"

1.2 ORGANISATION OF THE STUDY

A description of the layout of chapters included in the research report is provided below.

Chapter 1

Chapter One serves as an orientation to the research project. Current research on the topic is evaluated and shortcomings in the literature are described. The rationale for the study as well as the research question are formulated and explained within the context of the study field.

Chapter 2

This chapter entails the theoretical component of the study. The concepts and constructs regarding the subject are explored by means of a literature study and survey. The focus of this chapter is to evaluate the existing research on this specific issue critically and to determine the value and relevance of these studies for the current research project.

Chapter 3

The aim of Chapter Three is to describe the methodology of the research study. The research design, the main aim and sub-aims of the study are described. A quantitative research approach is embraced. In the context of applied research, explorative, comparative research techniques are utilized in a one group post-test-only exploratory research design that includes the use of test battery of measurements. A description of the participants, material, and apparatus used, and procedures for participant selection as well as for data collection, recording and analysis, are included in this chapter in such a way that the reader or any other researcher will be able to duplicate the study exactly in every aspect.

Chapter 4

Chapter Four presents all the collected and processed data as research results and findings.

Chapter 5

The results presented in Chapter Four are discussed according to the different sub-aims and followed by an interpretation of each finding.

Chapter 6

Conclusions are drawn from the results relating to each sub-aim and the conclusions are discussed based on the findings of the study. Clinical implications for the Pretoria Cochlear Implant Programme, audiologists and related professionals in the field of cochlear implantation as well as for possible sequentially implanted candidates are discussed and followed by a critical evaluation of the study. Recommendations regarding further research are indicated.

1.3 CONCLUSION

The advantages of simultaneous bilateral implantation are clear from international literature. Due to financial and socio-economical restrictions, however, simultaneous bilateral implantation is not always possible in South Africa, and therefore many patients receive sequential cochlear implantations. The advantages of bilateral hearing have been listed and these advantages are most often present in simultaneous implantation where binaural processing is better achieved. Therefore, an investigation into binaural processing with sequentially implanted adult cochlear implant users is important in order to determine the benefit that can be expected. Outcomes of this investigation may guide users of sequential implants in terms of realistic expectations and suggest clinical guidelines for future bilateral implantation and auditory rehabilitation.

1.4 SUMMARY

This chapter explored the auditory benefits of bilateral cochlear implantation, binaural processing skill and how it may differ between simultaneous and sequential implantation, as well as the current status of bilateral implantation in the South African context. The rationale and statement of the problem were also provided. Furthermore, the organisation of information in the chapters was briefly summarised.

2. BILATERAL COCHLEAR IMPLANTATION - HISTORICAL OVERVIEW AND FACTORS RELATING TO BILATERAL PROCESSING BENEFIT

AIM OF THE CHAPTER

This chapter presents the theoretical component of the study. The focus of this chapter will be to evaluate the already existing research critically and to determine the value and relevance of these studies investigation to this study at hand.

2.1 DEVELOPMENT OF COCHLEAR IMPLANTS

Cochlear implantation is regarded as one of the significant attainments of modern medicine (Wilson & Dorman, 2008:3). The concept of cochlear implantation was initiated in a simplistic form in the early 1790s when Allesandro Volt, an Italian professor of physics, connected the ends of a battery pile with a wire that terminated in a conductive rod. Subsequently, he placed each of the rods within his ear canals and experienced a sensation described as a “boom within the head” followed by an auditory sensation similar to “boiling, thick soup” (Clark, 2003:2; Wilson & Dorman, 2008:4). This was the first report of auditory perceptions elicited with electrical stimulation. However, there is uncertainty whether the percepts were produced by direct electrical activation of auditory neurons or by means of electro-mechanical effects (Wilson & Dorman, 2008:4). Furthermore, since this experience was primarily unpleasant, only sporadic attempts were made over the following 50 years to investigate this phenomenon further (Clark, 2003:3).

It was only in 1855 that a subsequent researcher, Duchenne of Boulogne, stimulated the ear with an alternating current, which was produced by inserting a vibrator into a circuit containing a condenser and an induction coil (Clark, 2003:3). Clark (2003:3) states as reason for Duchenne’s use of an alternating current an appreciation of the fact that sound is an alternating disturbance in an elastic medium, therefore stimulating the auditory system with a direct current could not reproduce a satisfactory hearing sensation.

One of the first recorded attempts to stimulate the auditory nerve directly was that by Lundberg in 1950, who ventured to activate the nerve by means of a sinusoidal current during a neurosurgical operation. The patient, however, could only hear “noises” (Clark, 2003:6).

In 1957, in Paris, Djourno and Eyriès conducted the first implantation of an electrical device for electrical stimulation of the auditory nerve (Clark, 2003:6). They made of use of an induction coil, with one end of a telecoil placed on the stump of the auditory nerve or adjacent brainstem and the other end within the temporalis muscle. After a few months of use, device failure was reported due to a breakage in the ground electrode in the temporalis muscle (Clark, 2003:6). With postoperative rehabilitation the patient was able to sense the presence of environmental sounds, although neither speech reception nor discrimination among speakers or sound sources were attainable. Still, he was able to distinguish between large changes of frequencies of stimulation below approximately 1000 Hz as well as among speech sounds in small, closed sets. This patient was re-implanted after the failure of the first device, but the second device also failed after a short period due to the same reason as for the first failure (Clark, 2003:6; Wilson & Dorman, 2008:4).

Djourno and Eyriès’s demonstration of direct electrical stimulation of the auditory system was not widely known outside France until years later (Wilson & Dorman, 2008:4). Doctor William F. House, in Los Angeles, read a newspaper article about the attempt by the two pioneers. Consequently, he initiated an effort to develop a practical and reliable way to treat severe to profound hearing loss by electrical stimulation of the cochlea. Doctor House performed the first single channel implants with a transcutaneous link in January 1961 on three patients by a short insertion of gold wire into their cochleas (Clark, 2003:6). These patients were able to perceive environmental sounds, speech rhythm, and music, but were unable to understand speech (Wilson & Dorman, 2008:4-5). The work was undertaken in conjunction with neurosurgeon John Doyle and James Doyle, an electronic engineer (Clark, 2003:6-7).

After the initial implantations by Doctors House and Blair, several other endeavours commenced worldwide in the late 1960s and 1970s. According to Clark (2003:7), Simmons implanted the first multichannel implant with a transcutaneous link in 1964. The patient was able to perceive speech signals, but could not attain speech discrimination. From Simmons's work it became clear that electrode placement was critical, as no hearing could be experienced unless two electrodes were aligned parallel to the nerve fibres. Furthermore, the tonotopic theory was confirmed by the finding that to produce a tone of a specific frequency artificially by electrical stimulation, the auditory nerve fibres that normally convey this frequency should be stimulated (Clark, 2003:7). All of the subsequent efforts involved electrical stimulation of the auditory system by means of an electrode or an electrode array inserted into the scala tympani.

Concurrent developments in cochlear implantation took place in various countries. In 1971 Michelson and Schindler presented their human cochlear implant research to the American Otology Society. Consequently, Advanced Bionics Corporation was founded in 1993 and approval was received from the Food and Drug Administration Regulatory body (FDA) in 1996 (www.advancedbionics.com). By 1975, 13 patients in the United States had functioning single channel cochlear implants. At this time the United States National Institutes of Health (NIH) commissioned a study under Doctor Robert C. Bilger and his colleagues. One of their key findings was that cochlear implant users' speech reception was not yet optimal, yet they were able to achieve significantly better on assessments of lipreading and recognition of environmental sounds with their cochlear implants than without it. Hochmair and Desoyer formed the Med-El Corporation in 1976 and it received approval from the FDA in 2000 (www.medel.com).

In Australia in 1978, Doctor Graham Clark implanted three patients with a ten channel device and they could achieve some speech discrimination. Subsequently, the Cochlear Corporation was formed. In 1985 the FDA granted approval for cochlear implantation for adults, and approval for cochlear implantation in children in 1990 (www.bionicear.org; www.cochlear.com).

In 1988, the NIH convened the first of two consensus development conferences on cochlear implants (Wilson & Dorman, 2008:3-21). The first consensus conference was held in 1988 and suggested that multi-channel implants (with multiple channels of processing and with multiple sites of stimulation in the cochlea) were more likely to be effective than single-channel implants. Approximately 3000 patients had received cochlear implants by 1988. New and highly effective processing strategies for cochlear implants were developed in the late 1980s and early 1990s, principally through the Neural Prosthesis Program (NPP). The continuous interleaved sampling (CIS, Wilson et al., 1991, in Wilson & Dorman, 2008:5) and spectral peak (SPEAK, Skinner et al., 1994, in Wilson & Dorman, 2008:5) strategies were among these, bringing large gains in speech perception performance. In 1995, approximately 12 000 patients had received implants and a second NIH consensus development conference was held. Progress in the field of cochlear implantation since the late 1980s and early 1990s was significant, and contemporary cochlear implants supported high levels of speech reception. A major conclusion that was reached was that the majority of individuals who received the latest speech processors would be able to score 80 percent correct on high-context sentences even without visual cues (Wilson & Dorman, 2008:3-21).

By the end of 2008, the cumulative number of cochlear implants worldwide had exceeded more than 170 000 which made the number of cochlear implants higher than the number of all other types of neural prostheses combined (Peters, Wyss & Manrique, 2010:S17-S18; Wilson & Dorman, 2008:4-6).

2.2 DEVELOPMENT OF COCHLEAR IMPLANTATION IN SOUTH AFRICA

The development of cochlear implantation in South Africa commenced in the late 1980s. Two surgeons, in Johannesburg and in Durban, without any prior experience and without following a team approach, implanted 30 to 50 single channel and early multichannel devices. Most of the implantees had very poor outcomes and have become non-users. After these early attempts by individuals, multi-disciplinary cochlear implant units were started up at various institutions of tertiary education where medical practitioners were trained and research could be conducted. During 1986 the first cochlear implant unit was established at the University of Stellenbosch at Tygerberg Hospital. The first adult was implanted on the 4th of November 1987 at Tygerberg Hospital, Western Cape, by Professor Derrick Wagenfeld. The cochlear implant units at the University of Pretoria and the University of Johannesburg were established in 1991. The Pretoria Cochlear Implant Programme (PCIP) was started with two adults being implanted in the first year. Currently, approximately 20 children and 15 adults are implanted annually (Cass, 2010). The cochlear implant unit in Bloemfontein was inaugurated in 2002 and initially started with auditory brainstem implants. By the end of 2010, more than 1120 implantations had been performed in South Africa at the various cochlear implant units (Cass, 2010).

Bilateral cochlear implantations can be considered as a fairly recent development in cochlear implantation field. The first study on bilateral cochlear implantation dates back to 1993 (Van Hoesel et al., 1993: 3178-3189). Out of the total of 321 patients of the PCIP, only 43 patients (approximately13%) received bilateral cochlear implants. All of these were sequentially implanted. The cochlear implant programmes of Johannesburg, Tygerberg and Port Elizabeth have recorded 49, 72 and five patients, respectively, with sequential implants. To date, the Johannesburg programme has one simultaneously implanted user and the Tygerberg programme has 14 simultaneously implanted users (Müller, 2010). In international reports on cochlear implantation research it is evident that there is a definite increase in bilateral cochlear implantations (Litovsky et al., 2004:648-655; Manrique et al., 2007:224; Sharma et al., 2007:218; Wolfe et al., 2007:589-596).

2.3 CURRENT STATUS OF SEQUENTIAL COCHLEAR IMPLANTATION IN THE SOUTH AFRICAN CONTEXT

Of the approximately 1121 implantees in South Africa, approximately 200 users received a second device, all of which were sequentially implanted except for the 14 simultaneous implantations at Tygerberg and one simultaneous implantation at the Johannesburg programme (Müller, 2010). The use of sequential implants influences the development of listening skills (Galvin et al., 2008:637), especially as these skills require bilateral processing. According to Galvin et al. (2008:637), the dominance of the first implanted cochlea, and reluctance to use the second implant alone together with a lack of confidence in the second implant can influence the patient’s progress in acquiring listening skills.

Gains from sequential cochlear implantation most likely arise from a partial or full restoration of the binaural difference cues and to the head shadow effect, as suggested above. Bilateral electrical stimulation, as provided by sequential implantation, utilises or reinstates a part of the natural auditory system (Wilson & Dorman, 2008:17). The extent of bilateral processing achieved, should be evaluated in order to determine the comprehensiveness of the bilateral advantages of sequential cochlear implantations.

2.4 A REVIEW OF BILATERAL COCHLEAR IMPLANTATION IN ADULTS

The first White Paper on bilateral cochlear implantation was drafted and published in 2008, namely, the William House Cochlear Implant Study Group: Position Statement on Bilateral Cochlear Implantation (Balkany et al., 2008:107). This paper underscored the importance of bilateral cochlear implantation in clinically suitable adults and children (Balkany et al., 2008:107). Since 2008, bilateral cochlear implantation is considered an accepted medical practice (Balkany et al., 2008:107). International literature indicates that improved binaural hearing abilities are regarded as the most significant benefits of bilateral cochlear implantation. Binaural listening involves the detection of similarities and contrasts in information arriving at each ear, which contributes significantly to sound localisation as well as speech perception in noise via mechanisms such as the head-shadow effect and binaural unmasking (Galvin et al., 2008:637). These binaural skills are dependent on bilateral balancing of both cochlear implants by a qualified audiologist, by using cochlear implant software to balance the two implants with regard to loudness and pitch (Litovsky et al., 2004:648-655). Bilateral electrical stimulation may reinstate at least to some extent the interaural amplitude and timing difference cues that allow people with normal hearing to lateralise sounds in the horizontal plane and to attend selectively to a primary auditory signal, i.e. speech, among multiple other sound sources at different locations (Wilson & Dorman, 2008:17). For binaural hearing abilities to be functional, binaural processing is necessary. Thus, to determine whether a bilateral cochlear implant user is able to process binaurally, the audiologist should investigate the client’s abilities of sound localisation and speech perception in noise, especially in spatially separated and spatially coincident speech and noise.

Table 2.1 summarises the results of previous and existing studies on bilaterally implanted adults’ bilateral processing benefit, i.e. speech perception in noise and sound localization abilities.

Table 2.1: A summary of reports on bilateral processing benefit in bilaterally implanted adults

Year	Title of study and author	Aim of investigation	Findings
1993	Psychophysical and Speech Perception Studies: A Case Report on a Binaural Cochlear Implant Subject. Van Hoesel, R. J. M., Tong, Y. C., Hollow, R. D. & Clark, G. M. *Journal of the Acoustical Society of America,* 94(6): 3178-3189.	To investigate further improvements in speech perception in quiet and in noise for cochlear implant patients with speech processing strategies using binaural implants. A series of initial psychophysical and speech perception studies on the authors’ first binaural cochlear implant patients is presented.	For an approximate matching of the places of stimulation on the two sides, the subject usually reported a single percept when the two sides were simultaneously stimulated. Lateralisation was strongly influenced by amplitude difference between the electrical stimuli on the two sides, but only weakly by interaural time delays. Speech testing, comparing monaural with binaural electrical stimulation, showed a binaural advantage particularly in noise. The authors concluded that advantages in speech perception may be obtained with bilateral implants, and therefore encouraged further research on subjects with bilateral cochlear implants.
2002	Speech Understanding in Quiet and Noise in Bilateral Users of the MED-EL COMBI 40/40+ Cochlear Implant System. Müller, J., Schon, F. & Helms, J. *Ear and Hearing,* 23(3): 198-206.	The purpose of this study was to investigate speech understanding in quiet and in noise (with speech and noise spatially separated) in subjects bilaterally implanted with multi-channel cochlear implants.	Bilateral cochlear implantation provides a significant benefit in speech understanding in quiet and in noise. The substantial improvement experienced by most subjects, correlated with the subjective benefit they experienced. They reported that sounds are “more natural”, “clearer”, “richer”, and “fuller”. All subjects concluded that bilateral speech perception is easier and less demanding, especially in difficult situations where competing noise is presents.
2002	Speech Reception Thresholds Obtained in a Symmetrical Four-Loudspeaker Arrangement from Bilateral Users of MED-EL Cochlear Implants. Schön, F., Müller, J. & Helms, J. *Otology & Neurotology,* 23:710-714.	To investigate speech reception in noise in subjects with sequential or simultaneous cochlear implantation of multi-channel implants.	The results indicated that bilateral cochlear implant users are able to binaurally process speech with a substantial gain in signal-to-noise ratios of approximately 4 dB on average. In addition, the gain in signal-to-noise ratios was essentially stable for as long as 4.4 years.
2002	Three-month Results with Bilateral Cochlear Implants.	To evaluate possible binaural listening advantages for speech in quiet, speech perception in noise	For speech perception in spatially coincident speech and noise (speech and noise presented form the front), a

	Tyler, R.S., Gantz, B.J., Rubinstein, J.T., Wilson, B.S., Parkinson, A.J., Wolaver, A. et al. *Ear and Hearing,* 23(1) Supplement: 80-89.	(with speech and noise spatially separated and coincident), and for localisation in a group of post-lingually deafened adults with bilateral cochlear implants functioning independently after 3 months of bilateral experience.	significant bilateral advantage was present for most subjects. In the spatially separated speech and noise condition, a significant bilateral benefit was evident for all subjects. Thus, bilateral implants can provide real advantages, particularly when it is possible to utilise the ear that is away from a noise source, thus taking advantage from the head shadow effect. Localisation ability was generally better with two implants than with one.
2003	Auditory Localization Abilities in Bilateral Cochlear Implant Recipients Using the Nucleus 24 Cochlear Implant. Verschuur, C. & Lutman, M. *Cochlear Implants International,* 4 (Supplement 1): 13-14.	The aim of this study was to quantify binaural advantage for auditory localisation abilities in the horizontal plane by sequentially implanted users, and also to determine whether the use of dual microphones with the signal combined from both sides and routed to one implant improves horizontal localisation.	The results showed clearly that bilateral cochlear implantation provides marked improvement in horizontal localisation abilities compared to monaural cochlear implant use for a range of stimuli having different spectral and temporal characteristics. There was no evidence of benefit for localisation with dual microphones.
2004	A Case of Bilateral Cochlear Implantation (MED-EL Combi 40+). Iwaki, T., Masumura, E. Y., Okumura, S. & Kubo, T. (2004). *Cochlear Implants International,* 5(Supplement 1): 228-229.	To assess the binaural listening advantages for speech perception in noise (spatially separated and coincident), and to investigate sound localisation by a simultaneously implanted cochlear implant user of the MED-EL COMBI 40+.	Results indicated that simultaneous bilateral implantation improves listening to speech performance in noise, and can restore the ability to localise sounds.
2004	Benefits of Bilateral Electrical Stimulation with the Nucleus Cochlear Implant in Adults: 6-month Postoperative Results. Laszig, R., Aschendorff, A., Stecker, M., Müller-Deile, J., Maune, S., Dillier, N. et al. *Otology and Neurotology,* 25(6): 958-968.	To evaluate the benefits of bilateral electrical stimulation for hearing-impaired adults in a multicentre study, and to compare and quantify performance on speech perception measures in quiet and in noise and localisation ability for unilateral and bilateral cochlear implant use.	A statistically significant binaural head shadow effect and binaural squelch effect were evident. Sequential or simultaneous cochlear implantation, and consequently bilateral electrical stimulation provides the foundation for the potential bilateral advantages of sound localisation, head shadow effect, and binaural auditory processing such as binaural redundancy and squelch effects, all of which combine to lead to improved speech perception over unilateral listening conditions.
2004	Bilateral Cochlear Implants in Adults and Children. Litovsky, R.Y., Parkinson, A., Arcaroli, J., Peters, R., Lake, J., Johnstone, P. & Yu, G. *Archives of Otolaryngology - Head and Neck Surgery,* 130(5): 648-655.	To measure the bilateral benefit, i.e. sound localisation and speech intelligibility in noise (speech and noise spatially separated and coincident) of simultaneously implanted adults and sequentially implanted children.	Findings of the study suggest that, for simultaneously implanted adults, bilateral implantation leads to better performance on the sound localisation task, on the speech perception in noise task when the noise is near the poorer of the two ears. In sequentially implanted children, localisation and right/left discrimination are slightly better under bilateral conditions, but not remarkably in speech perception in noise tasks.
2004	Sound Localization in Bilateral Users of MED-EL COMBI 40/40+ Cochlear Implants. Nopp, P., Schleich, P. & D'Haese, P. *Ear and Hearing,* 25(3):	The purpose of the study was to investigate sound localization with bilateral and unilateral cochlear implants for a group of early-deafened (after 5 to 6 years of age), late-implanted subjects.	This study's group of early-deafened, late-implanted subjects showed a statistically significant improvement in sound localisation when using both implants, compared with when using only one.

	205-214.		
2004	Head Shadow, Squelch, and Summation Effects in Bilateral Users of the Med-El COMBI 40/40+ Cochlear Implant. Schleich, P., Nopp, P. & D'Haese, P. (2004). *Ear and Hearing,* 25:197-204	Speech reception thresholds at which a 50% correct score was achieved were measured in spatially separated and coincident speech and noise.	Results showed a significant binaural summation effect. A mean 6.8 dB improvement binaurally due to the head shadow effect and 2.1 dB for summation was found. A mean binaural squelch effect of 0.9 dB was measured.
2005	Evaluation of Bilaterally Implanted Adult Subjects with the Nucleus 24 Cochlear Implant System. Ramsden, R., Greenham, P., O'Driscoll, M., Mawman, D., Proops, D., Craddock, L., et al. *Otology and Neurotology,* 25(6): 988-998.	To evaluate the speech perception benefits in quiet and in noise (in dichotic and diotic listening conditions) of sequentially implanted cochlear implant users.	A significant bilateral benefit for speech perception in quiet and in noise was evident. The second implanted ear had relatively poorer performance, compared to the first implanted ear. The authors concluded that sequential implantation with long delays between ears has resulted in poor second ear performance for some subjects and has limited the extent of bilateral processing benefit that can be obtained by these users.
2006	Simultaneous Bilateral Cochlear Implantation in Adults: A Multicenter Clinical Study. Litovsky, R.Y., Parkinson, A., Arcaroli, J. & Sammeth, C. *Ear and Hearing,* 27(6): 714-731.	Analysis of data from a multisite prospective study of simultaneously implanted adults with post-lingual acquired deafness on their speech recognition performance in quiet and in noise (spatially separated and coincident speech and noise) in unilateral and bilateral listening conditions at 1-, 3-, and 6-months post activation.	All subjects showed significant bilateral processing benefit on at least one of the speech perception measures, and no subjects performed consistently poorer with bilateral than with either of the unilateral test conditions. The strongest bilateral benefit was measured for the head shadow effect. Some subjects showed evidence of binaural squelch and summation.
2007	Sound-direction Identification with Bilateral Cochlear Implants. Neuman, A.C., Haravon, A., Sislian, N. & Waltzman, S.B. (2007). *Ear and Hearing,* 28(1): 73-82.	To compare the accuracy of sound-direction identification in the horizontal plane by simultaneously implanted cochlear implant users when localisation was measured with pink noise and with speech stimuli.	The data obtained in this study add to the growing body of evidence that sound-direction identification with bilateral cochlear implants is significantly better than with a single implant. The similarity in localisation performance obtained with the speech and pink noise supports the use of either stimulus for measuring sound localisation.
2007	Speech Perception and Localization With Adults With Bilateral Sequential Cochlear Implants. Tyler, R.S., Dunn, C.C., Witt, S.A., & Noble, W.G. *Ear and Hearing,* 28(2) Supplement: 86S-90S.	This study aimed to report on measures of binaural hearing benefits in terms of speech perception in quiet and in noise (spatially separated and coincident) and bilateral localization for sequentially implanted adults.	Results showed that all subjects received significant bilateral improvement on at least one speech perception test compared to either implant alone. A number of subjects demonstrated some bilateral localization abilities. The study concluded that sequential implants can be beneficial even after many years of monaural use and even with very different cochlear implants.
2008	Evaluation of Binaural Functions in Bilateral Cochlear Implant Users. Chan, J.C.Y., Freed, D.J., Vermiglio, A.J. & Soli, S.D. *International Journal of Audiology,* 47(6): 296-310.	As binaural abilities are difficult to assess, yet important to understand, this study aimed to develop a binaural assessment methodology using direct electrical input to the cochlear implant, "direct connect assessment", pre-processed by appropriate head-related transfer functions to simulate the binaural cues for spatial release from masking and sound localisation. In	The protocols and test methodology in this study were able to evaluate binaural processing abilities such as spatial release from masking, head shadow, binaural squelch, binaural summation, and sound localisation for bilateral implant users. All bilateral implants users who participated in this study reported that the sound of the direct connect input was as natural as the microphone input during sound

		addition, modified rules for adaptively measuring speech perception threshold in noise was created and evaluated. At third purpose was to develop a new sound localisation protocol whose difficulty is adjusted to the sound localisation ability of the individual cochlear implant user. Speech perception in noise thresholds and sound localisation scores were measured in the sound field and with the direct connect method in acoustic hearing subjects and cochlear implant subjects.	field testing, and that the clarity of the direct connect input was superior to the microphone input. The authors concluded that the results of this study together with participants' subjective observations, suggest that direct connect tests provide a realistic and convenient alternative to sound field tests in clinical settings.
2009	Hearing-in-Noise Benefits After Bilateral Simultaneous Cochlear Implantation Continue to Improve 4 Years After Implantation. Eapen, R.J., Buss, E., Adunka, M.C., Pillsbury III, H.C. & Buchman, C.A. *Otology and Neurotology,* 30: 153-159.	Assessing the stability of the binaural benefits of head shadow, summation, and squelch for simultaneously implanted adults over 4 years post-implantation in order to quantify these benefits for speech perception in noise benefits.	The bilateral processing benefits of head shadow and summation emerge early after simultaneous implantation and remain stable in the post-operative period. It was found that the squelch effect has the most protracted period of development, with increasing benefit only after a year or more of bilateral implant experience. This study concluded that binaural processing and integration continues to develop several years after simultaneous cochlear implantation.
2009	Spatial Hearing and Speech Intelligibility in Bilateral Cochlear Implant Users. Litovsky, R.Y., Parkinson, A., Arcaroli, J. & Arcaroli, J. *Ear and Hearing,* 30(4):419-431.	The abilities to localise sounds and understand speech in noise in a complex auditory environment (with speech and noise spatially distinct and coincident) were studied in a group of adults who were simultaneously or sequentially implanted (surgeries were not more than 1 month apart).	A bilateral benefit was evident when speech and noise were spatially separated, but not when they were presented from the same location. This benefit increased from 3 to 6 months of experience. Nearly all subjects were able to discriminate source locations to the right versus left, less than half were able to perform the more difficult task of sound localisation. The bilateral speech intelligibility scores were positively correlated with sound localisation abilities, so that listeners who were better able to hear speech in noise were generally better able to identify sound source locations.
2010	Bilateral and Unilateral Cochlear Implant Users Compared on Speech Perception in Noise. Dunn, C.C., Noble, W., Tyler, R.S., Kordus, M., Gantz, B.J. & Haihong, J. *Ear and Hearing,* 31(2): 296-298.	To evaluate the bilateral benefit of bilateral implant use versus unilateral implant use by comparing speech perception in noise 9spatially separated speech and noise) for simultaneously implanted users.	Simultaneously implanted users achieved significantly better performance on speech perception in noise compared with unilateral implant users.
2010	Can Adolescents and young adults with prelingual hearing loss benefit from a second, sequential cochlear implant? Galvin, K. L., Hughes, K. C. & Mok, M. *International Journal of Audiology,* 49(5):368-377.	This study aimed to determine if adolescents/young adults (≥ 10years of age, according to the United Nations definition) gained additional perceptual benefit from sequential bilateral cochlear implants within 12 months and to document adaptation the second implant. Assessment compromised a questionnaire (The Speech, Spatial and Qualities of Hearing Scale, SSQ), anecdotal reports of	The results of this study indicate that adolescents and young adults up to the age of 19 years may gain additional benefit from a second cochlear implant regarding bilateral perception, even if their hearing loss is congenital and it is more than 16 years than the receipt of their first implant

		device use and daily listening and speech perception in spatially separated speech and noise testing.	

From Table 2.1 it is clear that previous and existing studies on bilateral implantation in adults imply that bilateral cochlear implantation offers functional benefit ahead of that obtained by unilateral implantation. It is imperative that data collection and studies regarding second sequential implants in the adolescent and adult population continue, given the large number of potential second implant candidates in this age range internationally. These population groups differ from the paediatric group as they are able to make their own decision regarding surgery and are generally more responsible for their own device use and they are more independent (Galvin et al., 2010:369).

Bilaterally implanted adults' long-term outcomes may differ from early post-implantation outcomes. Studies that were conducted in time intervals (e.g. 3 months, 6 months, 12 months, and even 2 years and 4 years post-operatively) concluded that bilateral processing benefits may continue to improve over a period of time (Eapen et al., 2009:158; Litovsky et al., 2009:419-431). It is important to evaluate bilaterally implanted adults' bilateral processing benefits longitudinally as it may be difficult to ascertain bilateral processing benefits after 3 months of bilateral listening experience (Litovsky et al., 2004:648-655). Future work should be aimed at assessing and monitoring bilaterally implanted adults' bilateral processing benefits over time as their everyday living compromise of social, work, and learning situations in which the failure to communicate successfully is more likely to have significant consequences (Galvin et al., 2010:368-377).

In general, previous and existing studies on the adult population have had a small participant sample with an average of eight to ten subjects (Eapen et al., 2009:153; Galvin et al., 2010:368; Litovsky et al., 2004:648-655; Müller et al., 2002:198-206; Neuman et al., 2007:73-82; Schön et al., 2002:710-714; Verschuur & Lutman, 2003:13). Although a participant sample may be relatively small, subjects should present with different etiologies of deafness, duration of deafness, ear asymmetries, monolateral and bilateral listening experiences, MAP dynamic ranges, and microphone types. The latter are all variables known to affect bilateral processing performance (Chan, Freed, Vermiglio & Soli, 2008:296-310; Nopp et al., 2004:205-214; Litovsky et al., 2006a:43-59). Thus, further studies should aim to ensure that their participant sample is representative of the range of variables identified to have an effect on bilateral processing abilities as seen in a typical clinical setting (Chan et al., 2008:296-310).

There is limited data on early-deafened (after 5 to 6 years of age), late-implanted (in adolescence or later) subjects, and adults with delayed sequential implantation in previous studies. This might suggest that these populations may not benefit in bilateral processing, such as sound localisation and speech perception in noise. It is possible that early implantation for these subjects might allow better acquisition of bilateral processing and bilateral spatial hearing, thus leading to improved localisation and speech perception in noise performance (Nopp et al., 2004:205-214; Litovsky et al., 2006b:714-731). Thus, future studies should be aimed at determining these population's bilateral processing benefits of sound localisation and speech perception in noise.

It is difficult to pre-operatively predict which ear will be the superior performing ear after implantation (Eapen et al., 2009:158; Litovsky et al., 2006b:714-731; Ramsden et al., 2005:998). Bilateral cochlear implantation ensures that the better performing ear receives stimulation. Furthermore, Eapen et al. (2009:158), state that the better performing side post-operatively is not always consistent over time. Therefore, a possible shortcoming of some previous studies is to determine which ear is the superior cochlear implant post-operatively and monitor it over time, and compare the superior implant's performance with bilateral implant performance in order to determine the bilateral benefit attained.

A further possible shortcoming of some previous studies is the limited consideration of reasons for a failure to see large bilateral benefits due to bilateral processing effects. One problem, for example, is the lack of synchrony between the right and left speech processors' compression algorithms. Independent bilateral compression can introduce temporal and level distortions, both monaural and bilateral, that would limit individual listeners' ability to show maximal benefit during tasks of speech perception in noise. This might be specifically problematic for spatially separated speech and noise sources, whereby one of the devices is in head shadow and not compressing, whereas the other device is close to the noise and therefore entering compression. Consequently, future work should focus on the effects that compression has on speech perception in noise abilities, and on ways in which bilateral fitting can be optimised (Litovsky et al., 2006b:714-731).

2.5 *BILATERAL* VERSUS *BINAURAL* HEARING / PROCESSING / BENEFIT / ABILITIES

The terms *bilateral* and *binaural (*pertaining to *hearing, processing, benefit* or *abilities)* are used inconsistently and even interchangeably in the literature on cochlear implants. Auditory abilities have been shown to improve when normal-hearing listeners rely on both ears, that is, in *binaural* hearing. In the case of cochlear implant users, however, the listeners do not have two “normal” hearing systems or typical auditory pathways. It can be confusing, therefore, when the terms *binaural* and *bilateral* are used interchangeably in discussions about the benefits of *bilateral* cochlear implants (Litvosky et al., 2009:428).

Litovsky (Cochlear Corporation, 2008b) stated that *binaura*l refers to the integration of input along the auditory pathway after both ears have received sound, as happens in the normal auditory system. *Bilateral* input occurs when both ears are presented with sound. Unlike binaural hearing, coordination of sounds presented to the two ears may not occur in bilateral hearing.

Furthermore, according to Litovsky (Cochlear Corporation, 2008a) *binaural* hearing is specifically useful for sound localisation ability and to determine the meaning and content of those sounds. It can offer a combination of benefits that include the better ear effect (as found in the head shadow effect), binaural summation, and binaural unmasking. The better ear effect and binaural summation do not invoke any true binaural mechanisms that rely on the auditory system’s ability to compare information from the two ears effectively, but these effects are due to redundancy of information. It has often been argued that squelch represents the only “true” binaural processing measure whereby listeners use the interaural difference cues to identify sound sources and construct an internal representation of the sound scene (Eapen et al., 2009:153-159). Van Wieringen (2010) demonstrates this sentiment when stating that squelch is a true binaural mechanism while the other mentioned effects are bilateral. Binaural processing occurs at a central level. For example, in binaural masking level difference experiments one determines the detection of a tone in noise, with the same phase of the tone presented to the left and right ears. Then, in a second condition, the phase of the sinus in one ear is delayed by half a period. The detection of the tone in noise presented left and right is now easier, because processing of the two phases are compared at a central level. The difference between the two conditions is the binaural masking level difference (Van Wieringen, 2010).

Litovsky (Cochlear Corporation, 2008a) stated that binaural sensitivity to interaural time difference cues, which is essential for encoding information about a sound source's direction, are encoded in a way that requires very precise arrival of inputs from the right and left cochleas at the level of the medial superior olivary (MSO) in the ascending auditory pathway (see Figure 2.2). The inputs are matched by frequency, so that neurons in the MSO compare information that arrives at the right and left cochleas (Litovsky, Cochlear Corporation, 2008a). Current cochlear implant speech processors function in isolation of one another and, therefore do not coordinate the input to each auditory nerve (Grieco-Calub & Litovsky, 2010:654). Thus, commercially available speech processors do not synchronise the right and left cochleas, therefore interaural time differences (ITDs) may not be very robust (Litovsky, Cochlear Corporation, 2008a). Litovsky has urged researchers to focus on further enhancing and maximizing binaural sensitivity by introducing right-left match stimulation (Cochlear Corporation, 2008a). In the current cochlear implant systems, processing of two independent cochlear implants with their own independent speech processing algorithms cannot enable binaural processing of the specific and sensitive binaural cues of ITDs and interaural level differences (ILD), and therefore cannot necessarily guarantee that binaural cues are available to listeners with electrical hearing (Grieco-Calub & Litovsky, 2010:654; Van Wieringen, 2010). However, this level of processing will only be possible if a well-controlled experimental system is used where the timing between the left and the right cochlear implant systems are controlled and then only severely hearing impaired persons might be capable of using the ITD and ILD cues (Van Deun, Van Wieringen & Wouters, 2010:702-713; Van Wieringen, 2010). According to Van Wieringen (2010), controlling the timing between two implant systems might be possible in the next generation of bilateral cochlear implantations.

For the study in hand, adults with sequential implantations were selected as participants. Due to the test setup conditions available at the time of conducting the study, tests were administered in free field, thus control of ITD and ILD cues were not possible. Therefore, for this study, it was considered advisable to use the term *bilateral* hearing, processing, or benefit when referring to sound localisation and speech perception in noise (both where speech and noise were spatially separated and coincident) and to subsequent calculated bilateral spatial benefits (head shadow effect, summation, squelch and spatial release of masking). These effects were calculated in order to quantify the bilateral benefit (Eapen et al., 2009:153; Van Wieringen, 2010).

2.6 THE AUDITORY SYSTEM AND SOUND LOCALISATION ABILITIES

The function of the auditory system is sound identification and sound localisation (Tollin, 2007). Localisation is the term referring to the ability to know the location of a sound-producing object and depends on two types of hearing, namely directional hearing and distance hearing (Flamme, 2002:10). According to Flamme (2002:10) directional hearing allows the listener to know the direction of the sound source in a three-dimensional space, while distance hearing indicates how far away a sound source is from the listener. Sound localisation facilitates the detection and identification of sound by means of binaural hearing (Tollin, 2007). In his model of localization, Tollin (2007) states that sound localisation is dependent on (a) acoustic cues and (b) neural mechanisms. These will be discussed below:

2.6.1. Acoustical cues for sound localisation

According to Tollin’s (2007) duplex theory of sound localisation, a person is able to localise low frequency sounds by using interaural time difference (ITD) cues which originate due to the physical distance between the two ears. That is, when a sound originates from one side of a listener, it will arrive at the ear nearest to the sound source before it will arrive at the other ear (Dunn & Ou, 2008:1-8). ITD cues are essential for sound localisation in the horizontal plane. High frequency sounds can be localized by means of interaural level difference (ILD) cues which are created as the head casts an “acoustic shadow” causing less sound energy at the ear farther from the sound source than at the ear on the nearer side. Thus, the level of the sound at the ear closer to the sound source will be greater than the level at the ear farther from the source (Dunn & Ou, 2008: 1-8). According to Tollin (2007) this holds true for the average adults’ horizontal plane sound localisation in the frequency range of 1500 Hz and higher.

The division of acoustical cues is illustrated in Figure 2.1.

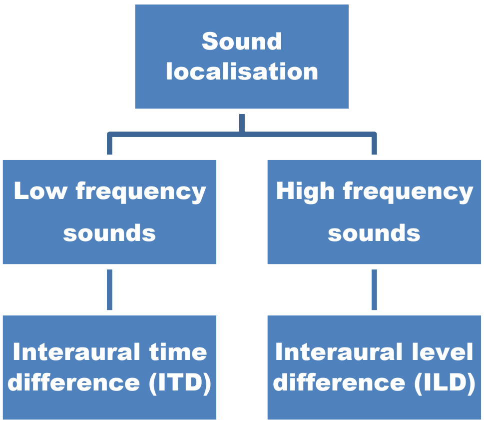

Figure 2.1: Acoustical cues to sound localisation

Figure 2.1 displays the two main acoustical cues, used mainly in the horizontal plane for sound localisation. Certain neural mechanisms also enable sound localisation, as will be discussed in the following section.

2.6.2. Neural mechanisms for sound localisation

It is clear that both ears are needed for sound localisation, which mostly occurs early in the ascending auditory system. After stimuli have been encoded by the cochlea and the auditory nerve, the nerve initially synapses in the cochlear nucleus (Cochlear Corporation, 2008a). Projections from the cochlear nucleus feed into two separate binaural systems (Litovsky, Cochlear Corporation, 2008a). In the ascending auditory system, the superior olivary complex is the first station of the binaural cue system, as auditory information from the two ears converges here (Tollin, 2007). Sound localisation cues are encoded in parallel in the auditory brainstem using simple neural circuits. The neurons of the medial superior olivary are mosty sensitive to low frequency sounds. Thus, ITDs are encoded in the medial superior olivary by means of an excitatory input from both ears as well as a coincidence of detector neurons. ILDs are encoded in the lateral superior olivary neurons via an excitatory input from the ear ipsilateral to the sound source and an inhibitory input from the contralateral ear (Tollin, 2007).

Figure 2.2 illustrates the ascending auditory pathway.

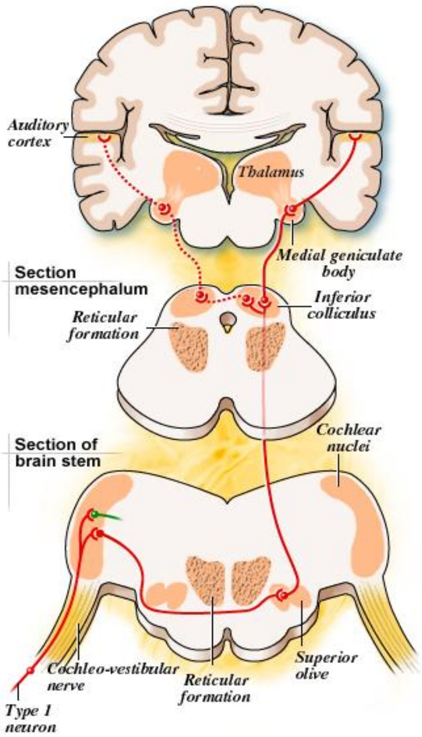

Figure 2.2: Ascending auditory pathway (*Auditory pathway*, n.d.)

Figure 2.2 depicts the superior olivary complex (SOC) as the primary neural location for sound localisation in the ascending auditory pathway. Being dependent on acoustical cues and neural mechanisms, sound localisation can psycho-acoustically be divided into two axes (Flamme, 2002:10). The one axis is the vertical plane, also known as elevation (the up-down dimension), and the other axis is the horizontal plane, also called the azimuth (the right-left dimension).

2.6.3 Vertical plane sound localisation

Flamme (2002:14) states that the primary acoustic cue for vertical plane localisation is generated by the pinna. As sound reaches the listener from different elevations, the concha has different effects on the sound, creating sharp peaks and valleys in the signal spectrum. Consequently, the listener uses these spectral patterns as cues to the vertical location of a sound source by comparing the observed spectrum of the sound with the expected spectrum and by applying his/her experience with the general effects of the concha to infer the location of the sound source (Flamme, 2002:14). As the cochlear implant's microphone is located on the behind-the-ear speech processor, cochlear implant users cannot make use of the pinna effect, and spectral cues are probably unavailable (Grieco-Calub & Litovsky, 2010:654-655). Consequently, determining the direction of a sound in the vertical plane can be limited. As Flamme (2002:14) pointed out, experience with utilisation of the pinna effect to localise sound in the vertical plane has a definite influence on the listener's conclusion of where the sound source is located. Thus, cochlear implant users with no or little experience of this pinna effect, such as paediatric users with congenital hearing loss, or users with a hearing loss acquired before speech and language development, may not have sufficient and reliable stored patterns of experience in terms of elevation identification. As a result, the extent of their ability to localise in the vertical plane may be restricted.

2.6.4 Horizontal plane sound localisation

Flamme (2002:10) states that monaural as well as binaural cues have been shown to be necessary for horizontal plane localisation. Binaural cues consist of ITDs and ILDs and are the cues used by the average adult for most horizontal plane sound localisation (Flamme, 2002:10-14; Tollin, 2007).

Monaural cues consist of the following:

- the overall loudness of sound, as sound originating from the side ipsilateral to the ear will have a greater overall loudness than sound coming from the contralateral side;
- the spectrum of the sound heard by the listener will change with the orientation of the sound source to the head and the body of the listener and

- the diffraction of the sounds around the features of the pinna causes sharp peaks and dips in the frequency response of the pinna.

Flamme (2002:10) emphasizes that is important to note that these cues rely on the presence of a stored prototype or template of the sound, thus cognition is involved in the use of monaural cues. The paediatric patient with a congenital hearing loss or loss acquired before speech and language development may not have had the opportunity, or not have had sufficient opportunity, to develop well-formed sound localization prototypes and their cognitive development is still in process. For these paediatric patients it is thus even more important to have access to bilateral cues to help him/her determine the location of a sound source, especially speech, than for adults with acquired hearing loss.

Optimal sound localisation is a function of the binaural auditory system. Binaural hearing requires input from both ears. According to Tollin (2007), this explains the poor sound localisation ability in those with a unilateral hearing loss. Subsequently, this statement holds true for those with a unilateral cochlear implant. Nopp et al. (2004:205-214) confirm this when stating that patients using unilateral cochlear implants have little or no sound localisation ability. This reduces effectiveness of the alerting function that could be supported by a prosthetic system for hearing and eliminates the advantage of binaural hearing (Wilson & Dorman, 2008:16).

Figure 2.3 displays an integrated illustration of the acoustical cues together with the neural mechanisms used for sound localisation in the horizontal plane for cochlear implant users.

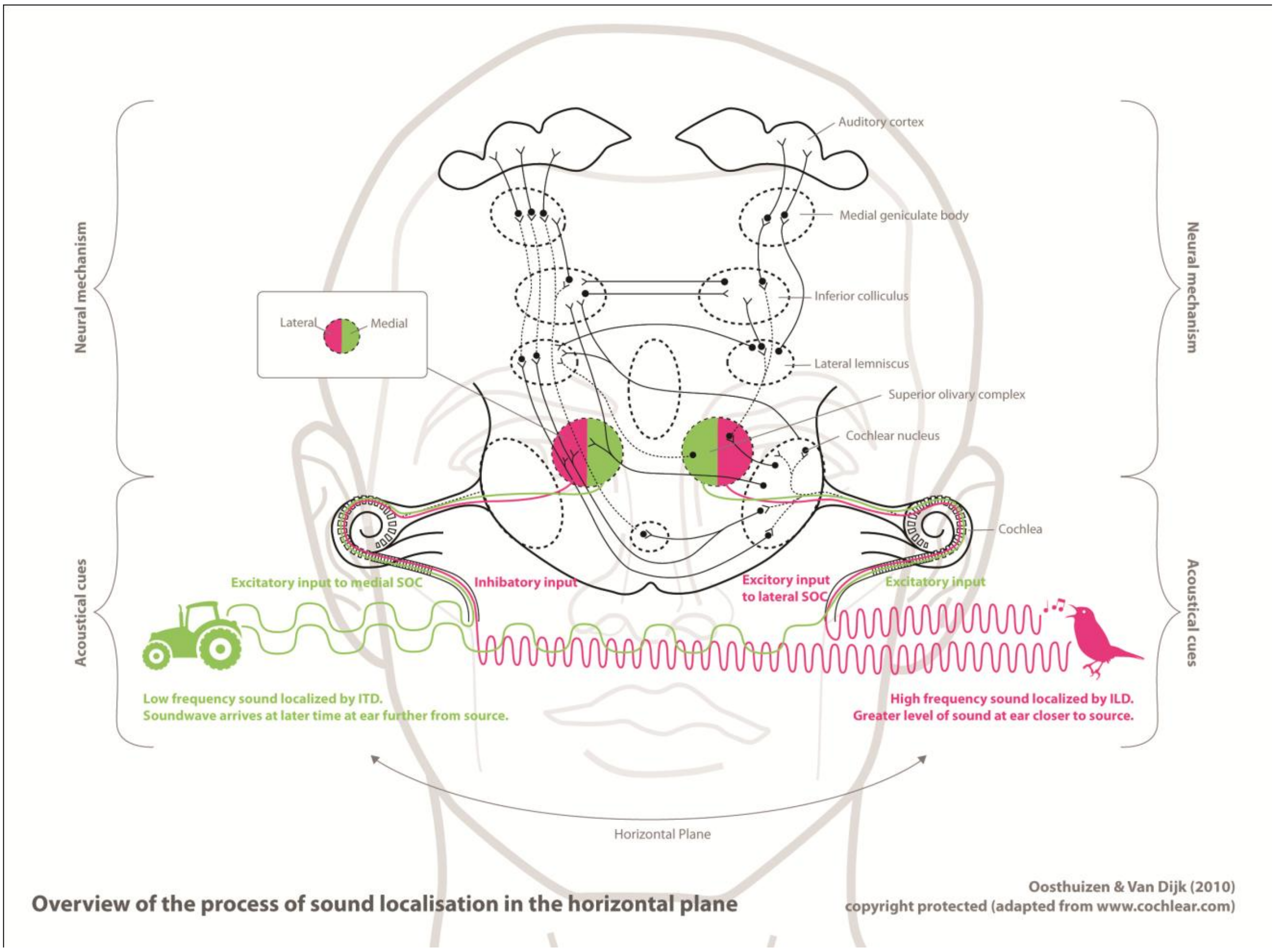

Figure 2.3: Summary of the process of sound localisation

Figure 2.3 depicts a simplified presentation of an exceedingly complex process.

2.6.5 The importance of sound localisation

The acquisition and production of (spoken) language are considered to be of the most significant aspects in any child’s development. Language is viewed as the doorway to successful communication. The ability to use language is essential for progress on academic grounds and for participating in the social interaction that forms a vital part of everyday life (Northern & Downs, 2002:127). Although it is the language abilities of a child that open the door to education, the successful acquisition of language is highly dependent on an adequately functioning auditory system (Northern & Downs, 2002:127).

Bilateral auditory abilities, namely sound localisation and speech perception in noise, may be essential for children to learn language incidentally in their everyday environments, as these environments and situations are generally characterized by multiple input sources and present background noise of the surrounding environment. Northern & Downs (2002:19) state that children with hearing losses have limited opportunities to overhear information from various sound sources. This leads to impoverished experiences, with detrimental consequences for language rule formation, world knowledge, and vocabulary development (Northern & Downs, 2002:19). The extent and type of early training, the type and timing of amplification, visual, emotional and intellectual factors, and cultural and family support as well as age at identification and intervention also influence language development in the child with a hearing loss (Northern & Downs, 2002:19).

The ability to localise a sound source, especially a speaker, is essential for language acquisition and development (Alpiner & McCarthy, 2000:184-185, 228; Northern & Downs, 2002:19-20). Localisation is an orienting analysis and serves as a bridge from the awareness of sound to being able to focus attentively on the primary signal (Alpiner & McCarthy, 2000:184). For children, sound localisation has direct application in everyday situations as they constantly monitor multiple ongoing sound sources in classrooms, playground situations, and sports activities. Safety also becomes an issue when the need arises to avoid moving objects or cross a busy street (Litovsky, Cochlear Corporation, 2008b). Just like a child with a unilateral hearing loss, a child with a unilateral cochlear implant may experience significant difficulties in localising the source of a sound, especially amidst background noise, for example in a classroom situation (Northern & Downs, 2002:24). A child's sound localisation ability is obviously influenced by aspects such as distance from the source and the presence of intervening factors, such as a hearing loss and consequently amplification/stimulation provided from only one ear (Alpiner & McCarthy, 2000:185). Even for adults, the ability to localise sounds is imperative in their place of work, social situations, recreational sport activities, and everyday activities such as crossing the street in traffic (Litovsky, Cochlear Corporation, 2008b). Sequential cochlear implantation leads to the child or adult having a periodic loss of the binaural summation effect that is provided by bilateral hearing, thus creating overall and ongoing communication difficulties (Northern & Downs, 2002:24). Being able to evaluate the sound localisation skills in the sequential implanted population might aid in determining the extent of bilateral processing, as localisation is a bilateral auditory ability.

The use of bilateral cochlear implants supports an improved ability to localise sounds, compared to a unilateral implant (Nopp et al., 2004:205-214). Nevertheless, sequential cochlear implants also seem to impact on optimal sound localisation abilities as subjective statements of ear dominance in the first implanted ear and thus unbalanced bilateral hearing is often prominent complaints of sequential implantees (Van Dijk, 2008). Consequently, the extent of bilateral processing, especially for different locations of the speech and noise is negatively influenced.

2.6.6 Stimuli used for determining sound localisation abilities

Bursts of speech-weighted noise (SWN) can be used as stimuli during a sound localisation task. This is a white noise that is filtered to simulate the long-term average spectrum of conversational speech (Cainer & Rajan, 2008:157). According to previous studies, the most frequent stimuli used during sound localisation tests with cochlear implantees are (a) broadband noise for example white noise or pink noise (Iwaki et al., 2004:228-229; Litovsky et al., 2004:648-655; Verschuur & Lutman, 2003:13-14), (b) speech signals, for example in the form of shortened sentences (Laszig et al., 2004:958-968; Verschuur & Lutman, 2003:13-14) and less frequently (c) 1000 Hz pure tones (Verschuur & Lutman, 2003:13-14). Neuman et al. (2007:73-82) investigated whether the type of stimulus used during sound localisation testing with bilateral cochlear implant users affects the users' performance. They stated that speech may be a more ecologically relevant stimulus than broadband noise, as the cochlear implant user would more frequently need to localise the speech source in daily life, than just different types of noise. Being able to turn towards the speaker will also allow access to facial expression and manner of articulation to further support speech understanding (Neuman et al., 2007:73-82). Neuman et al. (2007:73-82), however, found similar localisation performance with speech and broadband noise signals. This finding supports the use of either speech or broadband noise for measuring sound localisation in clinical or research studies (Neuman et al., 2007:73-82). SWN may be regarded as an appropriate stimulus as it mimics the long-term spectrum of speech (Cainer & Rajan, 2008:157; Katz & Lezynski, 2002:130). SWN is also expected to be only auditive ("energetic"), compared to for example babble noise which has both energetic and informational effects and consequently may present greater difficulty in localisation (Cainer & Rajan, 2008:159,162).

2.7 THE AUDITORY SYSTEM AND SPEECH PERCEPTION IN NOISE ABILITIES

Bilateral stimulation can provide substantial benefit in recognizing difficult speech materials such as perceiving speech presented in competition with spatially separated and/or coincident noise, in comparison to scores obtained with unilateral implant alone (Müller et al., 2002:198-206; Laszig et al., 2004:958-968).

2.7.1 The importance of speech perception in noise

Hearing abilities, especially speech perception, play a critical role in learning for all children (Alpiner & McCarthy, 2000:228). Hearing loss, on the other hand, has a wide-ranging negative impact on the development of speech, language, and later reading and writing skills (Alpiner & McCarthy, 2000:28)

As early as 1947, French and Steinberg noted that normal-hearing children require a signal-to-noise ratio (SNR) of +30 dB (that is, the speech signal must be 30 dB louder than the background noise) for the child to be able to learn speech and language (Northern & Downs, 2002:20). Unfortunately, such a favourable listening ratio is unusual in modern society. Alpiner and McCarthy (2000:228) state that classrooms are mainly auditory-verbal environments in which listening is often the primary modality used to gain input for learning. According to Northern and Downs (2002:20), however, the typical SNR in public school classrooms is +12 dB or less, thus an unfavourable SNR. Even a child with a minimal hearing loss will be disadvantaged under such listening situations. Moreover, the speech perception abilities of the child (and/or adult) are even more reduced under such decreased signal-to-noise ration conditions. Thus, for the child acquiring speech and language as well as the school-aged child, good speech perception in noise is of the utmost importance to be able to receive the model input signals from parents, family, and/or teachers as well as to access the academic environment.

Good speech perception in noise is equally important to adults, as most everyday environments, for example meetings, open-plan offices, public places (such as: shopping centres, banks, places of worship, restaurants) and forms of transportation are characterised by the presence of background noise, to a lesser or greater degree. The masking effect of noise depends on various parameters, namely the long-term spectrum, intensity fluctuations in terms of time, and the average intensity relative to the intensity of the speech signal (Alpiner & McCarthy, 2000:502). Background noise can be generated internally within the room (heating and cooling systems or movement of the occupants), or can originate externally (hallway noise or traffic). It can be steady-state (for example a fan), quasi-steady-state (for example speech babble) or time-varying (for example airplanes departing and landing). The overall effect of steady-state noise on speech perception can be expressed by a metric, namely the speech-to-noise ratio (SNR) (Alpiner & McCarthy, 2000:503). Most persons with normal hearing can communicate reasonably well at SNRs of approximately seven to 11 dB. However, people with sensori-neural hearing loss need much larger SNRs (Alpiner & McCarthy, 2000:503). Furthermore, the work of Pearsons et al. (1977, in Alpiner & McCarthy, 2000:334) demonstrated that people normally speak at 55 dB SPL (sound pressure level) for background noise up to 45 dB SPL; thus, a favourable SNR of at least +10 dB will exist. Individuals with hearing loss usually can perceive speech relatively well at a +10 dB SNR if the speech spectrum is audible. When the intensity of the background noise increases, however, speakers tend to raise their voices disproportionately (Alpiner & McCarthy, 2000:334). For example, when the background noise is 55 dB, average speech is 61 dB (+6 dB SNR), but when the background noise reaches 65 dB, average speech is only 68 dB (+3 dB). The SNR becomes 0 dB or worse when the background noise level exceeds 75 dB (Alpiner & McCarthy, 2000:334).

Good speech-perception-in-noise ability, therefore, is of the utmost importance for the adult cochlear implant user to be functional in everyday situations. Since speech perception in noise is considered a binaural hearing ability (Schön et al., 2002:710), unilateral cochlear implant users' benefit in terms of their speech perception abilities tend to be limited to understanding the majority of speech and communication with minimal or no lip reading in quiet listening environments (Cochlear Corporation, 2008b). Furthermore, the sequentially implanted user may find speech perception in noise more difficult due to the ear first implanted being a dominant ear. Consequently, evaluating adult sequentially implanted users’ speech in noise perception may aid in determining their bilateral processing abilities.

2.7.2 Stimuli used for determining speech perception in noise abilities

In the current study steady-state, speech-weighted noise (SWN) was used during speech perception in noise tasks as the general effect of such noise on speech perception can be expressed by a metric unit, namely the speech-to-noise ratio (SNR) (Alpiner & McCarthy, 2000: 502-503). This unit is also known as the speech-to-competition ratio or the signal-to-noise ratio where the signal is the preference stimulus (thus speech) and the noise or competition refers to the undesired stimulus (for example background noise) (Alpiner & McCarthy, 2000:503). The use of steady-state, SWN is also supported by most international research studies on speech perception in noise (Laszig et al., 2004:958-968; Müller et al., 2002:198-206; Wolfe et al., 2007:589-596). Relatively few researchers have made use of broadband noise, for example pink or white noise, as masker (Neuman et al., 2007:73-82). White noise may be regarded as an acceptable choice during measures of speech perception in noise, but SWN remains the preferred choice (Katz & Lezynski, 2002:130). This is due to the fact that SWN is filtered above 1000 Hz at a rate of 12 dB per octave, thereby providing relatively more energy in the low frequencies to approximate the frequency-energy distribution of speech. This reduction in the high frequencies produces a more limited bandwidth than that of white noise, making speech-weighted noise a more efficient masker during speech perception testing (Katz & Lezynski, 2002:130). In the current study, therefore, the speech-perception-in-noise abilities of participants were evaluated with the use of a recorded presentation of CID sentences on an iPod in the presence of steady-state speech-weighted noise selected and presented through the audiometer.

2.8 SEQUENTIAL VERSUS SIMULTANEOUS COCHLEAR IMPLANTATION

Bilateral cochlear implantation is not simply a duplication of a unilateral cochlear implantation, although many of the surgical steps are identical (Lustig & Wackym, 2005:125-130). Certain critical amendments need to be made to the surgeon's technique in order to ensure successful implantations. Sequential and simultaneous cochlear implantation will be described separately in the following section.

2.8.1 Sequential implantation

With sequential implantation, the second implant is performed at a later date than the first implant. According to Lustig and Wackym (2005:125-130) the main alterations in surgical technique involve the placement of the second implant.

Table 2.2 lists the three pivotal concerns to be considered during the surgery of the second implant, with the relevant justification for each issue.

Table 2.2: Three critical issues considered during surgery of the second implantation (Lustig & Wackym, 2005:125-130)

Critical issue during the second surgery of sequential cochlear implantation	**Justification**
1. Symmetrical placement of the implanted receiver-stimulator with respect to the contralateral set.	This is a cosmetic concern primarily, which also facilitates practical matters such as wearing a hat or glasses (Lustig & Wackym, 2005:125-130).
2. Strict avoidance of the use of monopolar electrocautery.	This is imperative to avoid damage to the fine microcircuitry of the first implanted device (Lustig & Wackym, 2005:125-130).
3. Preserving the nervus chorda tympani.	The possibility exists that the contralateral chorda tympani nerve may have been destroyed or injured during implantation of the first device. Consequently, special care needs to be exercised in trying to preserve the nervus chorda tympani on the operative side to avoid excessive loss of taste postoperatively. This is of vital importance for patients who rely on their sense of taste for employment, for example chefs (Lustig & Wackym, 2005:125-130).

Table 2.2 summarises the key aspects to be considered during the second implantation of sequential cochlear implant surgery as it could have an influence on the cosmetic, neural, and functional outcome of sequential surgery.

According to Lustig and Wackym (2005:125-130), direct communication with the anaesthesiologist before the operation is important and should include instructions for perioperative antibiotics and the avoidance of paralyzing agents to allow for facial nerve monitoring. Once the patient is under anaesthesia, surgery starts with a minimal shave and marking the surgical incision site. The surgeon should carefully note the placement of the first implanted receiver-stimulator to allow for a symmetrical placement on the second operative side, as stated in Table 2.2. The facial nerve monitoring electrodes (oribicularis oculi and orbicularis oris muscles) are subsequently applied together with the evoked auditory brainstem response (EABR) electrodes (Lustig & Wackym, 2005:125-130).

The previously outlined incision is opened with the scalpel down to the level of the temporalis fascia, the linea temporalis is delineated with the blade and dissected to the mastoid tip. Next, the triangular periosteal flap of the mastoid cortex is elevated anteriorly until the posterior external auditory canal wall is identified (Lustig & Wackym, 2005:125-130). The surgeon next moves to the opposite side of the head to create a pocket for the implant receiver-stimulator through the use of a minimal incision approach and the well for the receiver-stimulator is created within the temporo-parietal skull. An incision is subsequently made in the periosteum over the region of the well and the periosteum is elevated superiorly and inferiorly. The size of the drilled well is implant specific, and determination of the exact size is facilitated by the templates provided by each manufacturer (Lustig & Wackym, 2005:125-130). With the well adequately sized, drill holes are created for suture retention of the implant, followed by a small trough that is drilled toward the mastoid region to accommodate the electrode lead.

A standard mastoidectomy follows. The incus body is identified and canal wall appropriately thinned, and the facial recess is opened (Lustig & Wackym, 2005:125-130). Subsequently, the cochleostomy is executed just anterior and slightly inferior to the round window membrane. A small piece of cotton is used to cover the cochleostomy, and the middle ear, mastoid, and receiver-stimulator pocket are copiously irrigated with saline to remove traces of bone dust. A small pocket underneath the temporalis muscle is made to accommodate the ground electrode (Lustig & Wackym, 2005:125-130).

The implant is then removed from the packaging and secured in the previously created well. The ground electrode is placed in the dissected pocket medial to the temporalis muscle and the electrode is gently inserted into the cochlea. Once fully inserted, a small piece of fascia is used to seal the edges of the cochleostomy around the electrode in order to prevent a perilymphatic leak and reduce the risk of meningitis. The periosteal flaps are then re-approximated and sutured over the electrode lead and mastoid. The remainder of the skin incision is closed using the surgeon's usual or preferred fashion and a standard mastoid compression dressing is applied (Lustig & Wackym, 2005:125-130).

2.8.2 Simultaneous implantation

During simultaneous cochlear implantation the following technical alterations will contribute to a successful outcome (Lustig and Wackym, 2005:125-130):

- During preparation, both ears are simultaneously draped.
- The facial nerve and EABR electrodes need to be individually labelled on either side.
- As with sequential implantation, there is an aesthetic and functional need for symmetrical placement of the receiver-stimulators.
- The surgeon and anaesthesiologist should be prepared for an increased operating time during simultaneous implantation, with an average of three and a half to four hours, including 20 to 30 minutes for electrophysiology testing for both sides.
- Although surgery for both ears proceeds simultaneously, after placement of the first implant the periosteum, subcutaneous tissue, and skin are completely closed before inserting the contralateral implant in order to ensure stability of the first implant while implanting the second device.

As with sequential implantation, communication between the surgeon and anaesthesiologist is of utmost importance to discuss perioperative antibiotics and the avoidance of using paralyzing agents so that the facial nerve can be monitored throughout the operation (Lustig & Wackym, 2005:125-130).

The incision and pocket for the implant receiver are created as in the case of sequential implantation, first on one side and then on the contralateral side. According to Lustig and Wackym (2005:125-130) head rotation is limited as both ears are within the surgical field. Therefore, use of a headlight is important during simultaneous implantation to ensure adequate visualisation. In contrast to sequential implantation, during simultaneous cochlear implantation a monopolar coagulator can be used as there are no implanted components at this point (Lustig & Wackym, 2005:125-130).

Furthermore, with simultaneous implantation, all soft tissue work is completed on both sides followed by completion of all bony work on both sides: The wells for the receivers are drilled in the tempero-parietal skull, drill holes for suture stabilisation of the implant and bony troughs for the electrode leads are performed for each ear. This is followed by the mastoidectomy and facial recess on each side. The cochleostomy is left until just before the implant for each device to minimise exposure to the labyrinth and to assist with attempts at hearing preservation. Both sides are well irrigated to remove all bone dust, blood, and debris (Lustig & Wackym, 2005:125-130).

The cochleostomy is then created anterior and inferior to the round window (Lustig & Wackym, 2005:125-130). Thereafter the implant receiver is placed in its well, secured by the surgeon’s preferred method and the electrode is inserted into the cochleostomy. Subsequently, the edges of the cohleostomy are sealed with small pieces of fascia. However, before moving to the contralateral side, the periosteal layers are re-approximated and the remainder of the subcutaneous tissues and skin are closed to minimise motion of the implant during placement of the contraletaral implant. The identical procedure is then followed in the contralateral ear. After placement of the second implant and closure of the wound, EABR measures are conducted. Next, modification of a mastoid compression dressing is applied in which fluffs of gauze are placed over both implant sites as well as a gauze wrap that encompasses both fluffs (Lustig & Wackym, 2005:125-130).

In summary, the differences between sequential and simultaneous cochlear implantation relate mainly to the time requirements, which in turn affect the costs (one versus two admissions, transport, time off work etc.) and inconvenience.

The main medical differences can be summarised as follows:

- With simultaneous implantation, a single anaesthetic procedure means less total time, as it requires only one induction and one waking up, one pre-medication procedure and a single postoperative care period.
- One surgery for both implants requires less time than the sum of two separate surgeries mainly because of anaesthetic and theatre setup time being saved.
- Length of time required for post-implantation healing is not affected, but of course the healing process takes place only once.
- Surgery for simultaneous cochlear implantation takes much longer than for one implantation alone, and longer anaesthesia is associated with more complications particularly in very old and very young patients. In babies younger than a year, loss of even a small quantity of blood can represent loss of quite a significant percentage of their total blood volume, and one must therefore be careful to monitor this loss accurately. Lustig and Wackym (2005:125-130) state that bone wax can be used to control bleeding from the bone. The skulls of babies and young children are often very thin, however, and therefore completion of a craniotomy with preservation of a bone island is necessary to insert the device.

The surgical risks are therefore related to the duration of surgery and/or anaesthesia and blood loss rather than to the operation itself. The exception to this is the effect that the procedure has on the balance, which is unpredictable, but balance is more likely to be disturbed if both ears operated on simultaneously (Nauta, 2009).

2.9 CONCLUSION

The bilateral processes of sound localisation as well as speech perception in noise, whether spatially separated or coincident, are complex processes, since various acoustical and neural mechanisms need to function in an integrated manner to enable significant functioning of these abilities. One of the primary prerequisites for sound localisation and speech perception in noise is binaural hearing. This is the main reason why the importance of bilateral cochlear implantation is internationally recognized. It is necessary to consider, though, that the manner of bilateral implantation, thus sequential versus simultaneous, as well as how well the bilateral implants are balanced could have an influence on these binaural abilities. Bilateral implantation in South Africa currently mainly takes place in a sequential time frame. For this reason, an investigation of how well sequential implant users are able to process bilaterally with regard to sound localisation and speech perception in noise becomes highly relevant.

2.10 SUMMARY

Chapter Two discussed the main theoretical aspects concerning bilateral cochlear implantation, and factors relating to the bilateral processing benefit. An overview of the history of cochlear implantation both internationally and locally, and a summary of previous studies on adults with bilateral cochlear implants set the platform for discussing bilateral implantation in particular. The use of the terms *bilateral* versus *binaural* hearing, processing, and benefit received attention. Thereafter, the bilateral abilities namely sound localisation and speech perception in noise and its complex processing were discussed. The importance of these skills as well as the stimuli used to determine these abilities, as used in the study in hand and in other international research, were examined. This was followed by a critical discussion of the difference between sequential and simultaneous implantation as well as the current status of sequential implantation in South Africa, as it remains the general method of bilateral implantation in South Africa. The bilateral electrical stimulation in sequential implantees may utilise or reinstate a part of the natural auditory system, as reflected in the bilateral abilities of sound localisation and speech perception in noise (Wilson & Dorman, 2008:17). Against the background of these theoretical perspectives, the significance of determining the bilateral processing achieved by these users becomes clear.

3. METHOD

AIM OF THE CHAPTER

The aim of chapter three is to describe the methodology of the research study. The research design and aims are stated towards addressing the research question. A quantitative research approach is employed. In the context of applied research, explorative, comparative research techniques are utilised in a one group post-test-only exploratory research design and included the use of test battery measurements.

3.1 AIMS

The **main aim** of this study is to determine the bilateral processing benefit obtained by sequentially implanted adult cochlear implant users.

The following **sub-aims** were identified in order to attain the main aim:

- To determine which implant delivers superior or better performance[1] with regard to sound localisation and speech perception in noise.
- To determine the sound localisation ability in three listening conditions: first implant only (CI 1), second implant only (CI 2), and with bilateral implants (BiCI).
- To determine the speech perception ability in spatially separated speech and noise in three listening conditions (CI 1, CI 2, and BiCI), in each of two noise conditions (noise directed to CI 1 and noise directed to CI 2).
- To determine the speech perception ability in spatially coincident speech and noise in three listening conditions (CI 1, CI 2, and BiCI).
- To calculate the bilateral spatial benefits (head shadow effect, summation, squelch, and spatial release of masking) using above-mentioned results compared to normative data.

3.2 RESEARCH DESIGN

This study employed a quantitative research approach (Leedy & Ormrod, 2005:94). The goal of the research was to explore specific phenomena and the type of research was applied (Fouché & De Vos, 2005:105). In the context of applied

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[1] Also referred to as the *"dominant ear"* in literature.

research, explorative, comparative research techniques were utilised in a one group post-test-only exploratory research design (Fouché & De Vos, 2005:135). A cross-sectional research technique was utilised to collect data at a particular point in time for purposes of describing the variables and their patterns of distribution (Leedy & Ormrod, 2005:183; Maxwell & Satake, 2006:221) of the different outcomes of bilateral processing benefits in a group of sequentially implanted adults.

The **quantitative** approach is a form of conclusive research involving representative samples of fairly structured data collection procedures. According to Leedy and Ormrod (2005:94) quantitative research is used to answer questions about relationships among measured variables with the purpose of explaining, predicting and controlling phenomena. In quantitative research, formalised test and measuring instruments are applied to precisely and objectively specify the characteristics of the collected data (Maxwell & Satake, 2006:29). Thus, during this study a quantitative approach was used primarily to analyse and interpret the extent to which bilateral processing benefits will be achieved by sequentially implanted users. This was done by implementing sound localisation measurements and speech-in-noise measurements, specifically spatially separated speech and noise and spatially coincident speech and noise measures.

Applied research refers to the utilising of research in the degree of direct practical application inherent in the findings (Neuman, 2000:22). Thus, in the end applied research usually has implications for the practice. It is also most often seen as the scientific planning of induced change (Fouché & De Vos, 2005:105). The advancement of knowledge and the solution of problems are both seen as scientific necessities by Fouché and De Vos (2005:105). This was found to be applicable to the current study, as the objective and subjective outcomes could have practical implications for the professions of audiology and otolaryngology practice in cochlear implantations in terms of candidacy, surgery protocol, expectations and counselling. Thus, the outcomes could aid in understanding practices to ensure effective bilateral implantations for the client.

Exploratory research techniques were used to investigate an area that has not yet been sufficiently investigated. The major purpose is the development and clarification of ideas and the formulation of questions and hypotheses for more precise investigation later. Thus, a great deal of information was gathered from a relatively small sample (Struwig & Stead, 2001:7). An exploratory method of research can be put into practice via an analysis of selected cases (Struwig & Stead, 2001:7). Accordingly, these techniques were suited for the purpose of this study where the extent of bilateral processing benefits achieved by sequentially bilateral implanted participants, specifically of the Pretoria Cochlear Implant Programme (PCIP), was analyzed in depth by means of sound localisation measures as well as speech perception measures.

Research designs are strategies that can be used to address research questions (Struwig & Stead, 2001:9). An **exploratory research design** has the purpose of gaining insight into a situation, phenomenon, community or person (Fouché & De Vos, 2005:134). This purpose, according to Rubin and Babbie (2001:123), is typical when a researcher is examining a new interest. Exploratory research can therefore be conducted to get acquainted with a situation so as to formulate a hypothesis (Fouché & De Vos, 2005:106). The one-group post-test-only exploratory design implies a carefully studied single instance which is compared with other measurements. It involves tedious collection of specific detail and testing (Fouché & De Vos, 2005: 135,136). Bilateral processing abilities of bilateral implanted users can be viewed as central in attaining the benefits of localization and binaural hearing in everyday listening experiences. As bilateral cochlear implants in South Africa are primarily conducted sequentially, more research is required regarding the extent to which bilateral processing is actually achieved by these sequentially implanted users. An exploratory design is appropriate for this study which specifically investigates the adult population of the PCIP in the South-African context. Consequently, by using the exploratory one-group post-test only design, specific measurements of bilateral processing benefits were conducted and compared with data from the literature.

3.3 RESEARCH ETHICS

When human subjects form part of a research study, ethical implications of what the study proposes to do, need significant consideration. Adherence to ethical principles forms part of the pursuit of best practice in research and the clinical profession.

A request for ethical clearance was submitted to the Research and Ethics Committee of the Department of Communication Pathology and the research committee of the Faculty of Humanities, University of Pretoria before commencement of this study. Ethical clearance was obtained from the Research and Ethics Committee of the Department of Communication Pathology, University of Pretoria (see Appendix A) as well as from the head of the PCIP (see Appendix B) prior to commencement of the fieldwork. A request for permission to conduct the research at the Pretoria Cochlear Implant Programme (PCIP) was submitted to the head of the program (see Appendix C).

According to Leedy and Ormrod (2005:101), research has to comply with certain ethical principles. The following principles were adhered to in this study:

Protection of participants

Participants who took part in the study were not exposed to undue physical or psychological harm, as the audiological measurements were routine test procedures performed by qualified and registered audiologists (Leedy & Ormrod, 2005:101).

Informed consent

Autonomy of the participants was respected in that they had been informed by letter about the nature of the study to be conducted, what would be expected from them, and that they would be given the choice of either participating or not participating. Furthermore, if they agreed to participate, participants had the right to withdraw from the study at any time. A form that describes the nature of the research study as well as the nature of the participants’ participation was presented to all participants in order to obtain their informed consent (Leedy & Ormrod, 2005:102) (see Appendix D1 and D2).

Right to privacy

The participants' right to confidentiality was respected. The nature and quality of participants' performance and personal information was kept strictly confidential. Each participant who participated in the study was assigned a code number and any written or printed documents were labelled with that number to avoid using their names (Leedy & Ormrod, 2005:102).

Honesty to professional colleagues

Findings were reported in a complete and honest fashion without misrepresenting data or misleading other professional colleagues. Full acknowledgement was given if other authors' work was used during the study (Leedy & Ormrod, 2005:102).

3.4 PARTICIPANTS

During this study, measurements were performed on the adult clients of the PCIP who met the selection criteria as set out in section 3.4.2.

3.4.1 Sample size and sampling technique

The sample size must be sufficient to provide enough data to answer the research question (Maxwell & Satake, 2006). The PCIP, like most local and international progmmes, has a limited client base of bilaterally implanted adults, namely 33% (14) of a total of 321 clients, all of whom are sequential cochlear implant users (Cass, 2010). The total number of children who received bilateral implants is 29. Thus, more bilateral implants are evident in the paediatric population of the PCIP than in the adult population. As stated before, in similar previous research studies bilateral implantation in adults is less prevalent, with smaller sample sizes, compared to studies on the paediatric population. In general, studies on the adult population have used an average of eight to ten subjects (Eapen et al., 2009:153; Galvin et al., 2010:368; Litovsky et al., 2004:648-655; Müller et al., 2002:198-206; Neuman et al., 2007:73-82; Schön et al., 2002:710-714; Verschuur & Lutman, 2003:13) while paediatric studies' sample sizes mostly range from 20 to more than a 100 participants (Manrique et al., 2007:224-231; Sharma et al., 2002:532-539; Sharma et al., 2007:218-223). Therefore, the purposive convenient sampling method (part of non-probability sampling, Leedy & Ormrod, 2005:206) was applied in this study to select all participants who complied with the selection criteria as stated below (2.4.2). Using this method implies that:

- the participants were selected according to the purpose of the study (Leedy & Ormrod, 2005:206). A qualitative approach was used, and because this approach focuses primarily on richness of data, the sample was selected purposefully rather than randomly, thus yielding a sample of information-rich participants (Struwig & Stead, 2001:121-122);
- the participants were chosen on the basis of accessibility and because they articulated with the researcher's aim of study (Struwig & Stead, 2001:111).

3.4.2 Criteria for selection

The participant selection criteria are provided in Table 3.1 and characteristics not used as criteria for selection are provided in Table 3.2.

Table 3.1: Selection criteria for participants

Criterion	**Justification**
Clients with sequential bilateral cochlear implants.	All clients should have been sequentially implanted (cochlear implants implanted during separate surgeries) (Lustig & Wackym, 2005:126) as the main aim of the study is to determine the bilateral processing benefits achieved in sequentially implanted cochlear implant users.
Type of cochlear implant: All participants should be implanted with Nucleus cochlear implants from Cochlear™.	To date, the PCIP only implants Nucleus products. Furthermore, this criterion ensured uniformity of the product, thus lessening variability of the outcomes.
Model of cochlear implant: Freedom, Nucleus 22 or Nucleus 24.	These three models are products from Cochlear™, with which the clients of PCIP are implanted. Other types of cochlear implant models such as double array implants were not included. This contributed to diminish variability of the outcomes of the study.
Duration of time since implantation: Participants must already have been using their second cochlear implant for at least a period of one year.	The duration of time since the participants' second cochlear implantation should at least be one year. This is to ensure that the map for this implant would have been stabilised (Hughes et al., 2001:471). Furthermore, the participant must have had time to become adequately adjusted to his/her bilateral cochlear implantation status in terms of wearing and using both devices. According to the literature, adult cochlear implant users typically reach their performance plateau within six months to one year post-implantation (Teoh, Pisoni & Miyamoto, 2004a:1536-1540).
Participants' cochlear implants were required to have been bilaterally balanced with the company's (Cochlear™) software a month before conduction of the proposed test battery for data collection by an audiologist of the PCIP.	It is imperative to ensure even balance of the loudness of both devices, as sounds will lateralise to the louder ear if loudness is unbalanced (Cochlear Corporation Limited, 2005:5). To remove the influence of binaural loudness summation on performance as far as possible, Laszig et al. (2004:958-968) suggest that loudness balancing of unilaterally and bilaterally used processor programmes / maps be required.
Ear specific aided pure tone thresholds (air conduction) between 25-40 dB HL and ear specific aided speech discrimination scores of	Clients with aided thresholds greater than 40 dB HL and aided speech discrimination scores less than 70% may be viewed as not well adapted and thus not good cochlear implant users

≥70%.	(Moore & Teagle, 2002:160).
Type and degree of hearing loss (prior to implantation): Participants were required to have had a bilateral severe-to- profound (71 dB HL to > 90 dB HL) or moderate-to-profound (41 dB HL to > 90 dB HL) sensorineural hearing loss (Clark, 1981 in Harrel, 2002:82) prior to the implant.	The participants' type and degree of hearing loss should correspond with candidacy criteria as accepted by the PCIP. These criteria are based on the selection criteria of Cochlear™, where bilateral severe-to-profound or moderate-to-profound sensorineural hearing loss is stated as first criterion for adults (*Candidacy Criteria for Children and Adults,* n.d.).
Participants were required to be clients of the Pretoria Cochlear Implant Programme (PCIP) at the University of Pretoria.	This ensured uniformity among participants. Furthermore, it was logistically more convenient for the researcher to conduct the fieldwork at the PCIP as she had access to the premises as well as to clients' records. Thus, the relevant information was therefore easily available and obtainable.
Language: Participants should be Afrikaans and/or English speaking.	The participants must be able to participate in the required test battery. The majority of bilaterally implanted clients of the PCIP are either English or Afrikaans speaking. The researcher is also only proficient in these two languages. This ensured clear communication during informed consent and the course of fieldwork.
Ages: The participants were required to be 18 years or older.	The study aimed to investigate the adult population of the PCIP and this criterion also ensured that informed consent could be obtained from the participants themselves.

Table 3.2: Aspects not considered for the selection of participants

Aspects not considered	**Justification for omission of selection criteria**
Participants may use different processing strategies (CIS, ACE or SPEAK).	The literature states that in the general cochlear implant user population, patient characteristics are likely to be the major contributing factor responsible for observed audiological outcomes rather than device properties (Teoh et al., 2004a:1536) such as different processing strategies. Wilson and Dorman (2008:11) echo this sentiment when stating that cochlear implant users' performance differences can be linked to the size of the input dynamic range, rather than the use of a specific processing strategy *per* se. The use of a specific processing strategy therefore did not exclude or include a participant. It could be taken into account, however, in the analysis of data.
Duration of deafness.	This variable was utilised to interpret findings, for example the influence of the hearing loss duration on the client's ability to achieve bilateral processing benefits, i.e. sound localisation and speech perception in noise. According to Teoh et al. (2004a:1536-1537), duration of deafness is considered an important factor that predicts the success of post-implant outcomes, especially in relation to speech perception abilities. However, the selection of participants with aided speech discrimination scores of 70% or better will ensure that good candidates were selected regardless of the duration of deafness.
Inter-stage interval (duration between first and second cochlear implantation).	The inter-stage interval was not specified in order to avoid further confining the participant sample, since purposive convenient sample is limiting in nature. The effect of the inter-stage interval was analysed as delay between implantations could compromise the auditory pathways' binaural processing abilities (Papsin & Gordon, 2008:69).

3.4.3 Material and apparatus for participant selection

A discussion of the material and apparatus for participant selection will follow.

Material for participant selection

During participant selection, the prospective participants' biographical information was recorded on a form (see Appendix E). Participants' audiological history and information on both cochlear implants were obtained from their clinical records at the PCIP and documented on the biographical form. Furthermore, a standard audiogram form, as used by the University of Pretoria, was used to document the results of the otoscopic examination, tympanometry, aided pure tone audiometry and aided speech audiometry (see Appendix F). The *Phonetically Balanced Word List* in English (Egan, 1948 in Mendel & Danhauer, 1997) and the *Afrikaanse Foneties Gebalanseerde Woordelys* (Laubscher & Tesner, 1966) (depending on the language preference) were used to determine the participant's speech discrimination[2] abilities (see Appendix G1 and G2). The afore-mentioned information was of importance during conduction of localisation and bilateral speech perception measurements and to determine the bilateral processing benefits that could be achieved in the case of sequentially implanted users.

Apparatus for participant selection

The materials and equipment that were used in order to determine if individuals were suitable to participate in the main study are discussed in Table 3.3.

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[2] Also referred to as *speech recognition* abilities in literature.

Table 3.3: Apparatus for participant selection

Participant selection apparatus	Justification for the use of the apparatus
Welch Allyn Pocket Professional Otoscope (with specula)	An otoscopic examination forms part of an audiological test battery. The otoscope enabled the researcher to perform otoscopic examinations to ensure no abnormalities, infections, or obstructions were present in the auricle or the external auditory canal as any abnormalities need to be referred to a medical practitioner or Ear-, Nose- and Throat specialist (ENT) for prompt intervention (Rappaport & Provencal, 2002:17).
GSI-33 Immittance meter (calibrated in 2009/2010)	The researcher utilised this instrument to conduct tympanometric measurements and consequently determine the participants' middle ear status and functioning. It is essential to ensure that there are no abnormalities in the middle ear, as middle ear pathology might influence the results (Fowler & Shanks, 2002:175,202).
Disinfectant (Hibitane fluid) and paper towels	Disinfectant and paper towels were used to disinfect specula and probe tips (used during tympanometry) before and after use with each participant to ensure hygiene throughout procedures as well as to avoid contamination among participants.
Grason-Stadler clinical audiometer (GSI-61) (Viasys™ Healthcare) (calibrated in 2009/2010)	It was used to determine each prospective participant's aided pure tone thresholds as well as aided speech discrimination abilities with his / her cochlear implants.
Misco loudspeakers **Type:** 8" (inch) 20 cm co-motional Coaxial Transducer (40 Watt) **Model:** JC80PA **Frequency response:** > 93 dB **Impedance:** 8 Ω **Frequency spectrum:** 125 – 16 000 Hz (Hanekom, 2008).	To determine the participants' speech discrimination abilities, stimuli of the *Phonetically Balanced word list* in English and the *Afrikaans Foneties gebalanseerde woordelys* (depending on the language preference) were presented through the loudspeakers:
Soundproof room/Audiometric booth	An audiometric booth was used to provide a sound-treated environment during conduction of bilateral balancing testing. This was to ensure accurate and reliable pure tone and speech measurements (Bess & Humes, 1995:116; Hougton, 2002:333).
Audiogram	An audiogram was used to record the aided pure tone and speech audiometry measurements, tympanometry, and otoscopic results (see Appendix F).

3.4.4 Procedure for participant selection

During the selection of participants for the main study the following procedure was followed:

- A letter to the Head of the PCIP was prepared with the aim of requesting permission to engage the programme's clients and to gain access to the clients' records (see Appendix C).
- The co-ordinator of the PCIP was contacted to aid in the selection process by identifying prospective participants from a client register according to the selection criteria as set out in section 3.4.2**.**
- Each participant was contacted personally via telephone (if he/she has already acquired the ability to communicate telephonically), short message system (sms) or direct electronic mail (e-mail). Where it was not feasible to contact the participant personally, or a significant other was selected as the contact person. The nature, purpose, procedures, content, and implications of the study were explained to them. Subsequently, it was determined if the participant would be

willing to participate in the selection procedure and consequently the main study. Furthermore, a date and time for the test procedures for participant selection that was suitable for both the participant and researcher was arranged.

- On the arranged date and time, the participant met the researcher at the Department of Communication Pathology, University of Pretoria. A letter requesting informed consent was given to each participant (see Appendix D1 and D2), which he/she read and signed in the presence of the researcher. The participant's preferred language for completing the test battery was also determined.
- Subsequently, a suitable date and time for the data collection procedures was arranged with the participant.
- A battery of tests was performed, as a test battery approach is the foundation of responsible and effective auditory assessment (Hannley, 1986:1-6). The measurements included otoscopic examination, tympanometry, aided pure tone air conduction audiometry (with the cochlear implants switched on), and aided speech audiometry. Pure tone bone conduction audiometry, acoustic reflex and oto-acoustic emission testing that are part of a conventional diagnostic test battery were not included, as the purpose of the study is to evaluate aided thresholds and not residual hearing. Before commencement of the test, the battery of each processor was checked and correct placement of both speech processors was ensured.
- Participants whose test results conformed to the set criteria were required to have had their cochlear implants mapped recently (that is, in the past six to 12 months). This ensured that their threshold and comfortable levels were valid and that results obtained during the test battery for data collection would be valid (Clark, 2003:666, 667).

Table 3.4 provides a description of the specific measurements that were used to select participants.

Table 3.4: Description of the participant selection procedures

Participant selection procedure	**Description and purpose of the procedure**
Otoscopic examination	An otoscopic examination, by means of an otoscope, forms part of the audiological test battery as well as part of the basic adult test battery used at the PCIP and was therefore conducted as part of standard procedure. The purpose was to examine the external auditory meatus and tympanic membrane (Rappaport & Provencal, 2002:16,17). Specula of the appropriate size were used. Both normal and abnormal signs were recorded on the audiogram and referral to an Ear, Nose and Throat specialist was made when needed.
Tympanometry	Tympanometry objectively measures the middle ear status and function. It is considered an integral part of an audiological test battery (Fowler & Shanks, 2002:175). Appropriate probe tip sizes were used and fitted according to each participant. Tympanograms were obtained bilaterally for each participant. The tympanograms were classified according to the classification system by Jerger (1970, in Fowler & Shanks, 2002:177). Middle ear pathology might influence other test results (Fowler & Shanks, 2002:202) and thus the reliability and validity of the outcomes. As a result, all participants that did not have a Type A tympanogram (indicative of normal middle ear function - ear canal volume: 0.63-1.46ml; compliance: 0.32-1.46ml; middle ear pressure: 50-150 daPa. Hall & Mueller, 1998:199) were referred to the Ear, Nose and Throat specialist and were excluded from the main study until a Type A tympanogram was obtained bilaterally (Fowler & Shanks, 2002:177).
Aided pure tone thresholds, air conduction	Pure tone audiometry was conducted to determine the participants' sensitivity to pure tone stimuli of discrete frequencies (Hannley, 1986:253; Rappaport & Provencal, 2002:17) with their cochlear implant devices. The participant's aided pure tone air conduction thresholds with the cochlear implant devices switched on the regular setting were determined by means of using free-field warbled pure tones. Left or right routing was selected on the audiometer, depending on the ear to be tested. Frequency specific thresholds were obtained at: 250, 500, 1000, 2000, 3000 Hz, 4000, 6000 and 8000Hz, as the frequency range of most implant systems is approximately 250-7000 Hz (Moore & Teagle, 2002:154). Therefore, the 125 Hz frequency was excluded from pure tone testing. The threshold at each frequency was recorded using a capital letter [C] for the free field thresholds with the use of a cochlear implant. Thresholds for each ear were recorded on a separate audiogram on one form. Thresholds between 25-40 dB HL was considered as acceptable for a client who is well adapted, appropriately mapped and a good cochlear implantation user (Moore & Teagle, 2002:160).
Aided Speech audiometry: Speech Discrimination Testing	Speech discrimination measurements were included to determine how well the participants could identify words from a phonetically balanced list at a suprathreshold level (Brandy, 2002:101). Speech audiometric measurements are important as the ultimate significance of hearing loss lies in the extent to which hearing of speech for communication is affected (Hannley, 1986:153) and to determine whether the person is a "good cochlear implant user". Left or right routing was selected on the audiometer, depending on the ear to be tested. A list of 25 phonetically balanced words, from the *Phonetically Balanced word list* in English (Egan, 1948 in Mendel & Danhauer, 1997) and the *Afrikaanse Foneties gebalanseerde woordelys* (Laubscher & Tesner, 1966) depending on the language preference, (see Appendix G1 and G2) was presented through the loudspeakers in closed set. Results were expressed in percentage of words correct per list. The audiometer's starting intensity was set at 70 dB SPL. Performance level of at least 70% had to be reached for the participant to be considered for the main study (Moore & Teagle, 2002:160).

3.4.5 Description of participants

Eleven patients of the PCIP met the selection criteria as stated in Section 3.4.2. This information was obtained from the Biographical information form (see Appendix E). Table 3.5 depicts information on each participant's age at time of testing; age of onset of hearing loss; etiology of hearing loss; age at switch on, model of Cochlear™ implant, type of speech processor of the first implant (CI 1) and second implant (CI 2) respectively; duration between implants' switch on dates as well as duration of use of both implants (BiCI) (taken from the date that the second implant was switched on).

Table 3.5: Participants' details (n=11)

No	Age during testing (years)	Age at hearing loss onset (years)	Etiology	Age at CI 1 switch on (years)	Model of Cochlear™ implant and *speech processor of CI 1*	Age at CI 2 switch on (years)	Model of Cochlear™ implant and *speech processor of CI 2*	Interval between C1 an C2 switch on dates (years)	Dura-tion of BiCI use (years)
1	59.5	5	Chronic otitis media	51.8	Nucleus 24M *Freedom SP*	54.1	Nucleus 24CA *Freedom SP*	2.5	5.4
2	69.10	9	Mumps	59.2	Nucleus 24M *Esprit 24*	64.5	Nucleus 24CA *Esprit 3G*	5.3	5.5
3	66.8	28	Progressive	61.10	Freedom 24CA *Freedom SP*	64.6	Freedom 24CA *Esprit 3G*	2.8	2.2
4	66.3	31	Progressive	55.9	Nucleus 24M *Freedom SP*	61.7	Freedom 24CA *Freedom SP*	5.10	4.8
5	60.3	35	Progressive	45.10	Nucleus 22M *Freedom SP*	56.4	Freedom 24CA *Nucleus 5*	10.6	3.11
6	23	0	Extreme prematurity with complications	19.5	Freedom 24CA *Nucleus 5*	21.11	Freedom 24CA *Freedom SP*	1.4	2
7	21.10	2	Meningitis	4.6	Nucleus 22 *Freedom SP*	16.6	Nucleus 24CA *Freedom SP*	12	5.4
8	54.3	13	Progressive	47.7	Nucleus 24 *Freedom SP*	49.1	Nucleus 24CA *Esprit 3G*	1.6	5.2
9	32.6	0	Genetic	23.11	Nucleus 24K *Nucleus 5*	29.6	Freedom 24CA *Freedom SP*	4.7	4.1
10	44.6	22	Post-traumatic MVA	39.8	Nucleus 24CA *Freedom SP*	41.4	Freedom 24CA *Freedom SP*	2.8	3.2
11	20.11	0	Congenital	7.1	Nucleus 22M *Esprit 3G*	17	Freedom 24CA *Freedom SP*	9.11	3.11

Participants' ages ranged between 21 and 69 years at the time of testing (mean: 47 years). Age at first and second implantations' switch on ranged from 4.6 to 61.10 years (mean: 37.7 years) and 16.6 to 64.6 years (mean: 43.3 years) respectively. Duration between the first and second cochlear implants' switch on ranged from 16 months (1 year 4 months) to 144 months (12 years) (mean: 51 months) and duration of bilateral implant use ranged from 24 months to 54 months (mean: 49 months). As can be concluded form Table 3.5, most participants can be considered as late implanted with unfavourable interval periods. It was anticipated that results would be congruent with this configuration.

3.5 DATA COLLECTION INSTRUMENTS AND APPARATUS

The following measurement instruments and apparatus were utilised to collect data.

3.5.1 Instruments for data collection

The test battery instruments used to verify the participants' sound localisation and speech perception in noise (speech and noise spatially separated and coincident) skills in order to objectively determine their bilateral processing benefits achieved are provided in Table 3.6.

Table 3.6: Description of test material

Test material	Description
• **Sound localisation test**	A sound-direction identification task with speech-weighted noise (SWN) at 70 dB SPL (sound pressure level) (Cainer & Rajan, 2008:155; Cochlear Corporation Limited, 2005:4) was used to determine the participants' sound localisation abilities as described in section 3.6.1. SWN was the chosen type of stimuli due to the fact that its spectrum is equal to the long-term average spectrum of speech (Cainer & Rajan, 2008:157) and could be selected through the audiometer that was used.
• **Speech perception in spatially separated speech and noise**	The *Central Institute for the Deaf (CID) Everyday Speech Sentences* (Davis & Silverman, 1970, in Alpiner & McCarthy, 2000:622-623), in pre-recorded format in English and Afrikaans (Müller & De Stadler, 1987), was used to test each participant's aided speech recognition at a sentence level. Performance was recorded on the *CID* forms as well as the adapted version of the of standard speech audiogram used by the Hearing Clinic of the University of Pretoria (See Appendix H 1/2 and I, respectively).
• **Speech perception in spatially coincident speech and noise**	The *Central Institute for the Deaf (CID) Everyday Speech Sentences* (Davis & Silverman, 1970, in Alpiner & McCarthy, 2000:622-623), in pre-recorded format in English and Afrikaans (Müller & De Stadler, 1987), was used to test each participant's aided speech recognition at a sentence level. Performance was recorded on the *CID* forms as well as the adapted version of the of standard speech audiogram used by the Hearing Clinic of the University of Pretoria (See Appendix H 1/2 and I, respectively).

3.5.2 Apparatus for data collection

Table 3.7 provides a description of the apparatus used to determine the bilateral processing benefits achieved by the sequentially implanted adult cochlear implant users in this study.

Table 3.7: Data collection apparatus

Data collection apparatus	Justification for the use of the apparatus

Grason-Stadler clinical audiometer (GSI-61) (Viasys™ Healthcare) (calibrated in 2009/2010)	This was used to present the noise signal of speech weighted noise together with the pre-recorded speech material (Table 3.6) in order to determine each participant's aided speech perception abilities in the specified test conditions, namely (1) spatially separated speech and noise and (2) spatially coincident speech and noise. Furthermore, the stimuli for localisation test procedures were also produced by the audiometer.
Ipod Nano 8 GB	The speech material, namely the *CID Everyday Speech Sentences* (Davis & Silverman, 1970, in Alpiner & McCarthy, 2000:622-623) used to determine the speech perception in noise abilities of the participants, was pre-recorded on the Ipod. The Ipod was then connected with a shielded RCA to stereo audio cable to the audiometer to present the sentence material through the audiometer to the loudspeakers. The Afrikaans translated version of these sentences was used for Afrikaans speaking participants (Müller & De Stadler, 1987).
3 Misco Loudspeakers **Type:** 8" (inch) 20 cm co-motional Coaxial Transducer (40 Watt) **Model:** JC80PA **Frequency response:** > 93 dB **Impedance:** 8 Ω **Frequency spectrum:** 125 – 16 000 Hz (Hanekom, 2008).	To determine the extent of participants' bilateral processing benefits, the stimuli of the localisation measures and speech perception measures (in spatially separated as well as spatially coincident speech and noise) were presented through the loudspeakers:
Soundproof room / Audiometric booth	An audiometric booth was used to provide a sound-treated environment during conduction of bilateral processing testing. This was to ensure accurate and reliable pure tone and speech measurements (Bess & Humes, 1995:116; Hougton, 2002:333).
Measuring tape and permanent marker pen	To measure and mark equal distance for placement of speakers from participants and from each other. Ensuring that loudspeakers' placement is exactly the same for each participant is imperative for the reliability of results.
Headrest	The participant's head was kept in a fixed position during sound localisation testing by asking the participant to rest his/her head against a headrest. This would help to prevent any reflexive head movements during localisation tests (Nopp et al., 2004:205-214).
Audiogram	An adapted version of the standard audiogram used by the Hearing Clinic, Department of Communication Pathology at the University of Pretoria was used to record the results of sound localisation and aided speech perception in noise (spatially separated and coincident) (See Appendix I).

3.6 PROCEDURES

Data collection and analyses proceeded according to a specific schedule, which included a pilot study as first step.

3.6.1 Data collection

Steps in data collection

The following steps were taken during data collection:

- During the participant selection procedures the date and time for localisation and speech perception testing was determined. At the appointed time, the participant and researcher met at the Hearing Clinic of the Department of Communication Pathology at the University of Pretoria.

- After informed consent was confirmed and the results of the selection procedure were seen to have met the stated requirements, the test battery followed. Sufficient battery strength and functioning of speech processors and coils were ensured by means of a listening check and using a coil tester.
- The measurements that were performed to determine the participants' bilateral processing benefits included localisation measures as well as aided bilateral speech perception measures, specifically spatially separated speech and noise and spatially coincident speech and noise. For the speech perception in noise measures, participants were instructed to select the map they prefer to listen to speech in a noisy environment. Consequently, the default volume and sensitivity settings of the selected map were used by the participant. These measures were conducted in the following manner: initially, with only the first implanted cochlear implant switched on, then with the second implant switched on, and finally with both implants switched on simultaneously.
- Subsequently, bilateral spatial benefits, namely head shadow effects, summation, squelch, and spatial release of masking (SRM), were calculated as these measures can be used to furthermore quantify the extent of bilateral/binaural benefit (Eapen et al., 2009:153; Van Deun et al., 2010:702-713). Each of the bilateral spatial benefits listed above was calculated as follows (Van Deun et al., 2010:705-706):

  Head shadow 90°: The head shadow effect arose from a shift in the noise position of 90° and was calculated as the difference in the SRT value (in dB) obtained with the left/right ear in the NF versus NR/NL condition.

  Head shadow 180°: This head shadow effect was calculated as the difference in the SRT value (in dB) obtained with the left/right ear in the NL/NR versus NR/NL condition as there was a 180° change in the noise position.

  Squelch: The enhancement in speech perception due to the addition of an ear with a poorer SNR is known as the squelch effect (Cochlear Corporation Limited, 2005:1). It was calculated as the difference between the SRT values (in dB) for the left/right ear and both implants in the NR/NL condition.

  Summation: Summation is defined as the improvement in speech perception as a result of identical signals with the same auditory characteristics arriving at both ears (Müller et al., 2002:198-206). Summation is produced by binaural redundancy (also known as diotic summation), that is, the difference between bilateral and better ear performance in spatially coincident speech and noise and binaural loudness summation (Cochlear Corporation Limited, 2005:1; Schön et al., 2002:710). Summation was calculated as the difference between the SRT values (in dB) of the first/second implant (CI 1/CI 2) and bilateral implants in the NF condition.

Spatial release of masking (SRM): This effect is defined as the improvement in speech perception as a result of spatial separation of speech and noise when listening with both ears. Hence, SRM was determined as the difference in bilateral SRT values (in dB) in the NF versus NR or NL condition; for example, the SRM when noise is directed to CI 1 is calculated as the difference in SRT values (in dB) for BiCI in NF condition and BiCI when the noise is directed to CI 1. In support of the SRM effect, the benefit of adding the better SNR ear was determined. This implies the improvement in speech perception resulting from the addition of an ear with a better SNR. Thus, the difference between the SRT value for the left/right ear and the bilateral SRT in the NL/NR conditions was determined. This could possibly include all of the above stated spatial benefits because an ear is added in a situation with spatially distinct speech and noise.

- During testing, the participant was seated in a specific marked site and was asked to respond to certain sounds and repeat sentences presented to him/her. The test battery took approximately 2 hours to complete. Appendix J describes the instructions for the different tests conducted as well as the corresponding audiometer settings.
- The data obtained from these measurements were recorded on the appropriate forms and was later typed in the form of Microsoft Excel spreadsheets.

Test procedures for data collection

The tests to determine participants’ bilateral processing abilities, comprising sound localisation as well as speech perception in spatially separated and spatially coincident speech and noise, are discussed below.

- **Sound localisation test**

The procedure was performed in a soundproof booth. The test setup consisted of a loudspeaker array of three equidistant loudspeakers located in the horizontal plane in front of the participants at ear level. Each of the loudspeakers was clearly labeled by number. Loudspeaker 1 was located on the left (-90°), Loudspeaker 2 was located in the centre and Loudspeaker 3 was located on the right (90°). The participant sat in the centre of the array, facing Loudspeaker 2 (0° azimuth), at a distance of 1 meter from the loudspeakers (Neuman et al., 2007:73-82) (see Figure 3.1 on page 64). The participant was instructed to face Loudspeaker 2 and to keep his/her head in a fixed position during signal presentation by fastening the participant's head with a head band against a headrest. This would help to prevent any reflexive head movements (Nopp et al., 2004:205-214). Furthermore, the researcher monitored the participant's head position during the presentation of the stimulus to ensure that he/she did not move his/her head while the stimuli were presented. Before conducting the localisation test, the researcher instructed the participant to call out the number of the loudspeaker that was perceived as the sound source. In addition, stimuli were played consecutively through each of the loudspeakers (from left to right) to familiarise the participant with the test room, loudspeaker array, and listening condition. The stimuli consisted of speech weighted noise (SWN) at 70 dB SPL (sound pressure level) (Cainer & Rajan, 2008:155; Cochlear Corporation Limited, 2005:4). The order in which the stimuli were presented was randomised across loudspeakers (Nopp et al., 2004:205-214) according to a statistic standarised random number table (The Rand Corporation, 1955). A randomised order of presentation across the three loudspeakers was calculated for each participant (see Appendix K). No feedback was given to the participants during testing (Neuman et al., 2007:73-82). The stimuli correctly localised were recorded on the adapted version of the standard audiogram used by the Hearing Clinic, Department of Communication Pathology, University of Pretoria. These measures were conducted in the following manner: initially, with only the first implanted cochlear implant switched on (CI 1), then with the second implant switched on (CI 2) and finally with both implants switched on simultaneously (BiCI). Thus, there were three possible listening conditions for the localisation procedure.

- **Speech perception in spatially separated speech and noise test**

  Speech and noise were presented from separate loudspeakers. An angular separation of 90° between the speakers through which the speech signal and noise were presented, was applied (Cochlear Corporation Limited, 2005:1,2). The speech was always presented from a loudspeaker in front of the participant and the noise was presented from a different loudspeaker in order to direct the noise to the participant's right and then his/her left ear (see Figures 3.2 and 3.3 on pages 65 and 66, respectively). The above-mentioned procedures were performed to determine aided bilateral speech perception abilities as a measure of the bilateral processing benefits achieved (Cochlear Corporation Limited, 2005:1; Van Deun et al., 2010:702-713). Pre-recorded *Everyday Speech Sentences of The Central Institute for the Deaf (CID)* (Davis & Silverman, 1970, in Alpiner & McCarthy, 2000:622-623) was used to evaluate the participants' speech perception in noise at sentence level (Alpiner & McCarthy, 2000:324, 622-623). The Afrikaans translated version of these sentences was used for Afrikaans speaking participants (Müller & De Stadler, 1987). Before presentation of each sentence list, a calibration tone was presented in order for the researcher to monitor the volume unit (VU) meter of the audiometer to ensure that the audiometer presented the recorded speech material at the specified level (Wilber, 2002:51,61). The sentences were presented through the specified loudspeaker (see Figures 3.2 and 3.3 on pages 65 and 66, respectively), thus as a closed set. Participants were instructed to repeat each sentence as it was presented (Alpiner & McCarthy, 2000:324) and no feedback as to correct or incorrect response was given. Continuous speech noise was selected, and presented simultaneously with the sentences at a fixed level of 55dB HL (Van Deun et al., 2010:702-713). An adaptive procedure (Galvin et al., 2010:372; Van Deun et al., 2010:702-713) was used to determine the SNR at which the participant's speech reception threshold (SRT) was achieved, thus the level where the participant achieved at least 50% performance. In this process the first sentence was presented at 0 dB SNR. Hence, the speech signal as well as the noise was presented at 55 dB HL. The speech signal level of the first sentence was increased in steps of 2 dB until the participant could identify the first sentence correctly, based on the number of correct keywords. Subsequently, the remaining sentences were presented adaptively according to a one up, one down method. Thus, when the first sentence was identified correctly, the speech signal of the second sentence was presented at 2 dB lower. If the second sentence was identified correctly, the speech signal of the third sentence was presented at 2 dB lower again. But, if the second sentence was incorrect, the speech signal presenting level was increased by 2 dB. Thus, the test was made easier in terms of a more favourable SNR until the first sentence was identified correctly. Consequently the second and subsequent sentences were presented adaptively and stopped after 10 sentences. The maximum level to which the speech signal could be increased and that could be selected through the audiometer was 84 dB HL. The test result was the average SNR of the level of the last six presentations (Galvin et al., 2010:372; Van Deun et al., 2010:702-713). These measures were conducted initially with the noise directed to the participant's right ear (NR), firstly with only the first implanted cochlear implant switched on (CI 1), then with the second implant switched on (CI 2) and finally with both implants switched on at once (BiCI). Subsequently the noise was directed to the participant's left ear (NL) and the same routine regarding the implant(s) being switched on was then followed. Thus, for the spatially separated speech and noise conditions there were six possible listening configurations. Results were calculated in terms of noise ipsilateral to CI 1 and noise ipsilateral to CI 2 and will be discussed accordingly.

- **Speech perception in spatially coincident speech and noise test**

  Speech and noise were presented from a single loudspeaker in front of the participant. The speech signal as well as the noise were presented from the same loudspeaker, situated in front of the participant (0° azimuth) (Cochlear Corporation Limited, 2005:2) (see Figure 3.4 on page 67). This procedure was performed to determine aided bilateral speech perception abilities as a measure of the extent to which bilateral processing benefit is achieved (Cochlear Corporation Limited, 2005:1; Schon et al., 2002:710-713). Pre-recorded *Everyday Speech Sentences of The Central Institute for the Deaf (CID)* (Davis & Silverman, 1970, in Alpiner & McCarthy, 2000:622-623) was used to evaluate the participants' speech perception in noise at sentence level (Alpiner & McCarthy, 2000:324, 622-623). The Afrikaans translated version of these sentences was used for Afrikaans speaking participants (Müller & De Stadler, 1987). Before presentation of each sentence list, a calibration tone was presented in order for the researcher to monitor the volume unit (VU) meter of the audiometer to ensure that the audiometer presented the recorded speech material at the specified level (Wilber, 2002:51,61). The sentences were presented through Loudspeaker 2 (see Figure 3.4 on page 67), thus as a closed set. Participants were instructed to repeat each sentence as it was presented (Alpiner & McCarthy, 2000:324) and no feedback as to correct or incorrect response was given. Continuous speech noise was selected, and presented simultaneously with the sentences at a fixed level of 55dB HL (Van Deun et al., 2010:702-713). The same adaptive procedure as described above was used to determine the SNR at which each participant's speech reception threshold (SRT) was achieved, thus the level where the participant achieved at least 50% performance. The maximum level to which the speech signal could be increased and that could be selected through the audiometer was 78dB HL. The test result was the average SNR of the levels of the last six presentations (Galvin et al., 2010:372; Van Deun et al., 2010:702-713). The testing was conducted in the following manner: initially with only the first implanted cochlear implant switched on (CI 1), then with the second implant switched on (CI 2), and finally with both implants switched on simultaneously (BiCI). Thus, there were three possible listening configurations for the spatially coincident speech and noise testing condition.

Hence, for the speech in noise perception testing, there were altogether nine test conditions. The pre-recorded CID sentences in English had eight lists, each containing 10 sentences (see Appendix H 1). Thus, for the English participants list one to eight were played and then list one was repeated for the last test condition (listening with both implants switched on to spatially coincident speech and noise). The Afrikaans version of the pre-recorded CID sentences had nine lists of 10 sentences each, namely list A, B, C, D, E, G, H, I and J (see Appendix H 2). For the Afrikaans participants, therefore, the lists were played only once, consecutively for all nine test conditions.

Graphical illustrations of the different test-setups used for the data collection procedures to determine participants' bilateral processing are presented below.

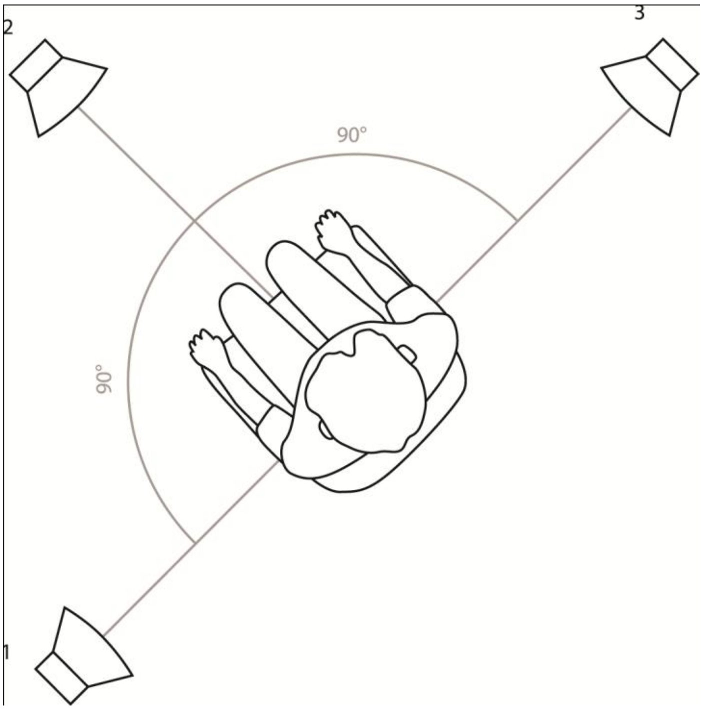

Figure 3.1: Test setup to determine sound localisation abilities

(Adapted from Cochlear Corporation Limited, 2000:6)

As can be seen from Figure 3.1, the participant faced the centre loudspeaker, which was labelled with the number 2. Loudspeakers 1 and 3 were on the participant’s left and right hand side, respectively.

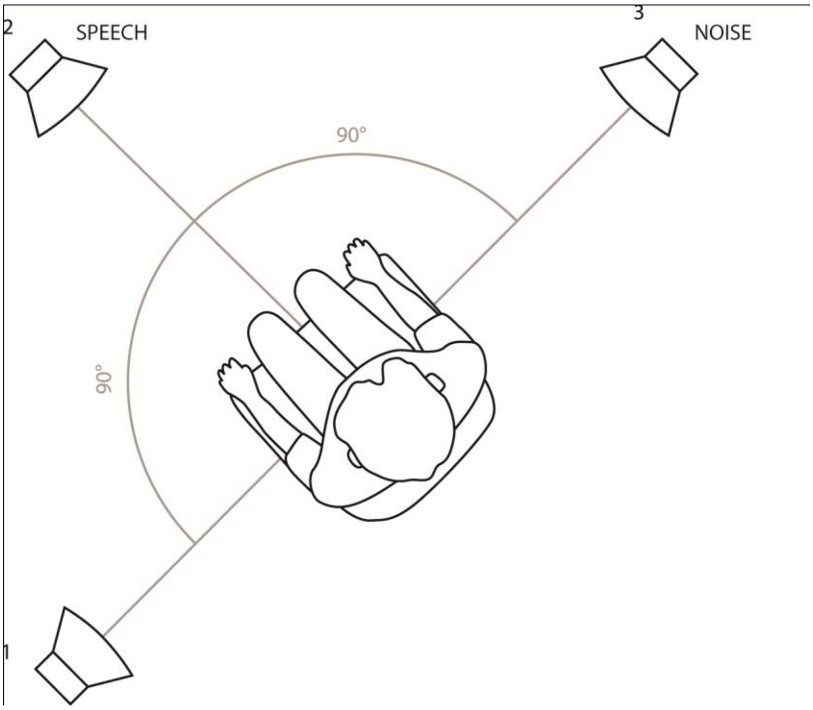

Figure 3.2: Test setup the determine speech perception in noise: speech and noise spatially separated with noise directed to the right ear

(Adapted from Cochlear Corporation Limited, 2005:1)

In the setup displayed in Figure 3.2, the participant faced Loudspeaker 2, situated in the centre. The speech signal was presented from Loudspeaker 2 and the noise signal from Loudspeaker 3 to determine the speech perception in noise abilities where the noise is directed to the participant’s right ear. The participant remained in this position to conduct three trials of speech perception in noise, first with only the first implanted cochlear implant switched on, then with the second implant switched on and finally with both implants switched on simultaneously.

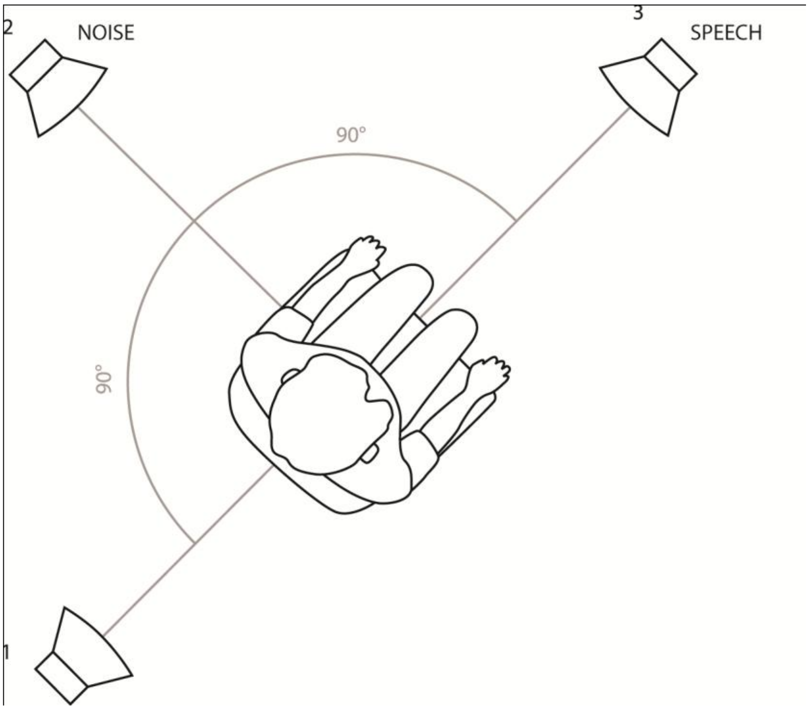

Figure 3.3: Test setup the determine speech perception in noise: speech and noise spatially separated with noise directed to the left ear

(Adapted from Cochlear Corporation Limited, 2005:1)

Consequently, the participant’s chair’s position was changed so that the participant faces Loudspeaker 3 on the right as displayed in Figure 3.3. Consequently, speech and noise signals were alternated in routing to loudspeaker 3 and 2 respectively, in order to evaluate the participant’s speech perception in noise abilities where the noise is directed to the participant’s left ear. Again, three trials of speech perception in noise in this position, first with only the first implanted cochlear implant switched on, then with the second implant switched on and finally with both implants switched on simultaneously, were conducted.

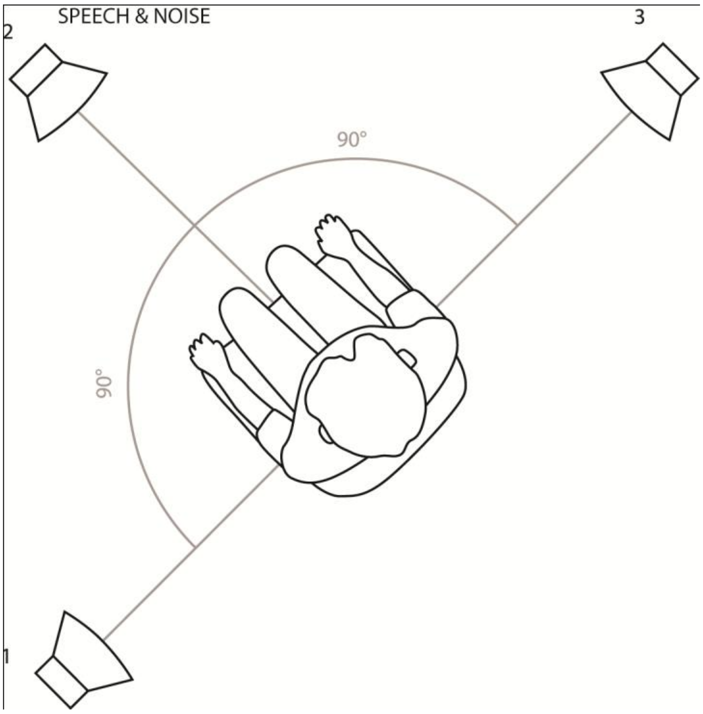

Figure 3.4: Test setup to determine speech perception in noise abilities: speech and noise spatially coincident

(Adapted from Cochlear Corporation Limited, 2005:2)

Figure 3.4 demonstrates that the participant faced only one loudspeaker (numbered as 2 for the participant) as the speech and noise were presented from the same loudspeaker. Again, these measurements were conducted initially with only the first implanted cochlear implant switched on, then with the second implant switched on and finally with both implants switched on simultaneously.

3.6.2 Data analysis

Participants' raw data obtained from the test battery was recorded on the different scoring sheets and analysed individually according to the procedures as set out in section 3.6.1. Consequently, the raw data information was recorded and analysed electronically on spreadsheets by means of the Microsoft Excel computer programme (Anderson, Sweeney & Williams, 2003). This computer programme was utilised to present results graphically in terms of tables and figures, in order to integrate the collected data and present it logically (Leedy & Ormrod, 2004:252-257).

Quantitative methods were utilised to analyse and process data in collaboration with statisticians from the Statistics Department, University of Pretoria. The data was also analysed electronically by means of a statistical software package, namely Statistical Package for Social Sciences (SPSS) (Field, 2005). Thus, descriptive statistics were used during this study. It yielded a summary of the general nature of the extent of bilateral processing benefits achieved by sequentially implanted users as collected during the test battery (Leedy & Ormrod, 2005:257). In addition, inferential statistics were utilised to reach inferences about larger populations by collecting data on a relatively small sample (Leedy & Ormrod, 2005:252).

As the sample size was limited, distribution-free tests were applied (Steyn, Smit, Du Toit & Strasheim, 2003:583-588; Miller & Miller, 2004:520-531). The term *distribution-free* refers to assumptions with regard to the distributions of the underlying populations from which the samples are drawn (Steyn et al., 2003:583; Miller & Miller, 2004:521). It has the advantage that it can be applied for quantitative data from a limited sample size (Steyn et al., 2003:583). For sub-aims two to four the Mann-Whitney U-test (or just U test or Mann-Whitney test), also known as the Wilcoxon rank sum test, was used to draw conclusions about the sample population at a 5% significance level. The Mann-Whitney U-test is a distribution-free test and was selected due to the small sample size (Steyn et al., 2003:583; Miller & Miller, 2004:529-531).

For sound localisation, the Mann-Whitney test tested the null hypothesis, namely that there is no difference in the sound localisation ability when listening with the superior performing cochlear implant or with both implants simultaneously, against the alternative hypothesis that when participants listened with both implants they were able to localise sound better. For the tests of a speech perception in noise, the Mann-Whitney U-test tested the null hypothesis, namely that there is no difference in the speech perception in noise ability when listening with the superior performing cochlear implant or with both implants simultaneously in spatially separated or coincident speech and noise, against the alternative hypothesis that when participants listened with both implants they were better able to perceive speech in the presence of noise in spatially separated or coincident speech and noise conditions.

For sub-aim five the Wilcoxon rank sum test was also applied. Subsequently, the analysed results of all the participants were interpreted together in order to provide the answer to the research question (Kruger, De Vos, Fouché & Venter, 2005:218). A comparison of the results among the participants was not considered since the purposeful convenient sample that was used, yielded a small sample number. Results were set out graphically in terms of tables, figures, graphs and charts as this integrated and logically presented the collected data (Kruger et al., 2005:227).

3.6.3 Pilot study

A pilot study is the recommended way to plan, evaluate and improve proposed research material. It entails that the research program be conducted with participants from the particular group for whom the research is specifically planned (Strydom, 2005:205). Only one participant was involved in the pilot study, as the purposive convenient population sample was already limited. In this proposed study, a pilot study served the purpose of ensuring the researcher's acquaintance with and adequate skills in conduction of the data collection procedures selected, as set out in section 3.6.1, as well as in the data analysis and interpretation.

It is imperative that the pilot study's participant possess similar characteristics to the participants of the study. The same selection criteria that guided the selection of participants were therefore implemented in the selection of the pilot study participant, with the exception of the selection criterion of bilateral cochlear implantation and consequently bilateral balancing. The participant used for the pilot study had a unilateral cochlear implant of the right ear only. The decision to use a unilateral cochlear implant user was based on the fact that the purposive convenient population sample was limited and moreover, the PCIP only had a total of 14 adults with sequentially implanted cochlear implants. Thus, a good unilateral user was chosen for the pilot study to avoid further limiting the already restricted prospective participant group. The same procedure for participant selection as described in section 3.4.4, as well as the data collection procedures for bilateral processing benefit (section 3.6.1.2), applied during the pilot study. The participant had a Nucleus Freedom Contour Advance cochlear implant with a Freedom speech processor on her right ear. She was implanted in December 2005 and was switched on the following February in 2006, so that there was an appropriate duration of implantation of 4 years, 4months (since implantation) at the time of testing. The procedures that were followed yielded the results anticipated with the stimuli used, and were completed in the estimated time of two hours.

From the pilot study it was concluded that adjustments had to be made for the main study. These adjustments will be discussed below.

Bilateral processing tests

- **Speech perception in spatially separated speech and noise test**
  Initially, a fixed SNR of +5 dB (speech signal presented at 60 dB HL and noise presented at 55 dB HL) was used to evaluate the pilot study participant's bilateral processing ability to perceive speech where the speech and noise is presented from different loudspeakers. Initially, the noise was directed to her right ear, the ear with the cochlear implant. Thus her "best" ear was masked. Consequently, she was not able to discern any of the words in the sentences presented to her. She reported that she could determine that it was a male voice, but she could not distinguish whether it was an Afrikaans or English speaking male. As a result, the SNR was increased to +10 dB, thus the speech was presented at 65 dB HL and noise presented at 55 dB HL. Again, she perceived 0% of the speech. Subsequently, the SNR was increased with another 10 dB to a SNR of +20 dB (speech signal presented at 75 dB HL and noise presented at 55 dB HL). Under these circumstances she achieved 6% speech perception. Subsequently, the noise was directed to her left ear, the unaided ear. Yet again, with a SNR of +5 dB, she was unable to perceive any of the speech signals. Therefore, the SNR was increased to the more favourable +10 dB and as a result she perceived ten percent (10%) of the speech presented to her.

  These measurements were also conducted on two normal hearing individuals to serve as a control. Their subjective report that it was difficult to perceive speech in noise with only a +5 dB SNR, also led the researcher to adjust the SNR to +10 dB ratio.

  Subsequently, the procedure for testing speech perception in noise was discussed with international researchers in the field of bilateral cochlear implantation. It was recommended that an adaptive procedure (Galvin et al., 2010:372; Van Deun et al., 2010:702-713) be used to determine the SNR at which the participant's speech reception threshold (SRT) was reached, i.e., the level where the participant achieved at least 50% performance. When using the adaptive testing the procedure, the first sentence should be presented at 0 dB SNR. Hence, the speech signal as well as the noise should be presented at 55 dB HL. The speech signal level of the first sentence should be increased in steps of 2 dB until the participant could identify the first sentence correctly, based on the number of correct keywords. Subsequently, the remaining sentences should be presented adaptively in a one up, one down method. Thus, when the first sentence was identified correctly, the speech signal of the second sentence should be presented at 2 dB lower. If the second sentence was identified correctly, the speech signal of the third sentence should be presented at 2 dB lower again. But, if the second sentence was incorrect, the speech signal presenting level should be increased by 2 dB. Thus, the test was made easier in terms of a more favourable SNR until the first sentence was identified correctly. The second and subsequent sentences should be presented adaptively and stopped after 10 sentences. The test result was the average SNR of the last six presentations' levels (Galvin et al., 2010:372; Van Deun et al., 2010:702-713).

Based on the findings of the pilot study, a conclusive decision was made to use the adaptive test procedure in spatially separated speech and noise conditions for the main study.

- **Speech perception in spatially coincident speech and noise test**

  To perceive speech in the condition where both the speech and noise signals were presented from the same loudspeaker, was reported to be even more challenging by the pilot study participant. With a SNR of both +10 dB and +15 dB, the participant could not achieve any significant percentage of speech perception. As a consequence, the SNR was increased to +20 dB where the speech signal was presented at 75 dB HL and the noise was presented at 55 dB HL. Still the participant achieved only 10% speech perception. Subsequently, the researcher was again advised to use the adaptive test procedure (Galvin et al., 2010:372; Van Deun et al., 2010:702-713) to determine the SNR at which the participant's speech reception threshold (SRT) was achieved when speech and noise were spatially coincident. Accordingly, for the main study the same adaptive testing procedure as stated above was applied for the speech perception in noise testing with spatially coincident speech and noise.

The pilot study, in addition, aided to determine the feasibility (Leedy & Ormrod, 2005:110) as well as the appropriateness and accuracy of the proposed research material and apparatus. The pilot study ensured the researcher's acquaintance with performing measurements and interpreting bilateral and binaural processing outcomes.

3.7 RELIABILITY AND VALIDITY

The reliability and validity of the measurement instruments that were used in this study would influence the extent to which meaningful information could be attained from this study, the probability of obtaining statistical significance in data analysis, and the extent to which meaningful conclusions could be drawn from the data collected (Leedy & Ormrod, 2005:29).

Reliability is a term that refers to an instrument's ability to obtain the same results every time that it is performed and this will therefore lead to test-retest reliability (Delport, 2005:163). To obtain reliability as far as possible, the following was implemented:

- Each participant was contacted personally, telephonic or via electronic mail to explain the purpose of the study to them and to obtain their consent to participate.
- A qualified and registered audiologist performed the measurements to determine the participant's bilateral processing abilities achieved.
- A pilot study was conducted to determine the suitability and effectiveness of the data collection instruments and procedure and necessary adjustments were concomitantly done (Strydom, 2005:210-211).
- A qualified service technician was involved to verify the use of the correct equipment and test setup.

- Sound level measurements of the intensity of the signals to be presented in sound field were done before commencement of the testing procedures to ensure that the signals were presented at the specific intensity for each of the tests (as specified in section 3.6.1).
- A specific test setup was used with each participant with marked places for the participant and speakers, according to recent literature (Cochlear Corporation Limited, 2005:1,2,4).
- A headrest was used during the sound localisation test to ensure that reflexive head movements did not influence participants' responses so that true localisation abilities could be measured.
- The clinical audiometer that was used during the test battery for speech perception tests was calibrated to ensure accurate measurements. The Calibration Standard of the International Standards Organisation (OSI) is accepted in South Africa (Soer, 2002:15). Thus, the GSI 61 clinical audiometer was calibrated according to the specified standards.
- Recorded CID sentence test material was used for the speech in noise tests, to further enhance reliability and to avoid the presenting variability of using live voice. Furthermore, the possibility of using speech reading or lip reading by participants to support their speech perception, was eliminated by the use of recorded sentence test material which increased the reliability even more.

The validity of a measurement instrument is the extent to which the instrument measures what it is supposed to measure (Leedy & Ormrod, 2005:28). According to Struwig and Stead (2001:136) it refers to the degree to which the research design is scientifically sound or appropriately conducted. The current study proposed to use an exploratory design. In order to ensure validity as far as possible, the following steps were taken:

- A literature study was conducted to determine the current and most recent information and research results regarding the extent to which sequentially implanted adult users achieve bilateral processing benefits. Such information would give an indication of the dimensions of benefit to be pursued in the current investigation.

- Furthermore, recent literature regarding the definition of bilateral versus binaural processing abilities was studied and critically evaluated in order to adjust the terminology employed in this study, so that the tests to be conducted would be an accurate reflection of the most recent definitions of these abilities.
- The pilot study added to the validity of the bilateral processing benefit measurements as it ensured the researcher's acquaintance with interpreting the results of these measurements accurately. As a result, the procedure for testing speech perception in noise was discussed with international researchers in the field of bilateral cochlear implantation. It was recommended that an adaptive procedure (Galvin et al., 2010:372; Van Deun et al., 2010:702-713), rather than a fixed SNR, be used to determine the SNR at which the participant's speech reception threshold (SRT) was reached, i.e., the level where the participant achieved at least 50% performance.

Furthermore, to ascertain internal and external validity of the proposed study, the following strategies were followed for internal and external validity, respectively:

- **Internal validity**
  Before conduction of the test battery, it was ensured that each participant's cochlear implants had been mapped and balanced to ensure optimal functioning for the testing procedures. The same measurements to determine the bilateral processing benefits were conducted with each participant by the same audiologist, the sole researcher. All participants received the same information regarding the purpose of the study and their role during the study as well as identical instructions during the measurements. A fixed head position during measures of sound localisation was ensured by means of a headrest in order to prevent any reflexive head rotation during localisation tests. Furthermore, during the tests, participants used the programme on their processors which they use for general listening in order to obtain a reflection of their everyday functioning.

- **External validity:** *Representative sample:* As the PCIP only has a small population of sequentially bilateral implanted adults, the purposive convenient sampling method and selection criteria were vigorously implemented to select a representative sample of sequentially implanted adult clients of the PCIP (Leedy & Ormrod, 2005:100).

3.8 CONCLUSION

As a developing country, the South African context poses funding, costs, and socio-economical factors as the main limitations for cochlear implantation, especially bilateral implantation in the adult population. Although the benefits of bilateral implantation are clearly stated in international literature, a need for scientific data particular to the South African context is important, especially as bilateral cochlear implantation in South Africa is steadily increasing. An investigation into the extent to which adults with sequential cochlear implants can attain bilateral processing benefits in bilateral hearing tasks of sound localisation and speech perception in noise, will aim to present professionals of cochlear implant teams with context-based literature/research findings to counsel users in terms of reasonable expectations. Additionally, cochlear implant team members may be empowered to make more scientifically grounded clinical pre- and postoperative informed decisions in future. The research was planned in such a way as to ensure reliable and valid methodology, results, and clinical applications.

3.9 SUMMARY

This chapter described the methodology of this research study. The main aim and sub-aims were stated, followed by the research design utilised. Primarily, a quantitative research approach was embraced. In the context of applied research, explorative, comparative research techniques were utilised in a one group post-test-only exploratory research design and included the use of test battery measurements. A description of the participant selection criteria, material and apparatus used for participant selection and participant description as well as apparatus and material for data collection, recording and analysis procedures followed. Subsequently, results of the pilot study as well as factors pertaining to the reliability and validity of this study were stated.

4. RESULTS

***"The problems of deafness are deeper and more complex…
Deafness… means the loss of the most vital stimulus –
the sound of voice that brings language, sets thoughts astir
and keeps us in the intellectual company of man."
(Helen Keller, 1905)***

AIM OF THE CHAPTER

Chapter four presents all the collected and processed data as research results and findings. The results are presented according to the different sub-aims.

4.1 INTRODUCTION

According to Wilson and Dorman (2008:11), one of the major remaining problems with cochlear implants is a great variation in outcomes of performance. That is, patients using identical implant systems, thus the same speech processor, transcutaneous link, implanted receiver/stimulator and implanted electrode array, can have outcomes ranging from floor to ceiling level. This is especially characteristic of the unilateral cochlear implant population. However, the overall variability in outcomes is reduced with the use of bilateral cochlear implants, although still far from eliminated (Wilson & Dorman, 2008:12).

4.2 RESULTS

The results of this study are presented in accordance with research sub-aims set out in Section 3.1.

4.2.1 THE SUPERIOR COCHLEAR IMPLANT (CI 1 versus CI 2)

The first sub-aim of the study was to determine the superior functioning cochlear implant in the participant group of adults with sequential implants. This was done in order to compare the superior implant's performance to the performance of both implants'(BiCI) in tests of sound localisation and speech perception in noise (with speech and noise spatially separated and coincident) so that the extent of the bilateral advantage could be determined (Galvin et al., 2010:372). If a particular cochlear implant is considered to be the superior functioning implant, it may be due to the fact that it is the ear with better residual hearing[3] and/or to improved technology used in that specific implant (Litovsky, Cochlear Corporation, 2008b; Van Wieringen, 2010). The results represent a comparison between the first cochlear implant (CI 1) and the second cochlear implant (CI 2) during a sound localisation test, speech perception in noise test where speech and noise were spatially separated (with noise directed to CI 1 and then to CI 2) as well as the test for speech perception where speech and noise were spatially coincident. Figure 4.1 shows the distribution for the superior performing implant during the sound localisation test.

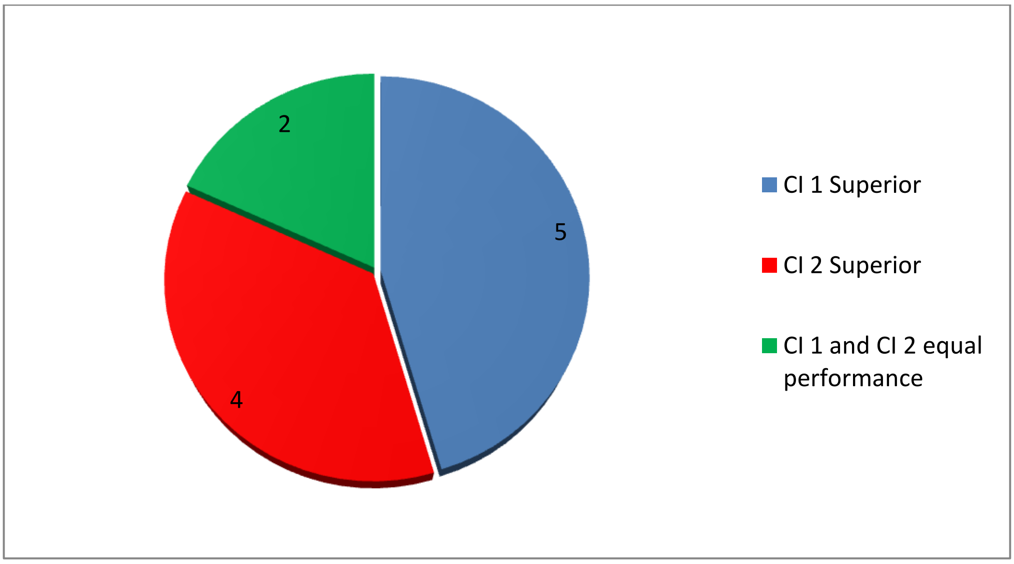

Figure 4.1: The superior performing implant for sound localisation (CI 1: first implant; CI 2: second implant) (n=11)

As displayed in Figure 4.1, superior performance in the unilateral conditions was found to be similar for the first and second implant. A slightly greater number of participants (n=5/11) demonstrated better performance with the first cochlear implant than the number (n=4/11) who demonstrated better performance with the second implant.

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[3] The more residual hearing in the ear implanted and stimulated effectively by the implant, the less auditory deprivation is present, consequently leading to better outcomes with the cochlear implant (Sharma et al., 2002:532-539).

Figure 4.2 displays the superior performing cochlear implant during speech perception in noise testing with spatially separated noise, with noise directed to CI 1 and with noise directed to CI 2 as well as for speech perception in spatially coincident speech and noise (NF). The superior performing implant represents the implant with which the participant could correctly perceive the speech material at the lowest SNR.

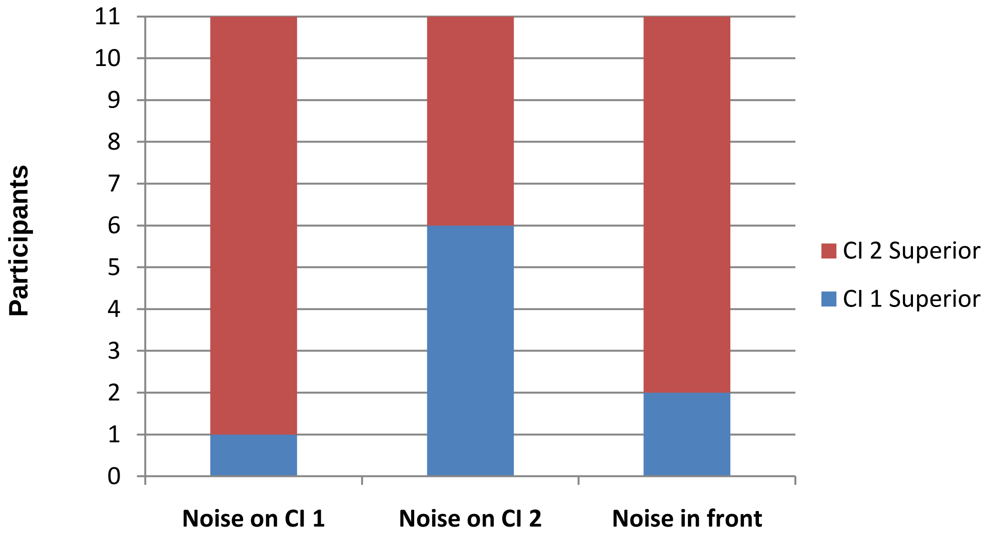

Figure 4.2: The superior performing cochlear implant during speech perception in noise testing, with speech and noise spatially separated (noise directed to CI 1 and to CI 2) as well as speech and noise spatially coincident (NF = noise from the front) (n=11)

From Figure 4.2 it is clear that for most participants (n=10/11) the second cochlear implant (CI 2) was the superior performing implant during speech perception in noise testing in spatially separated speech and noise conditions when noise was directed to CI 1. Furthermore, the majority of participants (n=9/11) performed significantly better with their CI 2 in the condition where speech and noise were coincident (both speech and noise presented from 0°).

4.2.2 SOUND LOCALISATION ABILITY IN THREE LISTENING CONDITIONS (CI 1 versus CI 2 versus BiCI)

The second sub-aim in order to determine the extent of bilateral benefit obtained for sound localisation in the horizontal plane, was to determine the sound localisation ability of a group of sequentially implanted users using CI 1, CI 2 and BiCI. .

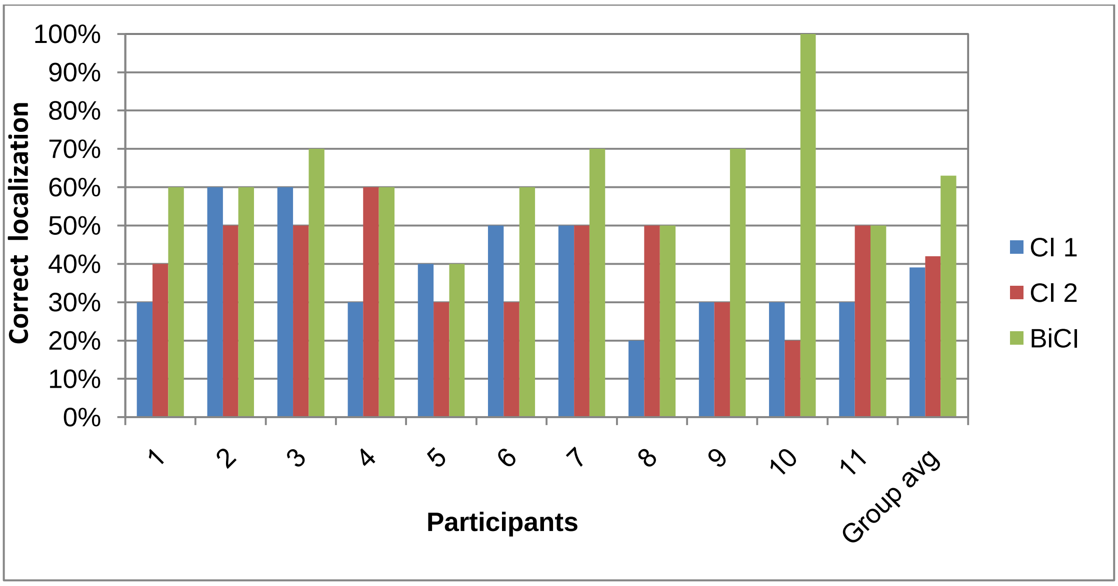

Figure 4.3: Sound localisation results for CI 1, CI 2 and BiCI in terms of percentage of correctly localised responses (n=11)

From Figure 4.3 it can be concluded that listening with both implants (BiCI) resulted in improved localisation results compared to the superior implant's results for six participants (n=11). Similar results were obtained for the superior implant and BiCI for five participants, where for two participants CI 1 was the superior implant (participants 2 and 5) and for three participants CI 2 was the superior implant (participants 4, 8 and 11). Only one participant (number 10) was able to achieve 100% accuracy in localisation results using both implants. On average, participants achieved 39%, 42% and 63% accuracy for sound localisation whilst listening with CI 1, CI 2 and BiCI respectively.

Furthermore, from the results set out in Appendix L it is clear that most participants favoured the loudspeaker that was ipsilateral to their implant that was switched on in the unilateral test conditions.

From Figure 4.3 it is clear that five participants (2, 4, 5, 8 and 11) did not show a bilateral benefit, that is, they achieved similar results for sound localisation when they used their superior implant alone and when they used both implants switched on together.

Inferential statistical analyses were performed by applying the Mann-Whitney test. This test is a distribution-free test and was selected due to the small sample size (Steyn et al., 2003:583). The Mann-Whitney test tested the null hypothesis, namely that there is no difference in the sound localisation ability when listening with the superior performing cochlear implant or with both implants simultaneously, against the alternative hypothesis that when participants listen with both implants they are better able to localise sound. The Mann-Whitney test statistic is 24 and the associated p-value for this one-sided test is equal to 0.006, that is, less than 0.05, the level of significance. The alternative hypothesis is accepted, therefore, as there is overwhelming evidence to infer that the null hypothesis can be rejected. Figure 4.4 summarises the inferential statistical analyses in the form of box plots to compare the first and second implant as well as the best performing cochlear implant versus the bilateral implant usage.

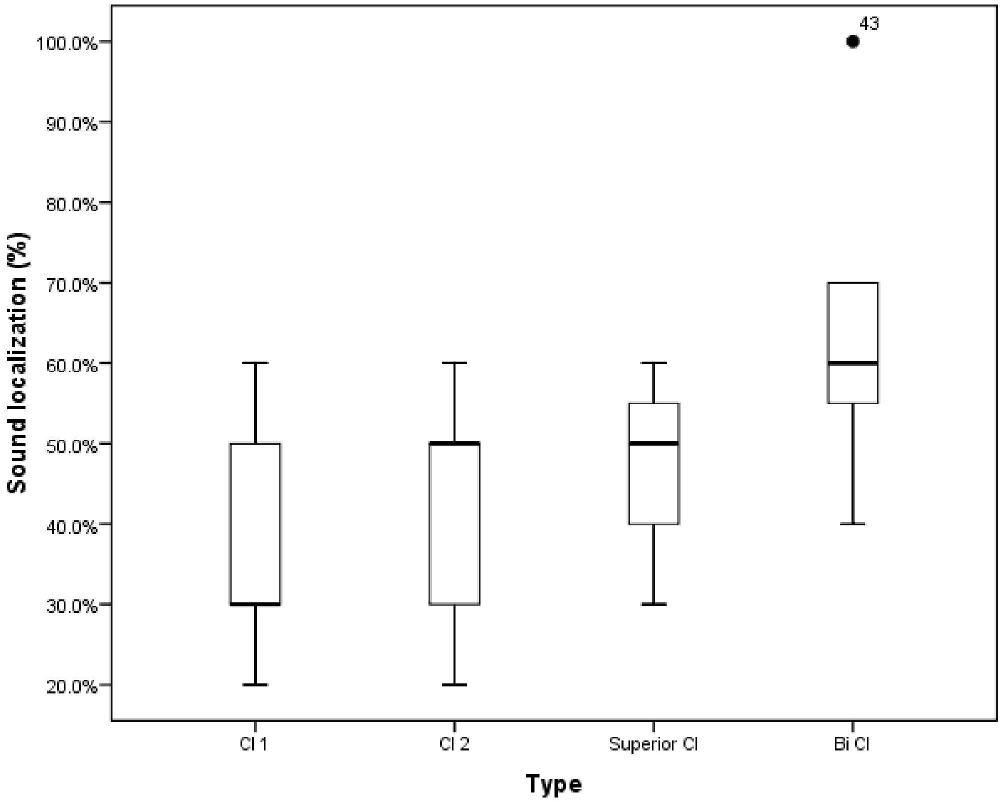

Figure 4.4: Sound localisation abilities with the first implant, second implant and superior performing implant versus listening with both implants (n=11)
Box plots represent the median (thick horizontal line), lower and upper quartiles (ends of boxes), minimum and maximum values (ends of whiskers) and extreme values (dark circle)

From Figure 4.4 it can be deduced that the mean values for the better performing implant and BiCI are 47.27% and 62.73% respectively. The observation point numbered as 43 corresponds with the results for participant 10 in Figure 4.3, indicating 100% localisation abilities in the horizontal plane when listening with both implants.

Table 4.1 presents the summarised descriptive inferential statistical values for the sound localisation performance with the best performing implant versus both implants as displayed in Figure 4.4.

Table 4.1: Descriptive inferential statistical values for sound localisation in the horizontal plane

	Sound localisation	
Descriptive	**Best performing CI**	**Bilateral CI**
Mean	47.27%	62.73%
Median	50%	60%
Standard deviation	11.04%	15.55%
Minimum	30%	40%
Maximum	60%	100%
Range	30%	60%

Inferential statistical analyses were performed on each of the best performing cochlear implants as well as on each of the BiCI sound localisation values (in percentage). The aim was to statistically verify if the BiCI values were better (greater percentage correctly localised) on a five percent level of significance. Differences between the superior performing CI and BiCI measurements were considered. As obtained from Figure 4.4 together with the statistic values presented in Table 4.1, it is noticeable that the results of the descriptive statistics (as displayed and discussed in Figure 4.3) and the results of the inferential statistics correspond with the findings for the greater population of sequentially implanted adults. Results indicate that a significant bilateral benefit was obtained for sound localisation in the horizontal plane for sequentially implanted adults.

4.2.3 SPEECH PERCEPTION ABILITY IN DICHOTIC LISTENING CONDITIONS

The third sub-aim of this study was to determine the ability to perceive speech in spatially separated speech and noise (with noise presented from the right and noise presented from the left) in a group of adults with sequential implants. Results for this sub-aim were obtained by first evaluating perception in terms of noise ipsilateral to CI 1 and noise ipsilateral to CI 2. Consequently, the superior performing implant's speech reception (SR) value in dB SNR (as determined in the first sub-aim) was compared to that of when participant used both implants in order to ultimately determine the extent of bilateral benefit achieved. Figure 4.5 and Figure 4.6 illustrate the SR value (in dB) of each participant for the three listening conditions (CI 1, CI 2 and BiCI) for the noise conditions with noise directed to CI 1 and to CI 2 respectively.

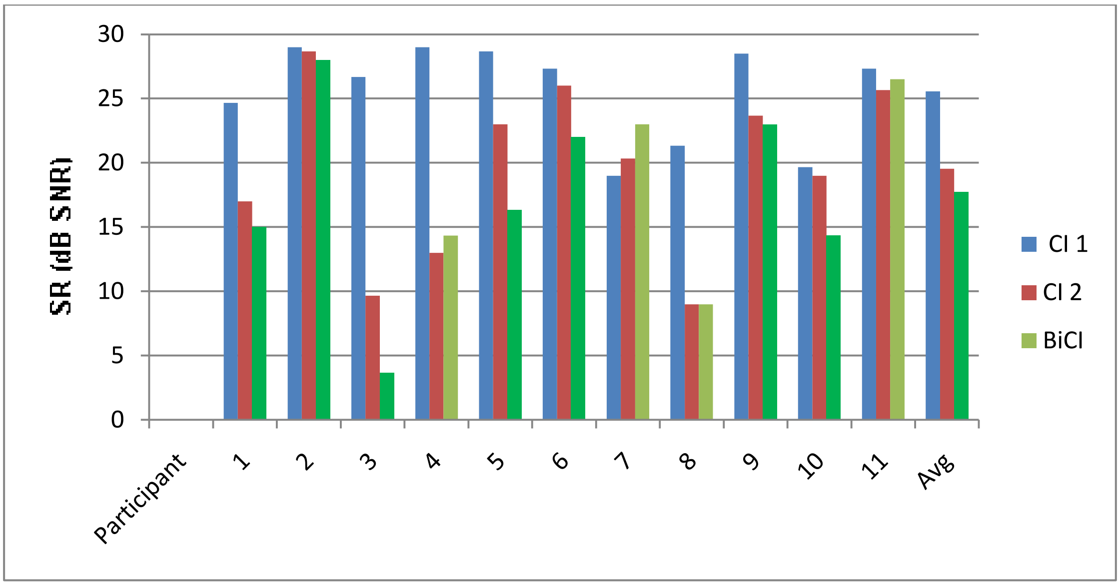

Figure 4.5: Speech reception (SR) in dB SNR with noise directed to CI 1 (n=11) (C1 – first implant; C2 – second implant; BiCI – bilateral implant condition)
The lower the SNR value, the better the speech reception ability. Dark green bars indicate a bilateral benefit.

As presented in the graph in Figure 4.5, it is clear that CI 2 was found to be the superior performing implant during the test of speech perception in noise with the noise directed to CI 1 for 10 participants (n=11), thus the implant contralateral to the noise source (which was directed to CI 1). Seven participants were able to attain a bilateral benefit. That is, when listening with both their implants (BiCI), seven participants (n=7/11) achieved speech reception material correctly at a lower SNR level (in dB) compared to the SNR value of the superior implant.

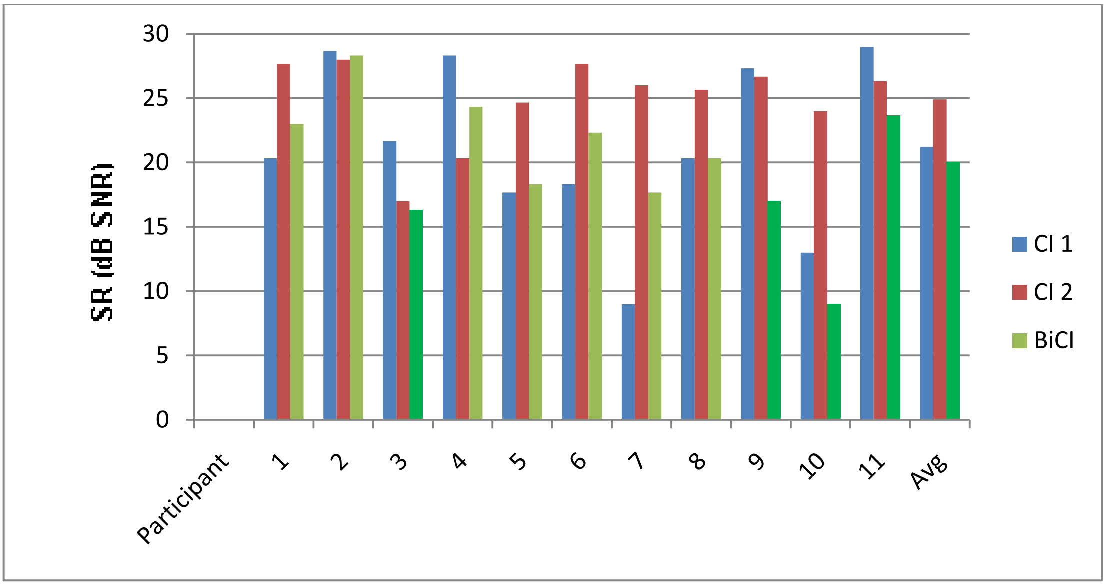

Figure 4.6: Speech reception (SR) in dB SNR with noise directed to CI 2 (n=11) (C1 – first implant; C2 – second implant; BiCI – bilateral implant condition)
The lower the SNR value, the better the speech reception ability. Dark green bars indicate a bilateral benefit.

As displayed in Figure 4.6, CI 1 was found to be the superior performing implant during the test of speech perception in noise with the noise directed to CI 2 for six participants (n=11), thus the implant contralateral to the noise source (which was directed to CI 2). Only four participants (n=11) were able to achieve a bilateral benefit.

Table 4.2 summarises the SNR values for speech perception in noise (SPIN) abilities when listening with CI 1, CI 2 and in the bilateral condition when noise was ipsilateral to CI 1 and ipsilateral to CI 2.

Table 4.2: SNR values for CI 1, CI 2, superior implant and bilateral implant condition in spatially separated speech and noise (n=11)

Partici-pant	SPIN Noise on CI 1				SPIN Noise on CI 2			
	CI 1	**CI 2**	**Superior CI**	**BiCI**	**CI 1**	**CI 2**	**Superior CI**	**BiCI**
1	24.67 dB	17 dB	CI 2 17dB	15 dB	20.33 dB	27.6 dB	CI 1 20.33 dB	23 dB
2	29 dB	28.67 dB	CI 2 28.67 dB	28 dB	28.67 dB	28 dB	CI 2 28 dB	28.33 dB
3	26.67 dB	9.67 dB	CI 2 9.67dB	3.67 dB	21.67 dB	17 dB	CI 2 17 dB	16.33 dB
4	29 dB	13 dB	CI 2 13 dB	14.33 dB	28.33 dB	20.33 dB	CI 2 20.33 dB	24.33 dB
5	28.67 dB	23 dB	CI 2 23 dB	14.33 dB	17.67 dB	24.67 dB	CI 1 17.67 dB	18.33 dB
6	27.33 dB	26 dB	CI 2 26 dB	22 dB	18.33 dB	27.67 dB	CI 1 18.33 dB	22.33 dB
7	19 dB	20.33 dB	CI 1 19 dB	23 dB	9 dB	26 dB	CI 1 9 dB	17.67 dB
8	21.33 dB	9 dB	CI 2 9 dB	9 dB	20.33 dB	25.67 dB	CI 1 20.33 dB	20.33 dB
9	28.5 dB	23.67 dB	CI 2 23.67 dB	23 dB	27.33 dB	26.67 dB	CI 2 26.67 dB	17 dB
10	19.67 dB	19 dB	CI 2 19 dB	14.33 dB	13 dB	24 dB	CI 1 13 dB	9 dB
11	27.33 dB	25.67 dB	CI 2 25.67 dB	26.5 dB	29 dB	26.33 dB	CI 2 26.33 dB	23.67 dB
Ave-rage	**25.56 dB**	**19.55 dB**	**19.43 dB**	**17.74 dB**	**21.24 dB**	**24.91 dB**	**19.73 dB**	**20.03 dB**

The results of this study in terms of superior performance between the first and second implant, for the conditions with noise directed to CI 1 and to CI 2 are also displayed in Figures 4.5 and 4.6, respectively, as well as in Table 4.2. With noise directed to CI 1, CI 2 proved to be the superior implant for 91% of participants (n=10/11). With noise directed to CI 2, CI 1 was the superior implant for 55% (n=6/11) of participants.

From Figures 4.5 and 4.6 it is clear that in unilateral listening conditions (listening with only CI 1 or only CI 2), a performance advantage for the ear opposite the noise source (thus with a superior signal-to-noise ratio) compared with that for the ear ipsilateral to the noise source (thus, with an inferior SNR) is demonstrated for 91% (n=10/11) and 55% (n=6/11) of participants, with noise directed to CI 1 and with noise directed to CI 2, respectively.

It is clear from Figure 4.5 and Table 4.2 (noise on CI 1) that participants' SNR values (in dB) had a large range, varying from 9 to 28.67 dB and from 3.67 to 28 dB for the superior implant and both implants, respectively. The large SNR range holds true with noise on CI 2 condition, varying from 9 to 28 dB for the superior implant and from 17 to 28.33 dB for listening with BiCI (see Figure 4.6 and Table 4.2). With noise directed to CI 1 and to CI 2, 64% (n=7/11) and 36% (n=4/11) of participants, respectively, demonstrated bilateral benefit during speech perception in spatially separated speech and noise (see Figures 4.5 and 4.6 as well as Table 4.2). That is, the CID sentences could be perceived at a lower SNR value (in dB) in comparison to the SNR value (in dB) of the superior performing implant. However, in contrast, with noise on CI 2, seven participants (n=11) did not show a bilateral benefit, but achieved a better SNR with their superior implant (Figure 4.6 and Table 4.2). For four of these seven participants (Participants 1, 5, 6 and 7) their first implant proved to remain superior in comparison to their performance with bilateral implant usage. An average SNR value of 19.43 dB and 17.74 dB were achieved for the best performing cochlear implant and the bilateral listening condition, respectively, with noise on CI 1. An average SNR of 19.73 dB and 20.03 dB were achieved for the best performing cochlear implant and the bilateral listening condition, correspondingly with noise on CI 2. Thus, a bilateral benefit was only present in the majority of the sample when noise was directed to CI 1 and indicated an improvement of 1.69 dB.

Inferential statistical analyses were performed by applying the Mann-Whitney U-test. The Mann-Whitney U-test tested the null hypothesis, namely that there is no difference between speech perception in noise ability when listening with the superior performing cochlear implant or with both implants simultaneously in spatially separated speech and noise, against the alternative hypothesis that when participants listen with both implants they are better able to perceive speech in the presence of noise in spatially separated speech and noise conditions. Results indicated that there was no statistically significant bilateral benefit for speech perception in spatially separated speech and noise conditions ($p = 0.562$ for noise on CI 1 and $p = 0.898$ for noise on CI 2). Figures 4.7 and 4.8 summarise the findings of these inferential statistical analyses conducted.

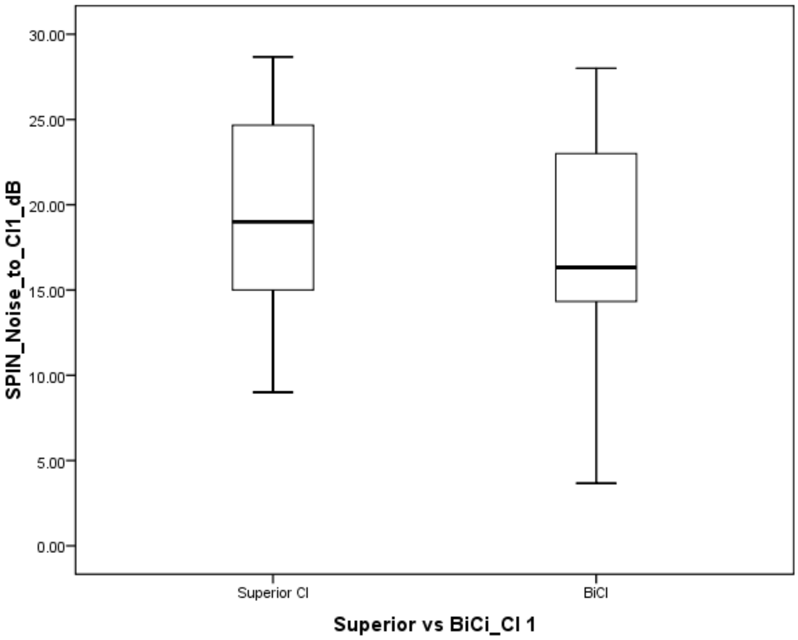

Figure 4.7: Speech perception in noise (spatially separated speech and noise) directed to CI 1 for the best performing implant compared to the bilateral CI condition in dB SNR (n=11)
Box plots represent the median (thick horizontal line), lower and upper quartiles (ends of boxes), minimum and maximum values (ends of whiskers)

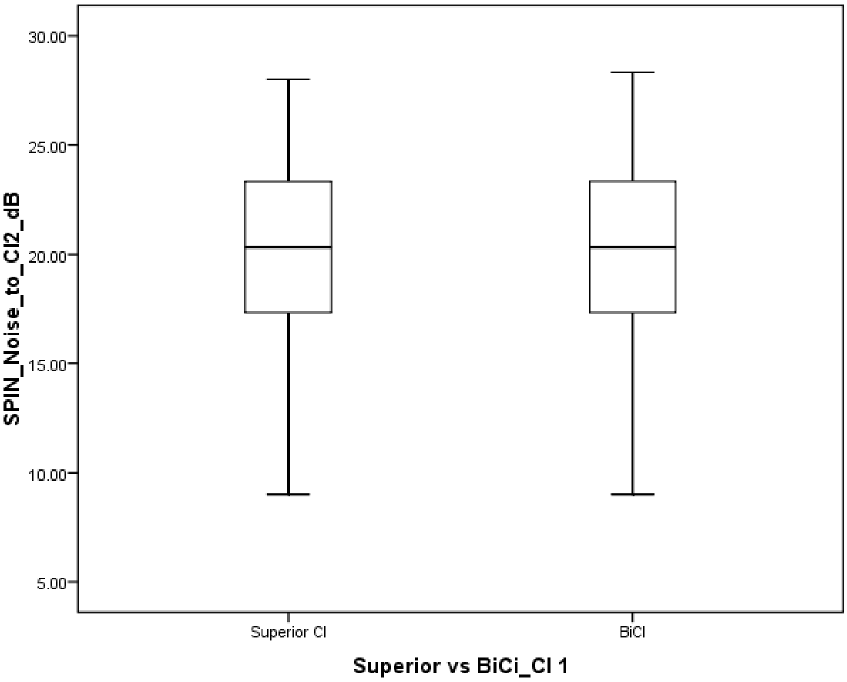

Figure 4.8: Speech perception in noise (spatially separated speech and noise) directed to CI 2 for the best performing implant compared to the bilateral CI condition in dB SNR (n=11)
Box plots represent the median (thick horizontal line), lower and upper quartiles (ends of boxes), minimum and maximum values (ends of whiskers)

From Figures 4.7 and 4.8 it is clear that with noise ipsilateral to CI 1, listening with BiCI may have had a bilateral benefit for this study's sample, although it was not statistically significant across the sample.

Table 4.3 summarises the speech perception in noise (spatially separated speech and noise) values across the sample as displayed in Figures 4.7 and 4.8.

Table 4.3: Descriptive statistical values for speech perception in noise in spatially separated speech and noise (Noise on CI 1 and noise on CI 2)

	Noise on CI 1		Noise on CI 2	
Descriptive	**Best performing CI**	**Bilateral CI**	**Best performing CI**	**Bilateral CI**
Mean	19.43 dB	17.74 dB	19.73 dB	20.03 dB
Median	19 dB	16.33 dB	20.33 dB	20.33 dB
Standard deviation	6.71 dB	7.50 dB	5.79 dB	5.18 dB
Minimum	9 dB	3.67 dB	9 dB	9 dB
Maximum	28.67 dB	28 dB	28 dB	28.33 dB
Range	19.67 dB	24.33 dB	19 dB	19.33 dB

Thus, inferential statistical analyses were performed on each of the best performing cochlear implants as well as on each of the bilateral SNR (in dB) values. The aim was to statistically verify if the bilateral SNR values were achieved at a better value (that is a lower SNR value) on a five percent level of significance. Differences between the superior performing CI and BiCI measurements were considered. Results of the descriptive and the inferential statistics correspond and indicate no significant bilateral benefit obtained for speech perception in noise for sequentially implanted adults in dichotic listening conditions. However, in terms of this study's participant sample, a bilateral benefit was observed in the listening condition with noise directed to CI 1 for 64% of the participants (n=7/11) with an average benefit of 1.69 dB.

4.2.4 SPEECH PERCEPTION ABILITY IN A DIOTIC LISTENING CONDITION

The fourth sub-aim of this study was to determine the speech perception ability of sequentially implanted users in spatially coincident speech and noise. Results were obtained by comparing the superior performing implant's speech reception (SR) in dB SNR (as determined in the first sub-aim) to that of both implants in order to finally determine the extent of bilateral benefit achieved. Figure 4.9 demonstrates the SR value (in dB) of each participant for the three listening conditions (CI 1, CI 2 and BiCI) with both speech and noise directed from the front (NF).

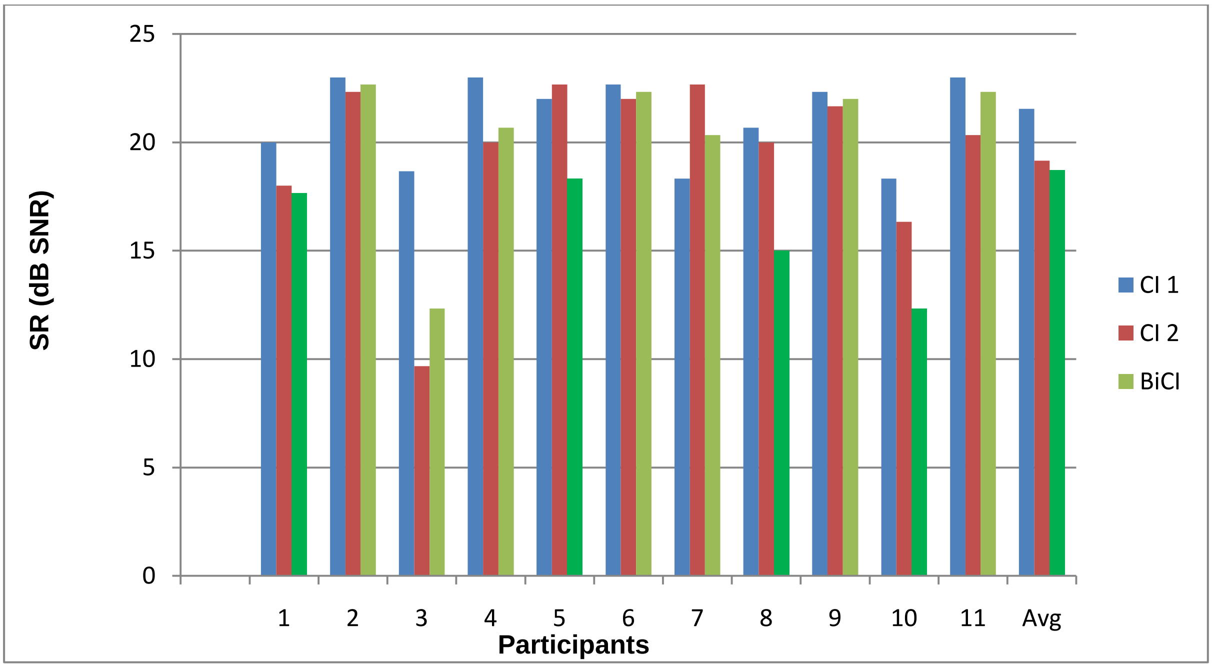

Figure 4.9: Speech reception (SR) in dB SNR with noise directed from the front (NF) (n=11) (C1 – first implant; C2 – second implant; BiCI – bilateral implant condition)
The lower the SNR value, the better the speech reception ability. Dark green bars indicate a bilateral benefit.

It is clear from Figure 4.9 that CI 2 was the superior performing implant for speech perception in noise with speech and noise being coincident for the majority of participants (n=9/11). Only four participants (n=4/11) achieved a bilateral processing benefit, that is, when listening with both their implants, they achieved speech reception at a lower SNR level (in dB).

Table 4.4 summarises the SNR values for speech perception in noise (SPIN) abilities when listening with CI 1, CI 2 and in the bilateral condition when speech and noise were simultaneously presented from the front.

Table 4.4: SNR values for CI 1, CI 2, superior implant and bilateral implant condition in spatially coincident speech and noise (n=11)

Participant	**SPIN: Speech and noise from the front**			
	CI 1	CI 2	Superior CI	BiCI
1	20 dB	18 dB	CI 2 = 18 dB	17.67 dB
2	23 dB	22.33 dB	CI 2 = 22.33 dB	22.67 dB
3	18.67 dB	9.67 dB	CI 2 = 9.67dB	12.33 dB
4	23 dB	20 dB	CI 2 = 20 dB	20.67 dB
5	22 dB	22.67 dB	CI 1 = 22 dB	18.33 dB
6	22.67 dB	22 dB	CI 2 = 22 dB	22.33 dB
7	18.33 dB	22.67 dB	CI 1 = 18.33 dB	20.33 dB
8	20.67 dB	20 dB	CI 2 = 20 dB	15 dB
9	22.33 dB	21.67 dB	CI 2 = 21.67 dB	22 dB
10	18.33 dB	16.33 dB	CI 2 = 16.33 dB	12.33 dB
11	23 dB	20.33 dB	CI 2 = 20.33 dB	22.33 dB
Average	**21.06 dB**	**19.61 dB**	**19.15 dB**	**18.37 dB**

As displayed in Figure 4.9 and Table 4.4, 36% of participants (n=4/11) (1, 5, 8 and 10) achieved bilateral benefit, that is, better speech understanding in the BiCI listening condition compared to that achieved with their superior implant. Also noteworthy is the large deviation in range of bilateral benefit in terms of SNR in dB HL, ranging from 15 to 22.67 dB. An average SNR of 19.15 dB and 18.73 dB were achieved for the best performing cochlear implant and the bilateral listening condition. Thus, using both implants, led to an average improvement of 0.78dB compared to using the superior unilateral implant alone.

Thus, only 36% participants (n=4/11) achieved bilateral benefit for speech perception when both speech and noise were directed from the front compared to 64% (n=7/11) and 36% (n=4/11) of participants who did attain bilateral benefit in spatially separated speech and noise, with noise directed to the right or left ear, respectively.

Furthermore, the Mann-Whitney U-test was performed during inferential statistical analyses. The Mann-Whitney U-test tested the null hypothesis, namely that there is no difference in the speech perception in noise ability when listening with the superior performing cochlear implant or with both implants simultaneously in spatially coincident speech and noise, against the alternative hypothesis that when participants listen with both implants they are better able to perceive speech in the presence of noise in spatially coincident speech and noise conditions. Results indicated that there was no statistically significant bilateral benefit for speech perception in spatially coincident speech and noise conditions (p = 0.442). Figure 4.10 summarises the findings of the inferential statistical analyses conducted.

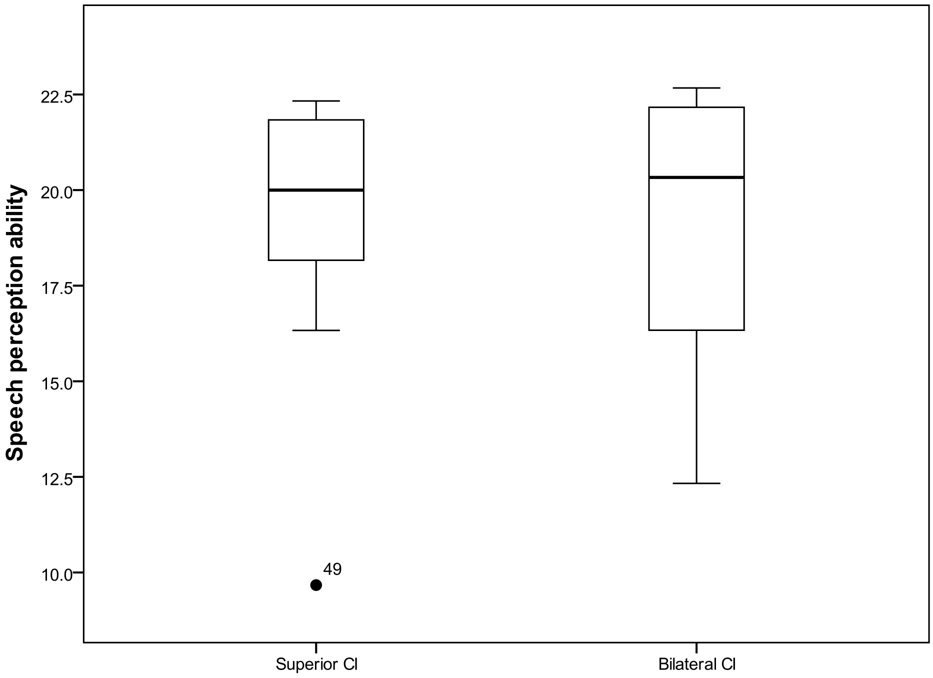

Figure 4.10: Speech perception in noise (spatially coincident speech and noise) for the best performing implant compared to the bilateral CI condition in dB SNR (n=11) ***Box plots represent the median (thick horizontal line), lower and upper quartiles (ends of boxes), minimum and maximum values (ends of whiskers) and extreme values (dark circle)***

The observation point 49 in Figure 4.10 emphasises the significant better performance of participant 3 with his best performing implant, which was notably better than the rest of the participants as the result was greatly lower than the participant sample's range with a value of 9.67. This is parallel with the descriptive findings in Figure 4.9.

Table 4.5 presents the summarised descriptive inferential statistical values for the speech perception in noise ability in spatially coincident speech and noise as displayed in Figure 4.1

Table 4.5: Descriptive statistical values for speech perception in noise in spatially coincident speech and noise (NF: noise directed from the front)

	NF	
Descriptive	**Best performing CI**	**Bilateral CI**
Mean	19.15 dB	18.73 dB
Median	20 dB	20.33 dB
Standard deviation	3.68 dB	3.94 dB
Minimum	10 dB	12 dB
Maximum	22 dB	23 dB
Range	13 dB	10 dB

Inferential statistical analyses were performed on each of the best performing cochlear implants as well as on each of the bilateral SNR (in dB) values. The aim was to statistically verify if the bilateral SNR values were achieved at a lower SNR value on a five percent level of significance. Differences between the superior performing CI and BiCI measurements were considered. As derived from Figure 4.10 as well as from the statistical values presented in Table 4.5, it is apparent that the results of the descriptive statistics (as displayed and discussed in Figure 4.9) and the inferential statistics correspond in terms of the findings for the greater population of sequentially implanted adults, namely that no significant bilateral benefit was obtained for speech perception in noise ability for sequentially implanted adults in diotic listening conditions. Nevertheless, for this study’s participant sample, a bilateral benefit was observed in the diotic listening condition for 36% of the participants (n=4/11) with an average benefit of 0.78 dB.

4.2.5 BILATERAL SPATIAL BENEFITS

The last sub-aim of this study was to determine bilateral spatial benefits, namely head shadow effect, summation, squelch, and spatial release of masking (SRM). This was done as bilateral spatial benefits are measures that further quantify the bilateral benefit and include the latter effects (Eapen et al., 2009:153; Van Deun et al., 2010:702-713). These benefits are not measured directly, but were calculated for each participant on a number of conditions by subtracting speech reception values in dB obtained in bilateral listening conditions from unilateral speech reception values in dB under selected conditions (Litovsky et al., 2009:424; Van Deun et al., 2010:705-706). Appendix M describes the calculations and consequent values obtained for each of the bilateral spatial benefits. In addition, inferential statistical analyses were performed by means of the Wilcoxon rank sum test (Miller & Miller, 2004:529-531).

Head shadow effect

The head shadow effect arises in the bilateral listening condition when the ear with the more favourable SNR is added in the bilateral listening condition (Litovsky et al., 2009:420). Thus, the head shadow effect is evident in spatially separated speech and noise conditions. This effect was measured with a 90° as well as a 180° change in the noise position. A benefit of 3dB or more advantage was taken as the accepted comparative value based on numerous findings of existing studies (Laszig et al., 2004:958-968; Litovsky et al., 2009:420; Litovsky et al., 2006b:714-731; Van Deun et al., 2010:702-713). Tables 4.6 and 4.7 present the results for the head shadow effect measured at a 90° and 180° shift in the noise position for CI 1 and CI 2 respectively. At 90° head shadow benefit of 3 dB of more was evident in 36% of participants (n=4/11) for CI 1 and 18% of participants (n=2/11) for CI 2. At 180° head shadow benefit of 3 dB or more was evident in 55% of participants (n=6/11) for CI 1 and 64% of participants (n=7/11) for CI 2 (see Table 4.7 below).

Table 4.6: Head shadow effect at 90° for CI 1 and CI 2 (green = benefit of 3 dB or more)

Participant	Effect for CI 1	Effect for CI 2
1	0 dB	1 dB
2	-6 dB	-6 dB
3	-3 dB	0 dB
4	-5 dB	**7 dB**
5	**4 dB**	0 dB
6	**4 dB**	-4 dB
7	**9 dB**	2 dB
8	0 dB	**11 dB**
9	-5 dB	-2 dB
10	**5 dB**	-3 dB
11	-6 dB	-5 dB
Median	**0 dB**	**0 dB**

Table 4.7: Head shadow effect at 180° for CI 1 and CI 2 (green = benefit of 3 dB or more)

Participant	Effect for CI 1	Effect for CI 2
1	**4 dB**	**11 dB**
2	1 dB	-1 dB
3	**5 dB**	**7 dB**
4	1 dB	**7 dB**
5	**11 dB**	2 dB
6	**9 dB**	2 dB
7	**10 dB**	**6 dB**
8	1 dB	**17 dB**
9	1 dB	**3 dB**
10	**7 dB**	**5 dB**
11	-2 dB	1 dB
Median	**4 dB**	**5 dB**

From Table 4.7 it is clear that only Participants 1, 7 and 10 were able to achieve positive head shadow effects of 3 dB or more for both CI 1 and CI 2 at 180°.

Inferential statistical analyses were performed to statistically verify if the median head shadow benefit values obtained fell within the value of 3 dB or more as stated by several previous reports (Laszig et al., 2004:958-968; Litovsky et al., 2009:420; Litovsky et al., 2006b:714-731; Van Deun et al., 2010:702-713). For the head shadow effect 90° the difference in the SRT value (in dB) obtained with the left/right ear in the noise front (NF) versus noise right (NR)/noise left (NL) condition were considered. For the effect at 180° the difference in the SRT value (in dB) obtained with the left/right ear in the NL/NR versus NR/NL condition were considered (see Appendix M). The median head shadow effect at 90°was found not to correspond statistically significantly with the ideal value range for the population. However, the median head shadow effect at 180° for both CI 1 and CI 2 fell significantly within the stated accepted range of 3 dB or more on a 5% level of significance.

For head shadow effect at 90°, Participants 3 and 4 recorded a negative head shadow effect for CI 1 compared to CI 2. Participants 6 and 10 obtained a negative head shadow effect for CI 2 compared to CI 1. In the head shadow effect at 180°, participant 11 achieved a negative effect for CI 1 compared to CI 2 and participant 2 recorded a negative effect for CI 2 compared to CI 1.

Squelch

The squelch effect can enhance speech perception in noise when listening with both implants as the ear with the poorer SNR is added (Litovsky et al., 2009:420). Results from previous studies suggest a benefit of up to 2dB and even zero or negative effects in bilaterally implanted adults (Laszig et al., 2004:958-968; Litovsky et al., 2006b:714-731; Tyler et al., 2002:80s-89S; Van Deun et al., 2010:702-713; Wolfe et al., 2007:589-296). Subsequently, a value range of negative to 2 dB was accepted for the squelch effect to be achieved in this study. Table 4.8 presents the squelch effect for CI 1 and CI 2. For the squelch effect, the accepted benefit of negative up to 2 dB was achieved by 55% of participants (n=6/11) and 64% of participants (n=7/11) for CI 1 and CI 2 respectively (see Table 4.8 below).

Table 4.8: Squelch effect for CI 1 and CI 2 (green = benefit value of negative up to 2 dB)

Participant	**Effect when noise is on CI 1**	**Effect when noise is on CI 2**
1	**-3 dB**	**2 dB**
2	**0 dB**	**-1 dB**
3	5 dB	6 dB
4	4 dB	**-1 dB**
5	**-1 dB**	7 dB
6	**-4 dB**	4 dB
7	**-9 dB**	**-3 dB**
8	**0 dB**	**0 dB**
9	10 dB	**1 dB**
10	4 dB	5 dB
11	5 dB	**-1 dB**
Median	**0 dB**	**1 dB**

To statistically verify if the median squelch benefit values fell within the accepted range of negative up to 2 dB as stated by several previous reports on adults with bilateral cochlear implants (Eapen et al., 2009:154; Laszig et al., 2004:958-968; Litovsky et al., 2006b:714-731; Tyler et al 2002:80S-89S; Van Deun et al., 2010:702-713; Wolfe et al., 2007:589-296), inferential statistical analyses were performed. The difference between the SRT values (in dB) for the left/right ear and both implants (BiCI) in the NR/NL condition was considered (see appendix M). For both CI 1 and CI 2 the median squelch effect was within the accepted values on a 5% level of significance.

When the noise was on CI 1 four participants obtained a negative squelch effect (Participants 1, 5, 6 and 7). This was also observed for four participants (2, 4, 7 and 11) when the noise was directed on CI 2. However, the range of negative values was greater when the noise was at the side of the CI 1 (ranging from -1 dB to -9 dB) and this implant was added in the bilateral condition.

Summation

Summation, also known as redundancy, can be obtained when speech and noise are spatially coincident and consequently result in improved bilateral speech intelligibility (Litovsky et al., 2009:420). Summation results of negative effects up to 6dB have been taken as acceptable summation benefit values as these values have been reported as typical for adult cochlear implant users in previous studies (Eapen et al., 2009:154; Litovsky et al., 2006b:714-731; Van Deun et al., 2010:702-713; Wolfe et al., 2007:589-596). Table 4.9 describes the summation benefit values when CI 1 and CI 2 are added in the BiCI listening condition in the NF condition. For summation, all participants (11/11) attained benefit values within the accepted value range of negative to 6 dB when CI 1 and CI 2 were added when listening with both implants in diotic conditions.

Table 4.9: Summation effect (green = benefit value of negative up to 6 dB)

Participant	Effect when CI 1 is added	Effect when CI 2 is added
1	**0 dB**	**2 dB**
2	**0 dB**	**0 dB**
3	**-3 dB**	**6 dB**
4	**0 dB**	**2 dB**
5	**4 dB**	**4 dB**
6	**0 dB**	**0 dB**
7	**2 dB**	**-2 dB**
8	**5 dB**	**6 dB**
9	**0 dB**	**0 dB**
10	**4 dB**	**6 dB**
11	**-2 dB**	**1 dB**
Median	**0 dB**	**2 dB**

Inferential statistics were performed to statistically verify if the difference between the median SRT values (in dB) of CI 1 and CI 2 and bilateral implants in the NF (see appendix M) condition were within the accepted value range of negative to 6 dB (Eapen et al., 2009:154; Litovsky et al., 2006b:714-731; Van Deun et al., 2010:702-713; Wolfe et al., 2007:589-596). It was concluded that the median summation benefits for both CI 1 and CI 2 added to BiCI in the NF condition were significantly within the accepted value range on a 5% level of significance.

Spatial release of masking (SRM)

SRM is the difference in the speech reception threshold (SRT), expressed in dB, between the bilateral listening condition (BiCI) in the noise front (NF) noise condition and the BiCI listening condition when noise is directed to the first implant (CI 1) or to the second implant (CI 2) (Van Deun et al., 2010:705-706). SRM values of 0 dB up to 4dB for bilaterally implanted adults are evident in existing studies (Litovsky et al., 2006b:714-73; Van Deun et al., 2010:702-713). Table 4.10 presents the SRM benefit values with noise directed to CI 1 and to CI 2. For SRM, the accepted benefit value range of 0-4 dB was attained by 27% (n=3/11) and 36% (n=4/11) of participants when noise was directed to CI 1 and CI 2 correspondingly.

Table 4.10: SRM effect (green = benefit value of 0-4dB)

Participant	**Effect when noise is directed to CI 1**	**Effect when noise is directed to CI 2**
1	**3 dB**	-5 dB
2	-5 dB	-6 dB
3	9 dB	-4 dB
4	6 dB	-4 dB
5	**2 dB**	**0 dB**
6	**0 dB**	**0 dB**
7	-3 dB	**3 dB**
8	6 dB	-5 dB
9	-1 dB	5 dB
10	-2 dB	**3 dB**
11	-4 dB	-1 dB
Median	**0 dB**	**-1 dB**

Inferential statistical analyses were performed to statistically verify if the median SRM benefit values obtained fell within the value of 0-4 dB or more as stated by previous studies (Litovsky et al., 2006b:714-73; Van Deun et al., 2010:702-713). The median SRM benefit values were significantly within in the accepted value range only when the noise was directed to CI 1 on a 5% level of significance. Additionally, from Table 4.10 an asymmetry between the values for noise directed to CI 1 versus CI 2 is observed, with greater values for shifting the noise to the first implant.

In support of the SRM spatial benefits, the improvement in speech perception in spatially distinct speech and noise from the addition of an ear with a better SNR was calculated. This was calculated as the difference between the SRT value for the left/right ear and the BiCI SRT value in the NL/NR condition (Van Deun et al., 2010:705-706) (see Appendix M). Table 4.11 displays these results.

Table 4.11: Bilateral spatial benefit values when the ear with the better SNR is added to CI 1 (thus the contribution of CI 2) and to CI 2 (thus the contribution of CI 1)

Participant	Better SNR added to CI 1	Better SNR added to CI 2
1	10 dB	5 dB
2	1 dB	0 dB
3	23 dB	1 dB
4	15 dB	-4 dB
5	12 dB	6 dB
6	5 dB	5 dB
7	-4 dB	8 dB
8	12 dB	5 dB
9	6 dB	10 dB
10	5 dB	15 dB
11	1 dB	3 dB
Average	**9 dB**	**5 dB**

From Table 4.11 it is clear that the average values for adding the SNR better ear to CI 1 (thus the contribution of CI 2) is greater than the average value when the SNR better ear is added to CI 2 (thus the contribution of CI 1). Therefore the contribution of CI 2 seems to be greater for bilateral spatial benefit.

4.3 CONCLUSION

The main aim of this research study was to determine the extent of bilateral processing benefit of sequentially implanted adult cochlear implant users. During the test of sound localisation, superior performance in unilateral conditions was found to be similar for the first and second implant, although slightly more participants (5/11) demonstrated better performance with the first cochlear implant. For most participants (10/11), the second implant was the superior performing implant during speech perception in noise testing in spatially separated speech and noise conditions when noise was directed to CI 1. Furthermore, all participants performed significantly better with their second implant in the condition where speech and noise were coincident. In terms of bilateral benefit, sequentially implanted adults obtained significant bilateral benefit only during horizontal sound localisation. In neither dichotic nor diotic conditions did sequentially implanted users achieve significant bilateral benefit. The median values for the head shadow effect 180°, squelch and summation for both CI 1 and CI 2 did correspond with the stated accepted benefit value ranges, in terms of bilateral spatial benefits. Yet for SRM, only the median value for noise directed to CI 1 corresponded to the accepted value range.

4.4 SUMMARY

This chapter provided a presentation of the results from the research study, which included tests of sound localisation in the horizontal plane, and speech perception in noise where speech and noise were spatially separated and coincident. Furthermore, findings regarding the superior performing cochlear implant as well as bilateral spatial benefits were presented. Results were organised according to the sub-aims and how they related to the main aim. The presented results established the platform for the discussion.

5. DISCUSSION

AIM OF THE CHAPTER

Chapter five presents a discussion and interpretation of all the collected and processed data as research results and findings according to the different sub-aims.

5.1 INTRODUCTION

Current evidence indicates that the variability in outcomes of cochlear implant users can probably be contributed to differences among patients in cortical or auditory pathway function (Lee et al., 2001:149-150; Sharma et al., 2002:532-539; Wilson & Dorman, 2008:12). Patients with a shortened duration of deafness prior to implantation fare better than those with an extended duration of deafness (Chan et al., 2008:307). This may be attributed to sensory deprivation for long periods, which adversely affects connections between and among neurons in the central auditory system and may allow cross-modal recruitment, that is, encroachment by other sensory inputs of cortical areas normally devoted to auditory processing (Lee et al., 2001:150). Numerous reports suggest that damage to the auditory pathways in the brainstem, or compromised function in the auditory processing cortical areas, or reduced cortical plasticity, or cross-modal plasticity, can produce highly deleterious effects on results obtained with cochlear implants (Lee et al., 2001:149-150; Sharma et al., 2002: 532-539;Wilson & Dorman, 2008:12).

In addition, different etiologies of hearing loss, duration of deafness and/or pre-implant auditory deprivation, ear asymmetries, the integrity and survival of neurons being stimulated, monolateral and bilateral listening experiences (MAP dynamic ranges and microphone types), as well as whether the implantation is simultaneous or sequential, are all variables known to affect performance results of bilateral implantees (Chan et al., 2008:307; Litovsky, Cochlear Corporation, 2008a). Due to the nature of the population of this study, the following variables are of special concern as they could have affected participants' performance results:

- ear asymmetries causing the one ear to offer clearly better hearing that the other (Litvosky et al., 2006b:714-731). Under these circumstances sequential users may subjectively perceive the ear first implanted as the dominant or superior ear and thus experience a limited bilateral processing benefit

- sequential cochlear implant users have had both monolateral and bilateral listening experiences as they first only have one implant and consequently monolateral listening experiences, followed by a second implant with a subsequent bilateral experience. Furthermore, the duration of the monolateral and bilateral listening experiences differs among participants due to differences in the inter-stage interval between implants. Although these intervals were not specified in the selection criteria in order to avoid further confining the limited purposive convenient participant sample, the effect of the inter-stage interval was analysed since delay between implantations could compromise the auditory pathways' binaural processing abilities (Papsin & Gordon, 2008:69).

Various factors are known to have an effect on cochlear implant users' bilateral performance results, as stated above. These factors will be examined and applied to the individual details of participants during the discussion of results to follow.

The results of this study are discussed in accordance with research sub-aims set out in Section 3.1.

5.2 THE SUPERIOR COCHLEAR IMPLANT (CI 1 versus CI 2)

In order to determine the extent of bilateral advantage, results of the *cochlear implant demonstrating the best performance* was compared to the results of *both implants* in tests of sound localisation and speech perception in noise (with speech and noise spatially separated and coincident). As mentioned before, the fact that a particular cochlear implant is considered as the superior functioning implant, may be related to the fact that it is the ear with better residual hearing and/or that improved technology was used in that specific implant (Litovsky, Cochlear Corporation, 2008b; Van Wieringen, 2010).

Participants' performance with the first and second cochlear implants (CI 1 and CI 2) was found to be similar during horizontal plane sound localisation (see Figure 4.1).

These results are comparable with those previously reported, which indicate similar performance between the first and second implants (Livotsky et al., 2004:648-655; Neuman et al., 2007:73-82 & Nopp et al., 2004:205-214). According to Galvin et al. (2008:645), however, the first implant may remain superior and this was evident for five participants in the current sample (5/11). Thus, superior performance during sound localisation was found to be very similar for CI 1 and CI 2.

From Figure 4.2 it is clear that for most participants (10/11) the second cochlear implant (CI 2) was the superior performing implant during speech perception in noise testing, where speech and noise were spatially distinct with the noise on CI 1. Furthermore, 82% of participants (9/11) performed significantly better with their CI 2 in the condition where speech and noise were coincident (both speech and noise presented from 0°). Thus, in the latter condition no effects such as the head shadow or better ear effect could have contributed to the results, as both ears received identical signals because there was no spatial separation of the signals. These results are in agreement with a previous report by Litovsky (Cochlear Corporation, 2008b), who stated that the second cochlear implant in the case of sequential implantation could be the superior functioning implant as it may have received improved and more refined technology compared to the first implant. In contrast, the majority of existing studies on bilaterally implanted users reported a performance advantage for the first implant compared to the second implant (Galvin et al., 2010:376; Manrique et al., 2007:224-231; Sharma et al., 2007:218-223; Van Deun et al., 2010:712-713). Manrique et al. (2007:228) attributed this phenomenon to long-term auditory deprivation in the second implanted ear. An alternative consideration is that sequential implantation in some international implant programmes is scheduled in such a way that the second implant is done shortly after the first implant (Litovsky et al., 2009:419; Van Deun et al., 2010:704-705). In the South African context sequential implantation is unique in terms of there generally being a long time delay between implantations (≥ 2 years for this study, see Table 3.5). Consequently, by the time the second implant is done, that ear might have received a great technology upgrade compared to the first implant. A technology upgrade in the second implanted ear may occasionally cause superior functioning or improvement compared to the first implanted ear (Van Wieringen, 2010). Nine of the 11 participants' second implant was a technology upgrade compared to the first implant in terms of the model of the Cochlear™ standard electrode array implanted (Participants 1, 2, 4, 5, and 7 to 11). Furthermore, it is clear that most participants (9/11) achieved speech reception at a lower dB SNR when only using their CI 2 opposed to only using their CI 1 in spatially coincident speech and noise (see Figure 4.9). For the nine participants whose CI 2 had newer generation technology compared to their CI 1, 89% (8/9) and 44% (4/9) of participants' CI 2 proved to be the superior implant for speech perception in noise, with noise directed to CI 1 and to CI 2, respectively (see Figures 4.5 and 4.6).

5.3 SOUND LOCALISATION ABILITY IN THREE LISTENING CONDITIONS (CI 1 versus CI 2 versus BiCI)

Sequentially implanted adults demonstrated a significant ($p < 0.05$) bilateral benefit in sound localisation abilities. Yet, only one participant (number 10) was able to achieve 100% accuracy in localisation results using both implants (see Figure 4.3). This may be attributed to the fact that this participant had a post-lingual onset of hearing loss at the age of 22 years after a motor vehicle accident (MVA). Hence, his central auditory system was intact during the critical sensitive periods for development (Sharma et al., 2002:532-539). He therefore had the opportunity to develop well-formed sound localisation prototypes which, according to Flamme (2002:10), are essential because bilateral cues of interaural time differences (ITD) and interaural level differences (ILD) used for horizontal plane sound localisation rely on the presence of such a stored prototype or template. Litovksy et al. (2009:428) echo this statement when pointing out that post-lingually deaf adults are likely to have been able to develop auditory spatial maps, which may facilitate their ability to localise sounds when, after deafness, their hearing is activated with bilateral cochlear implants. Furthermore, the interval between Participant 10's two implants can be considered favourable as it is less than five years (Manrique et al., 2007:230-231; Sharma et al., 2002:532-539), affording him an enhanced bilateral experience. In addition, he had an acquired loss, which, according to Dowell (2005:10-11), is a predictive factor, favouring better performance than that of implant users with a pre-lingual or congenital hearing loss.

The average result for localisation ability with both implants, namely 63%, is close to previous findings for normal hearing adults, namely 70% sound localisation accuracy (Chan et al., 2008:304). Concurrently, the accuracy for bilateral sound localisation for Participants 3, 7, and 9 was equal to that of normal hearing listeners. Thus, the minority of the participants (n=4/11) (participants 3, 7, 9 and 10) could achieve similar or better bilateral sound localisation performance compared to normal hearing adults. For Participant 3, this improved accuracy may be attributable to the fact that his hearing loss was progressive in nature and the onset was post-lingual, which is considered a positive predictive factor for performance (Dowel, 2005:10-11). Although Participants 7 and 9 both had a pre-lingual onset of hearing loss, they were able to achieve enhanced localisation in the BiCI condition. This may be due to the length of their bilateral cochlear implant stimulation period (> 4years) which could be regarded as sufficient to provide them with opportunities to improve their sound localisation skills. Furthermore, only one participant’s sound localisation accuracy was better than the average for normal hearing listeners, namely Participant 10 who achieved 100% with both implants. As previously stated, his onset of hearing loss was postlingual, therefore he had early exposure to bilateral auditory inputs. Consequently he had opportunities to develop sound localisation prototypes or auditory spatial maps which are considered a determining factor with regard to the extent of bilateral benefit attained during sound localisation (Flamme, 2002:10; Litovsky et al., 2009:428). The well-known variability in performance among cochlear implant users during tests of sound localisation is clearly evident in this study’s results (Neuman et al., 2007:73-82).

The minority of participants (4/11) (Participants 3, 7, 9 and 10) could achieve similar or better bilateral sound localisation performance to normal hearing adults. Litvosky et al. (2009:428-429) ascribe this to the possibility that normal-hearing listeners have many frequency specific channels for processing information across their two ears. Additionally, regardless of the number of channels, frequency specific acoustic stimulation in normal hearing listeners is matched between the two ears. In contrast, cochlear implant users have only a finite number of electrodes which are tonotopically distributed along the cochlea axis. Furthermore, the electrode placement can vary substantially, causing frequency-matching of bilateral implants to be imprecise (Litovsky et al., 2009:428). Moreover, Litovsky et al. (2009:428-429) state that most speech processors do not preserve fine-structure information present in speech signals, but they primarily extract and encode the envelope or the slowly varying amplitude modulation in speech. As mentioned above, Flamme (2002:10) argues that ITD and ILD cues are necessary for sound localisation in the horizontal plane. These cues must be preserved by the speech processors and presented to the listener with good reliability (Litovsky et al., 2009:429). In a study by Van Hoesel (2004:234-246), it was found that some bilateral implant users have good sensitivity to both ITDs and ILDs, but ILD sensitivity seemed to be within normal limits for more bilateral users. Furthermore, ILD cues are more likely to be preserved with greater fidelity by speech processors, causing ILDs to be the more expected cues used for sound localisation in free field as sounds are transmitting through the clinical processors (Litovsky et al., 2009:429).

Neuman et al. (2007:73-82) state that a tendency for bilateral cochlear implant users to have a right ear bias in their response may occur, although no reason for this phenomenon is offered. Response bias to the side of the aided ear is often found when sound-direction identification is measured in persons with only a unilateral cochlear implant (Neuman et al., 2007:73-82). From the participants' data sheet in Appendix L it is clear that when testing was done in the unilateral conditions, most participants had a large bias toward the side where the implant was switched on. Nopp et al. (2004:205-214) and Iwaki et al. (2004:229) confirmed this finding when stating that there is a significant tendency for bilateral cochlear implant users to lean towards different sides when using the left or right implant only. Nopp et al. (2004:205-215) emphasised, however, that the use of the term *sound localisation* for a unilateral implant only is somewhat ambiguous. When listening with only one implant, the person lacks the essential binaural cues of interaural time and level differences which are vital for sound localisation in the horizontal plane. Thus, in the unilateral condition, participants could have identified the loudspeaker ipsilateral to the active implant, since the sound is heard more loudly in that ear; or they could have identified the same loudspeaker with every presentation of sound and thus based their inappropriate judgements on guessing; or participants could have made judgements based on "secondary" cues such as a change in sound timbre and/or perceived loudness if the loudspeaker from which the sound was presented changed (Nopp et al., 2004:205-214).

Five participants (2, 4, 5, 8, and 11) did not show a bilateral benefit (see Figure 4.3), that is, they achieved similar results for sound localisation when they used only their superior implant alone and when they used both implants switched on together. Persons who became deaf before five to six years of age and are implanted in adolescence or later in adulthood may have little or no benefit from bilateral implantation in sound localisation (Nopp et al., 2004:205-214). Of the five participants mentioned above who did not attain a bilateral benefit, only Participant 11 had a congenital hearing loss. According to Nopp et al. (2004:205-214), bilateral hearing abilities probably did not fully mature when a congenital hearing loss is present. Additionally, the longer a person with severe to profound hearing loss goes without receiving appropriate amplification, the poorer his/her localisation abilities may be. There could be a critical developmental period for acquiring bilateral hearing abilities (Nopp et al., 2004:205-214). Furthermore, Participants 2, 4, 5, and 8 were implanted late in adulthood. Previous studies reported that age at implantation correlates negatively with performance results, which means that performance declines with age of implantation (Clark, 2003:576; Dowell, 2005:10). This might explain these participants' inability to achieve a bilateral benefit. Furthermore, it should be recognized that the test setup for sound localization in the horizontal plane may not have been efficient to conduct more in-depth measures to determine the bilateral benefit during sound localization, such as minimal audible angle or root mean square error (RMS: the error for a sound localization response converted into degrees) (Laszig et al., 2004:958-968; Neuman et al., 2007:73-82; Nopp et al., 2004:205-214; Verschuur & Lutman, 2003:13-14). At present, in South Africa, an ideal test setup with more than three loudspeakers (as used in this study) is available. This can be ascribed to insufficient funding in the South African context to enable ideal test setups for research purposes. Yet the test setup can be considered as adequate to reach assumptions regarding the extent of bilateral benefit in a broader sense.

Significant benefit during the sound localisation task was found as expected. These results are consistent with the main findings regarding bilateral benefit in previous studies (Cochlear Corporation Limited, 2005:4; Iwaki et al., 2004:229; Litovsky et al., 2004; Nopp et al., 2004:205-214; Verschuur & Lutman, 2003:13-14). Significantly improved accuracy of sound-direction identification in simultaneously implanted users is well reported (Laszig et al., 2004; Neuman et al., 2007:73-82; Nopp et al., 2004:205-214) and from the results of the present study, it seems that sequentially implanted users may also achieve bilateral benefit during sound localisation in terms of the accuracy of responses. Even for participants who were implanted late, bilateral implant use offered substantial benefit in horizontal plane sound localisation. This finding corroborates that of Nopp et al. (2004:205-214), although earlier implantation might allow better acquisition of spatial hearing, leading to even more improved localisation performance.

Thus, improvement in accuracy and consistency of sound localisation could thus be indicative of the extent of bilateral benefit achieved with sequential implanted users.

5.4 SPEECH PERCEPTION ABILITY IN DICHOTIC LISTENING CONDITIONS

The second cochlear implant (CI 2) was found to be the superior performing implant in the majority of participants (10/11) during the test of speech perception in noise with the noise directed to CI 1. For these 10 participants, their superior implant was CI 2, thus the implant contralateral to the noise source (which was directed to CI 1). CI 1 was found to be the superior performing implant during the test of speech perception in noise with the noise directed to CI 2 for six participants (6/11) (see Figure 4.6 and Table 4.2). For these 6 participants, their superior implant was CI 1, thus the implant contralateral to the noise source (which was directed to CI 2). These findings are similar to those of previous studies that reported better performance for the implant contralateral to the implant to which the noise was directed (Laszig et al., 2004:958-968; Litovsky et al., 2006b:714-731; Van Deun et al., 2010:706-707). There was one participant (number 2) in the condition with noise on CI 2 whose SNR value for the best performing implant was significantly higher than that of the rest of the participants. This participant’s ability to perceive speech in the presence of background noise with the use of only the best performing implant was therefore worse than that of the rest of the participants. This may be attributable to a predictive factor, namely his age at implantation (≥ 60 years), as reported by previous studies

(Clark, 2003:577; Dorman, 2005:10). This participant (number 2) was the oldest of all the participants and his age at the switch on of his first and second implant was 59.2 and 64.5 years respectively. According to Clark (2003:577-578) and Dowell (2005:10,18), speech perception ability may decline with age, as learning is more difficult for the elderly because they tend to have reduced neural plasticity leading to slower learning and processing. Learning and processing skills are required for using the speech processing strategy in post-linguistically deaf adults (Clark, 2003:577-578).

In the cochlear implant population with sequential implantation, elevated auditory thresholds for the second implanted ear relative to the first implanted ear can be expected for the first two years post-implantation. This may reflect the long-term consequences of auditory deprivation on the second implanted ear, consequences that are not ameliorated by early implantation in the opposite ear (Manrique et al., 2007:228) or by simultaneous implantation. Consequently, superior performance in the first implanted ear was expected. Litovsky et al. (2004:648-655; 2006b:714-731) confirm that the largest bilateral effect is evident when noise is presented to the second implanted ear so that hearing is added in the first implanted ear. However, the results of this study are contrary to the results of previous reports, as a bilateral benefit was recorded only when noise was presented to CI 1, so that hearing in CI 2 is improved. With noise presented to CI 1 91% (9/11) of participants’ CI 2 proved to be the superior implant, and with noise presented to CI 2, 45% (5/11) of participants’ CI 2 proved to be the superior implant (see Figures 4.5 and 4.6 and Table 4.2). These findings correspond with those of Litovsky (Cochlear Corporation, 2008b) and Van Wieringen (2010) who pointed out that the second implanted ear possibly received enhanced and more refined technology compared to the first implanted ear, with the result that it operates as the superior functioning implant. This may be the case for 82% of the participants (Participants 1, 2, 4, 5, and 7 to 11) (9/11) whose second implant was a technology upgrade compared to the first implant in terms of the model of the Cochlear™ standard electrode array that was implanted, as displayed in the biographic details (see Table 3.5). In addition, Manrique et al. (2007:231) state that a performance advantage for the first implanted ear relative to the second implanted ear often remains evident during the initial stages of bilateral input; however, these differences decline with increased bilateral experience.

When participants listened with only one implant (CI 1 or CI 2), 91% (10/11) of participants showed a performance advantage for the implant closest to the speech source (thus with a superior signal-to-noise ratio) compared to the implant closest to the noise source (thus, with an inferior SNR) when noise was directed to CI 1 (see Figure 4.5). Correspondingly, with noise directed to CI 2, 55% (6/11) participants achieved better performance with the implant furthest from the noise source (see Figure 4.6). Thus, this finding was evident in both the conditions with noise directed to CI 1 and to CI 2. This is known as a head-shadow benefit, demonstrating bilateral benefit in speech perception in noise abilities (Laszig et al., 2004: 958-968).

From the results presented above it is clear that the head-shadow effect presented a robust and significant benefit for the majority of participants (91% with noise on CI 1 and 55% with noise on CI 2) for perception of the CID sentences in noise, where speech and noise signals are spatially distinct. Laszig et al. (2004:958-968) state that the bilateral head-shadow effect is an important advantage of bilateral stimulation as it permits the implant user the flexibility to attend to the ear with the superior SNR in everyday, real listening environments. This is of special importance when speech is presented in a noisy environment that cannot easily be altered to suit a monaurally implanted user, for example in a car, in a theatre, at a dinner table, in a restaurant, at a meeting, or walking alongside a busy street (Laszig et al., 2004: 958-968).

Participants’ SNR scores for speech perception (in dB) varied significantly in both the superior implant condition and the bilateral condition (see Figures 4.5 and 4.6, and Tables 4.2 and 4.3). This is not surprising, however, as variability in performance on speech perception measures are characteristic of cochlear implant users under both unilateral and bilateral listening conditions (Litovsky et al., 2009:429-430; Tyler, Dunn, Witt & Noble, 2007:86-90). The varying range of SNR values in this study is in accordance with that previously reported with SNR values varying from 0 to >20 dB (Litovsky et al., 2009:429 ; Ramsden et al., 2005:990; Tyler et al., 2007:87S).

Statistically, sequentially implanted adult cochlear implant users did not demonstrate a significant ($p > 0.05$) bilateral benefit in speech perception abilities in spatially separated speech and noise conditions. In the conditions with noise presented to CI 1 and to CI 2, only 64% (7/11) and 36% (4/11) participants respectively, achieved bilateral benefit during speech perception in spatially separated speech and noise (see Figures 4.5 and 4.6, and Table 4.2). That is, a lower SNR value (in dB) was achieved in the bilateral listening condition compared to that of the superior performing implant. Yet, as stated, this trend was not found to be statistically significant. However, for this study's sample, in the condition with noise on CI 2, the majority of participants (7/11) (Participants 1, 2, 3, 5, 6, 9, and 10) were better able to process the speech signal when they listened with both their implants. This is presumably because they were better able to segregate the speech signal from the noise (Dunn et al., 2010:298).

Furthermore, Participants 1, 2, and 9 had a relatively long duration of bilateral implantation of 5.4, 5.5 and 4.1 years respectively (see Table 3.5), which corresponded to better speech perception performance (Clark, 2003:578; Dowell, 2005:10). In addition, Participants 2, 3, 5, and 10 presented with an acquired hearing loss, which according to Dowell (2005:10-11) may lead to improved speech perception outcomes in contrast to users with congenital hearing loss. In contrast, in the condition with noise on CI 2, most participants (7/11) did not show a bilateral benefit, but achieved a better SNR with their superior implant (Figure 4.6 and Table 4.2). For four of these seven participants (Participants 1, 5, 6, and 7) their first implant remained superior. This finding is in accordance with the findings of Galvin et al. (2008:645; 2010:376).

Tyler et al. (2007:87S) also found that most of their participants' first implant remained superior during tests of speech perception. Participant 6 presented with a congenital hearing loss, which may cause poorer speech perception abilities (Clark, 2003:580; Dowell, 2005: 10-11). Participant 7 was also not able to achieve a bilateral benefit. This participant contracted meningitis at the age of 2 years. With regard to etiology, meningitis correlates negatively with performance in adults (Clark, 2003:584; Douglas, Sanli & Gibson, 2008:90-98). Meningitis is considered one of the most common causes of acquired profound sensorineural hearing loss in children and is frequently accompanied by labyrinthitis ossificans, that is, ossification of the cochlea and semicircular canals (Douglas et al., 2008:90-91; Garcia, Aparicio, Penaranda, Baron & Cutha, 2009:48). Severe ossification may occlude the cochlear lumen, making full insertion of the implant difficult or impossible, consequently reducing the number of available active electrodes (Clark, 2003:584; Douglas et al., 2008:91). Therefore, literature advocates early bilateral implantation in order to provide surgery prior to the development of extensive ossification, which may occur as early as two months after meningitis (Douglas et al., 2008:91).

Furthermore, Garcia et al. (2009:48-52) reported that meningitis may affect central auditory processing, especially for cochlear implant users who received implantation at a later age (later than 2 year of age). Thus, for Participant 7, the etiology of meningitis and the fact that she may be considered as late implanted according to Garcia et al. (2009:48-52) with the switch on of her first and second implantations at age 4.6 and 16.6 years respectively, may be considered the reason why she did not achieve significant bilateral benefit.

Superior performance in the first implanted ear for speech perception in noise was found for four participants (1, 5, 6 and 7). This result could imply a more limited extent of bilateral processing than what is typically expected with sequentially implanted users due to long-term consequences of auditory deprivation on the second implanted ear, consequences that are not ameliorated by early implantation in the opposite ear (Manrique et al., 2007:228). The latter holds true especially for Participants 5 and 7, for whom the interval between the switch on of CI 1 and CI 2 were 10.6 and 12 years, respectively (see Table 3.5). It can be assumed, it seems, that sequential cochlear implantation in adults with extended time periods between the first and second implantation may result in poorer second ear performance for some adults. Consequently, this may limit the extent of bilateral benefit that can be obtained by these users (Ramsden et al., 2005:988-998).

An average SNR value of 19.43 dB and 17.74 dB was achieved for the best performing cochlear implant and the bilateral listening condition respectively, when noise was directed to CI 1. With noise directed to CI 2, an average SNR of 19.73 dB and 20.03 dB was achieved for the best performing cochlear implant and the bilateral listening condition, respectively. According to existing studies simultaneously implanted listeners required a SNR value of at least 6.8 dB to achieve speech perception in noise after one year, decreasing to 1.8 dB after four years of bilateral simultaneous implantation use (Eapen et al., 2009:156). The latter SNR value of 1.8 dB is thus significantly lower than the SNR values recorded in this study, although most participants (6/11) had a bilateral experience of more than four years at the time of testing (see Table 3.5). Yet, in this study, all participants were sequentially implanted, which may limit the extent of bilateral performance as optimal concurrent stimulation of the bilateral auditory pathways are affected, with a negatively effect on the processing of signals (Manrique et al., 2007:224).

A bilateral benefit of 1.69 dB was recorded only with noise on CI 1. This may further denote the superior performance of CI 2 as the addition of CI 2 in the BiCI condition leads to a measurable bilateral benefit, only when noise is directed to CI 1. This improvement of 1.69 dB correlates with that found by Galvin et al. (2010:368-377) who stated an average improvement during BiCI use of 0.49 to 4.8 dB in spatially separated speech and noise conditions for sequentially implanted young adults (≤ 19 years of age). Yet, using both implants compared to only one implant led to an average improvement of more than 5 dB for simultaneously implanted adults in a multi-centre study done in the United States in spatially separated speech and noise conditions (Cochlear Corporation, 2005). Thus, this study's improvement of 1.69 dB for sequentially implanted adults is less than what was achieved by simultaneously implanted adults. Manrique et al. (2007:228-231) stated that a performance advantage is evident for two to three years after implantation, then a decline may be evident and users may reach their performance plateau. Thus, participants could have already reached their plateau phase for performance, therefore not demonstrating such a significant bilateral benefit as was seen in previous studies that evaluated performance mostly between 3 and 9 months after implantation (Cochlear Corporation, 2005; Galvin et al., 2010:368-377).

The SNR achieved with bilateral cochlear implant use may improve over time (Eapen et al., 2009:156,158), however, as the bilateral implant user's bilateral processing abilities are developed and enhanced. Therefore, it is noteworthy that Participants 1, 2, and 9 had a longer period of bilateral implant use (> 4 years, which is the average duration of bilateral use for this study - see Table 3.5), potentially favouring their test performance in the condition where noise was directed to CI 1 (Clark, 2003:578; Dunn et al., 2010:29). These participants' SR values in dB were lower, denoting improvement in speech perception in noise when listening in the BiCI condition when noise was presented to CI 1. This finding is in accordance with the clinically relevant conventional view as stated by Litovsky et al. (2009:425,429), namely that increased bilateral listening experience results in improved performance for speech perception in spatially separated speech and noise and thus an improved extent of bilateral benefit. This emphasises the benefits and importance of early implantation and/or a short interval between sequential implants, as well as the importance of aural rehabilitation therapy and counselling, of which audiologists working in the field of cochlear implants should take note.

5.5 SPEECH PERCEPTION ABILITY IN A DIOTIC LISTENING CONDITION

During the test for speech perception in noise with speech and noise being coincident, 82% of participants (9/11) demonstrated the best performance with their second cochlear implant, as stated and discussed in section 5.2.1 above. As evident from the descriptive and inferential results (see Figures 4.9 and 4.10), it is clear that Participant 3 achieved the best speech perception in noise with his second implant, which was also his best performing implant. This may be attributable to the fact that he had a progressive loss, which as a predictive factor is known to correlate positively with speech perception outcomes (Dowell, 2005:10-11).

Statistically, sequentially implanted adult cochlear implant users did not demonstrate a significant ($p > 0.05$) bilateral benefit in speech perception abilities in spatially coincident speech and noise. Only 36% of participants (4/11) (Participants 1, 5, 8, and 10) achieved bilateral benefit (see Figure 4.9). Litovsky et al. (2009:429) found that 60% of bilateral users in their study received bilateral benefit when speech and noise were spatially coincident. An average SNR of 19.15 dB and 18.73 dB were achieved for the best performing cochlear implant and the bilateral listening condition. Thus, using both implants compared to the superior unilateral implant, led to an average improvement of 0.42 dB. This improvement is less than what was found in German centres, where a significant bilateral benefit of 1.4 dB was recorded for simultaneously implanted users after six months of implantation (Cochlear Corporation, 2005). In addition, various previous studies reported significant bilateral advantage for adults with simultaneous bilateral implants during speech perception in diotic listening conditions (Litovsky et al., 2006b:714-731; Ramsden et al. 2005:992; Tyler et al., 2002:80-89). Greater improvement in terms of bilateral benefit can be anticipated for simultaneously implanted cochlear users as simultaneously implantation presents stimulation to both ears and subsequently both auditory pathways concurrently from the switch on dates. This concurrent stimulation of both peripheral and central auditory systems may lead to improved interaction between these ipsi- and contralateral auditory pathways and provide more robust processing of signals (Manrique et al., 2007:224). Moreover, simultaneous implantation could result in longer bilateral experience with minimal to no unilateral stimulation only. It may be assumed that simultaneously implanted users may achieve better speech perception performance in bilateral listening compared to sequentially implanted users. According to Litovksy et al. (2009:420 and 2006a3:43-59), a longer experience with bilateral cochlear implant use may be related to improvements in speech understanding in noise. Therefore, the bilateral benefit observed for Participants 1, 5, 8, and 10 in the study in hand could be due to the fact that they had a significant period of bilateral use, with a minimum of 3.2 years (see Table 3.5). In accordance, these participants had lower SR values compared to values achieved with their superior performing cochlear implant. Of the remainder of participants who did not show a bilateral benefit (7/11), Participants 2, 4, 7, and 11 had an extended interval between implantations (> 5 years, see Table 3.5) that could have limited the obtainable bilateral benefit (Ramsden et al., 2005:988).

The known performance variance of cochlear implant users performance is also evident in the large deviation in the range of bilateral benefit in terms of SNR in dB HL, ranging from 15 to 22.67 dB. This finding is in accordance with international literature which reports SNRs varying from 0 to > 20 dB (Litovsky et al., 2009:429; Ramsden et al., 2005:990; Tyler et al., 2007:87S).

Thus, only 36% participants (4/11) achieved bilateral benefit for speech perception when both speech and noise were directed from the front, compared to 64% (7/11) and 36% (4/11) of participants who attained bilateral benefit in spatially separated speech and noise with noise directed to the right or left ear, respectively. Litovsky et al. (2006b:714-731) also found that when listening bilaterally with speech and noise presented from the front, simultaneously implanted adults' average performance in speech perception was not as significant as when speech and noise were spatially separated. This finding may be attributable to the circumstance of the spatially coincident speech and noise condition being the more difficult one, in that spatial cues for differentiating between target speech and noise are not available (Litovsky et al., 2009:429). The results obtained in this study for speech perception in diotic listening condition could therefore have been anticipated. Spatial separation of speech and noise signals, it appears, enhances speech perception performance for bilateral cochlear implant users (Litovsky et al., 2006b:714-731).

As stated previously, bilateral summation comprises loudness summation and bilateral redundancy (Cochlear Corporation Limited, 2005:1; Litovsky et al., 2009:420; Schön et al., 2002:710). According to Schön et al. (2002:713) it can be assumed that loudness summation does not lead to a significant increase in the bilateral cochlear implant user's speech perception in noise ability, as the SNR is not affected by loudness summation. Moreover, beyond a certain presentation level, speech perception does not increase with increasing loudness. Thus, in situations where the speech and noise signals are spatially coincident and the bilateral implant user has to rely on his/her bilateral summation abilities, it is hypothesised that he/she will benefit more from bilateral redundancy (Schön et al., 2002:714). Furthermore, summation can be obtained when speech and noise are spatially coincident and consequently result in improved bilateral speech intelligibility (Litovsky et al., 2009:420). It can therefore be assumed that the 36% (4/11) of participants who did achieve bilateral benefit during speech perception in the spatially coincident speech and noise condition, had acquired some measure of bilateral summation.

Based on previous studies, it has been speculated that potential auditory capability, consistency of device use, and the attitude and motivation of the user may impact on the outcome with sequential cochlear implants (Galvin et al., 2008:644). Adaptation to sequential implant use and the development of functional listening skills with the second implant, which requires bilateral processing abilities, may be expected within six months. Some dominance of the first implant may remain, however, particularly in difficult listening situations (Galvin et al., 2008:645). From a clinical point of view, the importance of counselling patients and their relatives regarding the extent and functionality of bilateral processing that can be expected with sequential cochlear implants is accentuated (Galvin et al., 2008:637). This implies that audiologists should discuss the possible extent of bilateral processing achievable for adults receiving sequential cochlear implants in relation to the patients' age, time lapse between the first and second implant, binaural listening experiences, and auditory therapy.

5.6 BILATERAL SPATIAL BENEFITS

The last sub-aim of this study was to determine bilateral spatial benefits, namely head shadow effect, squelch, summation, and spatial release of masking (SRM). Bilateral spatial benefits are measures that further quantify the bilateral benefit and include the effects stated (Eapen et al., 2009:153; Van Deun et al., 2010:702-713).

It is important to note that there may have been overlapping contributions of these bilateral processing components, as it is not possible to separate the various bilateral spatial effects completely when listening in the soundfield, as was the case during this study (Litovsky et al., 2006b:714-731). For example, for the comparisons intended to estimate the extent of bilateral benefit primarily related to the head shadow effect, there is likely to have been some contribution from the squelch effect and vice versa (Litovsky et al., 2006b:714-731). Nevertheless, the comparisons of selected bilateral spatial benefit effects represent an approach that has commonly been used in bilateral cochlear implant research literature in an attempt to determine the potential extent of each in order to quantify the bilateral benefit (Eapen et al., 2009:153; Litovsky et al., 2006b:714-731; Müller et al., 2002:198-206; Tyler et al., 2002:80-89). Any comparison can reasonably be expected to represent the primary contribution of each effect.

5.6.1 Head shadow effect

The head shadow effect is recognised as the most robust bilateral benefit effect concerning spatially separated speech and noise testing to achieve better speech perception with a benefit of 3dB or more advantage (Laszig et al., 2004:958-968; Litovsky et al., 2009:420; Litovsky et al., 2006b:714-731; Van Deun et al., 2010:702-713). The head shadow effect is an acoustic phenomenon as the physical presence of the head in the way of the travelling signal wave acts to reduce the noise at the ear further from the noise source (Ramsden et al., 2005:989). This effect arises in the bilateral listening condition when the ear with the more favourable SNR is added (Litovsky et al., 2009:420).

Statistically, sequentially implanted adults' median head shadow effect at 180° (4 dB for CI 1 and 5 dB for CI 2) corresponded significantly to the accepted range of 3 dB or more, but not at 90° on a 5% level of significance. These head shadow benefit values of 4 dB and 5 dB correspond with the benefit values of 3 to 11 dB in implanted adults reported in previous studies (Laszig et al., 2004:958-968; Van Deun et al., 2010:702-713). A positive head shadow effect (3 dB or more) at 90° was achieved, however, by 36% participants (4/11) for CI 1and 18% participants (2/11) for CI 2. At a 180° change in the noise source, 55% participants (6/11) and 64% participants (7/11) demonstrated a positive head shadow benefit of 3 dB or more for CI 1 and CI 2 respectively. Thus, it seems that the greater the spatial separation between the speech signal and the noise source, the greater the head shadow effects obtained by sequentially implanted adults. This observation is supported by the above stated inferential statistical finding of significant head shadow effect only at 180°. Müller et al. (2002:198-206) reported significant head shadow benefits for 67% of participants tested. Litovsky et al. (2006b:714-731) also reported this benefit on at least one of the two unilateral cochlear implants comparisons for 94% of participants, which is a higher percentage than was observed in this study. These participants of Müller et al. (2002:198-206) and Litovsky et al. (2006b:714-731) were all simultaneously implanted, however, therefore they had no period of monaural auditory stimulation. A period of monaural stimulation is characteristic of this study's sequentially implanted participants, and this could have had a detrimental effect on users' bilateral benefit effects. Auditory deprivation may have been present in the second implanted ear, which may have limited the attainable bilateral benefit (Litovsky et al., 2004:648-655).

Furthermore, Participants 1, 7, and 10 achieved positive head shadow effects of 3 dB or more for both CI 1 and CI 2 at 180° (see Table 4.7). This may be attributable to the fact that they had more bilateral listening experience than other participants, that is, more than 4 years, which is the average duration of bilateral use for this study (see Table 3.5). Increased bilateral experience is recognised as particularly effective for performance improvement (Clark, 2003:578; Litovsky et al., 2009:424). Thus, plasticity in the auditory binaural circuitry may render larger benefits in terms of bilateral processing with greater exposure to bilateral stimulation (Litovsky et al., 2009:429).

For head shadow effect at 90°, Participants 3 and 4 recorded a negative head shadow effect for CI 1 compared to CI 2. Participants 6 and 10 obtained a negative head shadow effect for CI 2 compared to CI 1 (see Table 4.6). A negative head shadow effect was also found by Ramsden et al. (2005:994). This may be attributable to the finding that for Participants 3 and 4, CI 1 was performing worse than CI 2 as displayed in terms of SNR values in spatially separated speech and noise conditions with noise directed to the first implant and noise directed to the second implant (see Figures 4.5 and 4.6). For both Participants 6 and 10, their speech reception values with CI 2 were much higher than CI 1’s value when noise was directed to CI 2 (see Figure 4.6). In the head shadow effect at 180°, Participant 11 achieved a negative effect for CI 1 compared to CI 2 and Participant 2 recorded a negative effect for CI 2 compared to CI 1. Considering Participant 11’s speech reception values for CI 1 compared to CI 2 in the dichotic listening conditions, it is clear that CI 1’s performance was inferior to that of CI 2 (see Figures 4.5 and 4.6). Despite the fact that Participant 2’s second implant was the superior performing implant during speech perception in dichotic conditions, the differences between the SR values for CI 1 and CI 2 in both dichotic conditions where noise was directed to CI 1 and to CI 2 were very small (see Figures 4.5 and 4.6).

5.6.2 Squelch

According to Eapen et al. (2009:154) and Ramsden et al. (2005:989), the squelch effect is believed to result from interaural time (phase) and intensity (amplitude) differences, which in turn support sound source segregation and auditory scene analysis. Thus, squelch can lead to enhanced speech perception in noise when listening with both implants, as the ear with the poorer SNR is added (Litovsky et al., 2009:420). This effect is small. Even in normal-hearing listeners it is in the order of 3 dB (Eapen et al., 2009:154). Furthermore, this effect is the largest for low frequencies and is related to the phase locking of neural firing patterns and therefore contributes less to the intelligibility of a speech signal than the head shadow effect (Ramsden et al., 2005:989). The squelch effect has been reported in only approximately 50% of participants in previous studies (Eapen et al., 2009:154; Laszig et al., 2004: 958-968; Müller et al., 2002:198-206). Existing studies reported a benefit of 2dB and even zero or negative effects in bilaterally implanted adults (Laszig et al., 2004:958-968; Litovsky et al., 2006b:714-731; Van Deun et al., 2010:711).

For this study, the median squelch effects for both CI 1 (0 dB) and CI 2 (1 dB) added in the bilateral condition were within the accepted value range (negative to 2dB) on a 5% level of significance. Squelch measures resulted effects of up to 2 dB in implanted adults (Laszig et al., 2004:958-968; Litvosky et al., 2006b:714-731). Thus, this study’s findings correspond with the effect value in previous reports. The squelch effects were within the accepted range of negative up to 2 dB for 55% of participants (6/11) and 64% participants (7/11) when noise was directed to CI 1 and to CI 2 respectively (see Table 4.8). Ramsden et al. (2005:994) also reported a squelch effect for 33% of sequentially implanted adults.

When the noise was on CI 1, four participants obtained a negative squelch effect (Participants 1, 5, 6, and 7). The same number of participants obtained a negative squelch value when the noise was directed to CI 2 (Participants 2, 4, 7, and 11). When the noise was on CI 1, however, and this implant was added in the bilateral condition, the range of negative values was greater (ranging from -1 dB to -9 dB) than the range of negative values for when the noise was directed to CI 2 (see Table 4.8). According to Van Deun et al. (2010:702-713), this might be explained by the fact that turning on the cochlear implant ipsilateral to the noise source, involved degradation in the SNR at that ear. The decrease in SNR might be more significant when the noise was near the first CI, which was the inferior functioning ear in the condition with noise directed to the first implant for Participants 1, 5, and 6 (see Figure 4.6) (Van Deun et al., 2010:702-713). Furthermore, the negative squelch effect values obtained by Participants 1, 2, 4, 5, 6, 7 and 11, may also be attributed to distorted timing cues due to the lack of integration between the processing of the two processors (Ramsden et al., 2005:989).

5.6.3 Summation

Summation, or redundancy, is a bilateral spatial benefit that can be obtained when speech and noise are spatially coincident to subsequently enhance bilateral speech intelligibility (Litovsky et al., 2009:420). Sequentially implanted adults demonstrated a significant bilateral spatial benefit on a 5% level of significance for summation when CI 1 and CI 2 were added to listen with both implants in diotic conditions, with a median value of 0 dB and 2 dB for addition of CI 1 and for CI 2, respectively. All participants' summation values were between negative effects and up to 6 dB (see Table 4.9). These results are in accordance with various existing studies that reported a summation benefit of up to 6dB as well as no or negative effects in adult cochlear implant users (Eapen et al., 2009:154; Litovsky et al., 2006b:714-731; Van Deun et al., 2010:702-713; Wolfe et al., 2007:589-596).

5.6.4 Spatial release of masking (SRM)

SRM is calculated as the difference in the speech reception threshold (SRT), expressed in dB, between the bilateral listening condition (BiCI) in the noise front (NF) noise condition and the BiCI listening condition when noise is directed to the first implant (CI 1) or to the second implant (CI 2) (Van Deun et al., 2010:705-706). In previous studies SRM values of 0 dB up to 4 dB for bilaterally implanted adults were reported as typical (Litovsky et al., 2006b:714-73; Van Deun et al., 2010:702-713).

Inferential statistical analyses demonstrated that sequentially implanted users' median SRM benefit value (0 dB) was statistically significantly within the value of 0-4 dB or more only when the noise was directed to CI 1.

Van Deun et al. (2010:702-713) found an asymmetry in SRM with larger values for a noise shift toward the side of CI 2, suggesting better functioning with CI 1 than with CI 2 for speech perception in noise. Results of the current study, however, seem to be contrary to the latter finding. Asymmetries were present, but with greater values for shifting the noise to the first implant (see Table 4.10). Consequently, it could be assumed that most participants of this study performed better with their second implant relative to their first implant for speech in noise perception.

The improvement in speech perception in spatially separated speech and noise from the addition of an ear with a better SNR was calculated in support of the SRM (see Appendix M). The average value for adding the SNR better ear to CI 1 (thus the contribution of CI 2) was 9 dB. Thus, the latter value was greater than the average value of 5 dB when the SNR better ear was added to CI 2 (thus the contribution of CI 1) (see Table 4.11). Therefore, this may further denote the superior contribution of CI 2 for bilateral benefit during speech perception in spatially separated speech and noise for the sequentially implanted adults of this study.

5.7 CONCLUSION

The human auditory system is specialised for binaural processing, that is, for speech perception in noisy situations, and to localise sound sources (Chan et al., 2008:296). These bilateral functions are important for a person’s ability to interact with people and their everyday environment (Chan et al., 2008:296). As stated, previous research reports indicated that bilateral cochlear implantation improves bilateral users’ bilateral abilities (Laszig et al., 2004:958-968; Litovsky et al., 2006b:714-731; Litovsky et al., 2004:648-655; Nopp et al., 2004:205-214; Tyler et al., 2002:80-89). Thus, a tendency towards improvement in terms of speech perception abilities in spatially separated and coincident speech as noise as well as for sound localisation was expected. Inferential statistical analyses revealed, however, that sequentially implanted adults demonstrated a significant ($p < 0.05$) bilateral benefit in sound localisation abilities but not in speech perception in noise abilities. Consequently, difficulty in the functional use of sound localisation and speech perception in noise may not be optimal due to a limited extent of bilateral processing benefit present in this study's sample of sequentially implanted users. In terms of bilateral spatial benefits, it is evident from the results that this study's sequentially implant users' head shadow effect at 180°, squelch effect, and summation effect for both CI 1 and CI 2 corresponded with previous reported effect values on a 5 % level of significance. Yet, for SRM, only when the noise was directed to CI 1 did the median value correspond with existing studies' values. Chan et al. (2008:296) state that although bilateral abilities might be difficult to assess, it remains important to understand the extent of these abilities, as they play an essential role in the rehabilitation of sequential cochlear implant users.

5.8 SUMMARY

Chapter Five aimed at discussing the results (as presented in chapter four) of this study according to the different sub-aims. The presented results in the previous chapter were analysed, discussed, and compared to the results of previous and existing studies in order to reach conclusions and/or assumptions regarding the results obtained. These discussed results indicated possible measures that can be implemented to determine and monitor the extent of bilateral benefit attainable by sequentially implanted adult cochlear implant users.

6. CONCLUSIONS AND IMPLICATIONS

AIM OF THE CHAPTER

Inferences are drawn from the results of each sub-aim and the conclusions are presented based on the findings of the study. Clinical implications for cochlear implant programmes, audiologists and related professionals in the field of cochlear implantation as well as sequentially implanted candidates are discussed. This is followed by a critical evaluation of the study. Recommendations regarding further research are indicated.

6.1 INTRODUCTION

The role of bilateral benefit in clinical populations has been a topic of considerable interest, in particular for cochlear implant users (Litovsky et al., 2009:419). This study focused mainly on determining the extent of bilateral processing benefit achieved by sequentially implanted adults. The results confirmed the importance of implementing valid and appropriate procedures to assess the bilateral benefit of sequentially implanted adults. Consequently, these results may be utilised by audiologists as well as other members of cochlear implant teams to guide sequentially implanted adults in terms of realistic expectations regarding bilateral benefit achievable.

To address the aim of the study, tests of sound localisation in the horizontal plane together with speech perception in noise tests (in dichotic and diotic listening conditions) were conducted on 11 participants to determine the bilateral benefit achieved.

6.2 CONCLUSIONS

The conclusions regarding the superior cochlear implant as well sound localisation, speech perception in noise (spatially separated and coincident) and the bilateral spatial benefits are discussed below.

6.2.1 THE SUPERIOR COCHLEAR IMPLANT (CI 1 versus CI 2)

During the test of sound localisation in the horizontal plane, performance for participants' CI 1 and CI 2 was found to be very similar. However, for the majority of participants (10/11), the second cochlear implant (CI 2) was the superior performing implant during speech perception in noise testing, in spatially separated speech, and in noise conditions where noise was directed to the first implant. Most participants (9/11) performed better with their second implant in the condition where speech and noise were spatially coincident. This listening condition can be considered more difficult since no effects such as the head shadow or better ear effect could have contributed to the results as happens in conditions where speech and noise are spatially separated and thus. Litovsky (Cochlear Corporation, 2008b) and Van Wieringen (2010) have pointed out that a second cochlear implant may receive improved and more refined technology compared to the first implant and as a result may be the better performing implant.

6.2.2 SOUND LOCALISATION ABILITY IN THREE LISTENING CONDITIONS (CI 1 versus CI 2 versus BiCI)

Improved sound localisation was evident for most participants (6/11) when listening with both implants compared to performance with the superior implant only. These results indicate the presence of a bilateral benefit for localisation in the majority of participants. Sound localisation accuracy of 70% is typically considered to be the norm for normal hearing listeners (Chan et al., 2008:304). A minority of participants (4/11) were able to achieve this percentage in the current study. Only one participant (number 10) achieved 100% accuracy in the bilateral mode.

A statistically significant bilateral benefit ($p < 0.05$) was attained for sound localisation in the horizontal plane for sequentially implanted adults, even for participants who were late implanted. Therefore, in order to determine and monitor the extent of bilateral benefit achievable for sequentially implanted adults, it is imperative to evaluate sound localisation abilities over a period of time.

6.2.3 SPEECH PERCEPTION ABILITY IN DICHOTIC AND DIOTIC LISTENING CONDITIONS

Figure 6.1 summarizes the results regarding speech perception in noise, with speech and noise spatially distinct and coincident.

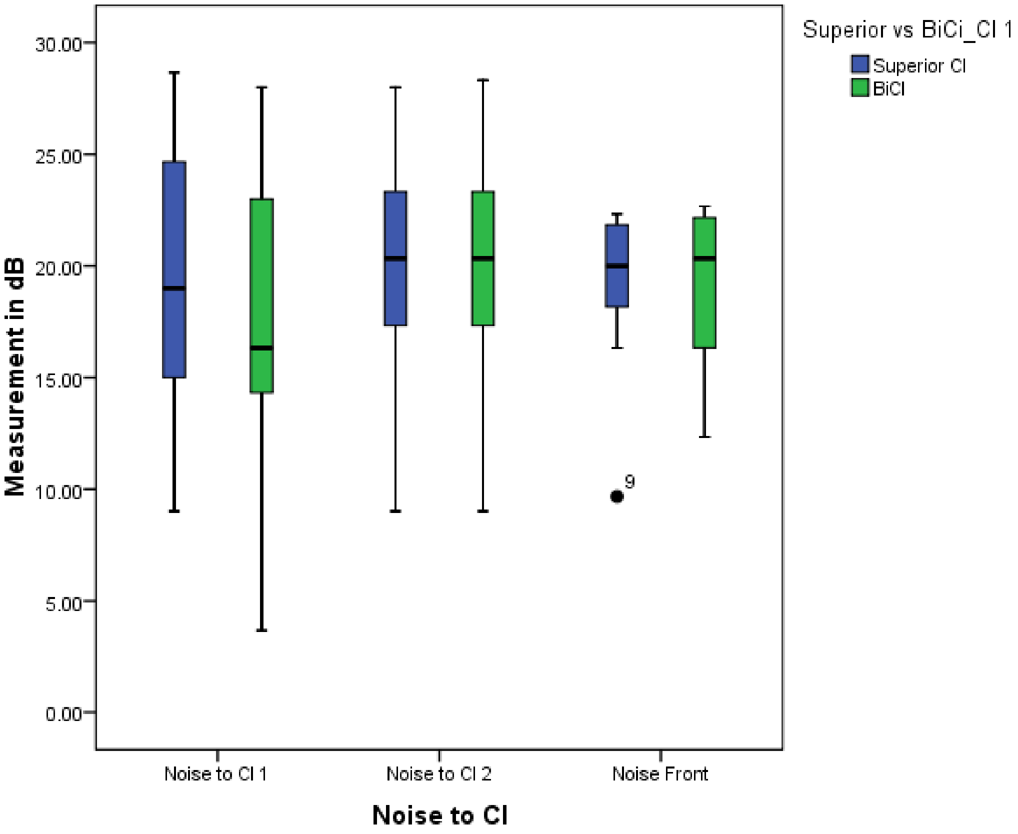

Figure 6.1: Summary of speech perception in noise ability for the superior performing implant versus both implants (n=11) ***Box plots represent the median (thick horizontal line), lower and upper quartiles (ends of boxes), minimum and maximum values (ends of whiskers) and extreme values (dark circle)***

Bilateral benefit (achieving speech reception at a lower SNR value with BiCI compared to the superior performing CI) for speech perception in spatially separated speech and noise was obtained by 64% (7/11) of participants with noise directed to CI 1 and by 36% (4/11) participants with noise directed to CI 2. No statistically significant bilateral benefit for sequentially implanted adults' speech perception in noise ability in spatially separated speech and noise conditions was evident. An average bilateral benefit of 1.69 dB was observed, however, when noise was directed to CI 1 in 64% of the participants (7/11) (Figure 6.1). This is known as a head-shadow benefit. The head-shadow effect was therefore present in the majority of participants for perception of the CID sentences in noise during dichotic listening conditions. This could be indicative of some bilateral benefit.

In the diotic listening condition, no statistically significant bilateral benefit for the greater population of sequentially implanted adults was found for speech perception in noise. Only 36% of participants (4/11) demonstrated a bilateral benefit during this listening condition.

6.2.4 BILATERAL SPATIAL BENEFITS

Head shadow

The head shadow effect at 180° was found to be the strongest and most robust bilateral spatial benefit for sequentially implanted adults of this study. A benefit value of 3 dB or more was attained on at least one of the two unilateral cochlear implant comparisons for nearly all participants (9/11). The head shadow effect at 90° was not statistically significant. Thus, it seems that the greater the spatial separation between the speech signal and the noise source, the greater the head shadow effect obtained by sequentially implanted adults.

Squelch

The accepted benefit of a negative value up to 2 dB was achieved by 55% (6/11) and 64% (7/11) of participants for CI 1 and CI 2 respectively on a 5% level of statistical significance (Laszig et al., 2004:958-968; Litvosky et al., 2006b:714-731).

Summation

All participants demonstrated a significant bilateral spatial benefit for summation on a 5% level of statistical significance when both CI 1 and CI 2 were active, enabling participants to listen with both implants in diotic conditions.

Spatial release of masking (SRM)

Only when noise was directed to CI 1 did sequentially implanted users' median SRM benefit value of 0 dB fall within the accepted value range of 0-4 dB or more on a 5% level of statistical significance. This is in accordance with findings of previous studies where SRM values of 0 dB up to 4 dB for bilaterally implanted adults were reported

(Litovsky et al., 2006b:714-73; Van Deun et al., 2010:702-713). An asymmetry was present, though, with greater SRM values for shifting the noise to the first implant.It may therefore be assumed that the majority of this study's participants performed better with their second implant relative to their first implant for speech in noise perception. The improvement in speech perception in spatially distinct speech and noise from adding the ear with a better SNR was calculated in support of the SRM. The average value for adding the better SNR ear to CI 1, thus the contribution of CI 2, was greater than the average value when the better SNR ear was added to CI 2 (thus the contribution of CI 1). This may be a further indication of the superior contribution of CI 2 for bilateral benefit during speech perception in spatially separated speech and noise for the sequentially implanted adults of this study.

6.3 CLINICAL IMPLICATIONS

It is important to acknowledge that to a large extent the results from this study may not be directly comparable to those obtained in several other previous studies (Dunn et al., 2010; Eapen et al., 2009; Galvin et al., 2010; Galvin et al. 2008; Iwaki et al., 2004; Laszig et al., 2004; Litovsky et al., 2009; Litvosky et al., 2006b; Livotsky et al., 2004; Manrique et al., 2007; Müller et al., 2002; Neuman et al., 2007; Nopp et al., 2004; Ramsden et al., 2005; Sharma et al., 2007; Schön et al., 2002; Tyler et al., 2007; Van Deun et al., 2010; Wolfe et al., 2007). This may be due to the differences in methodologies across studies, such as the use of a fixed SNR in speech perception in noise testing as opposed to the variable SNR approach followed in this study. Furthermore, models and types of cochlear implants and speech processors, materials used to test speech perception in noise, as well as participant populations differ across different studies (Litovsky et al., 2006b:714-731). Despite these dissimilarities, the findings are in agreement with respect to the presence of bilateral benefit , although the extent may vary.

If neural survival differs across a recipient's ears, bilateral implantation may possibly improve performance simply by ensuring that the "better ear" will receive auditory stimulation (Eapen et al., 2009:153). This possibility is significant in the light of the fact that predictions of the ear that will show superior performance post implantation have not been successful (Eapen et al., 2009:153). Clinically, this implies that audiologists should determine the superior cochlear implant in bilaterally implanted users, especially in the sequentially implanted population. From this study it is evident that one cannot assume that a specific ear will be the better performing ear, as it may differ between users. Therefore it is important to determine the superior functioning implant. Moreover, determining the superior performing implant aids in determining the bilateral benefit achieved in sound localisation and speech perception in noise by comparing the superior performing implant's performance with that of both implants (Galvin et al., 2010:372). The clinical value for audiologists on cochlear implant teams of determining the superior implant, may include the following: helping to determine which ear to upgrade (in terms of speech processor technology), helping to determine which ear to train for telephone usage, and helping to counsel patients as they themselves might not be aware which implant is their better performing implant.

Hence, from a clinical perspective, it should be asked if asymmetries in performance between the left and right implant predict less bilateral benefit. Results from Litovsky et al. (2006b:714-731) suggested that predictability of post-implantation bilateral performance from the "better" ear pre-operatively is not reliable. Moreover, in everyday communication situations it is not always possible for cochlear implant users to situate themselves so that the better ear has the superior SNR in the environment. In situations such as a noisy restaurant, where listeners are likely to be surrounded by multiple speakers and noises from numerous directions, functioning with only one implant will most likely pose significant challenges. Thus, if a better ear effect is present, bilateral implantation ensures that the better performing ear will be implanted (Litovsky et al., 2006b:714-731).

Eapen et al. (2009:153) state that if the ears differ in the type of speech cues they can encode then bilateral cochlear implantation could enhance performance by virtue of providing complementary cues across ears. Interaural time and intensity differences that are essential for sound localization can be obtained with bilateral implantation (Eapen et al., 2009:153). In the study in hand, only 55% of participants (6/11) could achieve better sound localisation when listening with both implants. Clinically, it may therefore be advisable to implant cochlear implant candidates concurrently in order to achieve better sound localisation abilities. This is due to the fact that localisation is a bilateral function and relies on the essential binaural cues of interaural time and level differences, which are vital for sound localisation in the horizontal plane. Localisation abilities are necessary and essential for everyday living. Localisation enhances a person’s orienting analysis of his/her environment and serves a bridge from the awareness of sound to being able to focus attentively on the primary signal (Alpiner & McCarthy, 2000:184). Thus, for both children and adults, sound localisation translates directly to utility in everyday situations.

Most participants showed some degree of bilateral benefit in at least one of the dichotic or diotic listening conditions. Clinically it accentuates the importance of routinely determining the extent of bilateral benefit attainable in this population and of monitoring the progress over time in order to determine when a user has reached his/her performance plateau (Eapen et al., 2009:153-159). Thus, from a clinical point of view, the importance of counselling patients and their relatives regarding the extent and functionality of bilateral processing that can be expected with sequential cochlear implants is accentuated (Galvin et al., 2008:637). Audiologists should discuss the possible extent of bilateral processing achievable for adults receiving sequential cochlear implants in relation to the patients’ age, duration of deafness (especially pre- or post-lingual onset of hearing loss), duration between the first and second implant, binaural listening experiences, and aural rehabilitation therapy.

It is clear that bilateral cochlear implantation is better than unilateral implantation. Consistent with previous studies (Litvosky et al., 2006a:43-59; Tyler et al., 2007:89S) it can be concluded that adults with sequential implants may achieve some degree of bilateral benefit even with many years of unilateral implant use. This bilateral benefit is possible even when the speech processors differ, when CI 2 is implanted as much as 17 years after CI 1, and in people with prelingual deafness (Tyler et al., 2007:89S). Yet, from the results of this study and findings of previous studies, it is clear that simultaneous implantation is the ideal for enhanced development of bilateral processing abilities. Litovsky (Cochlear Corporation, 2008b) states that several other improvements are possible with bilateral implantation, including facilitation of language acquisition, learning, cognition and memory as well as improved quality of life, although it is not systematically measurable. These last mentioned possible benefits would be especially important for the paediatric population. Thus, it can be concluded that a key benefit of bilateral implantation appears to be related to the advantageous aspect of having hearing on both sides so that the ear with the more favourable environmental SNR is always available.

The value of the measures used in this study to determine bilateral benefit achievable for sequentially implanted adults is that they allow clinicians and clients to set realistic functional goals, especially for adults who are late implanted. These measures also have clinical value for monitoring this population’s progress in terms of bilateral processing benefit achieved over time. Functional, efficient bilateral hearing abilities form the foundation for cochlear implant users to ultimately achieve satisfactory quality of life, as the bilateral abilities of sound localisation and speech perception in noise enhance listeners’ communication ability and enable them to thrive in everyday living. The findings of this study will support the members of cochlear implant teams to provide more realistic pre- and post-operative counselling. Ultimately it will contribute in allowing adults with sequentially implanted cochlear implants to achieve the most favourable auditory performance and in ensuring effective monitoring of their bilateral benefit abilities.

6.4 CRITICAL EVALUATION OF THE STUDY

This research study was critically evaluated in terms of strengths and limitations in order to make recommendations for further research of a similar nature.

Strengths of the study:

- The methodology, the data analyses, and the data presentation conformed to existing studies in the field of bilateral cochlear implantation. Care was taken to ensure a high degree of reliability and validity.
- A pilot study was conducted before commencement of the main study to determine the validity and reliability of the data collection materials, apparatus, and procedures and the necessary adjustments were made.

- Results from this study can be utilised as a basis for similar and/or extended research in the future, since the data pertains specifically to the South African context.
- The unique contribution of the research lies in the fact that the majority of studies on bilateral cochlear implantation are aimed at the paediatric population. This is largely due to the international trend to implant children bilaterally, rather than adults (Peters et al., 2010:S21). This strong focus and increasing trend to provide bilateral implantation for children as opposed to adults is related at least in part to funding priorities. The National Health Services (NHS) in the United Kingdom and most of the non-United State countries (e.g. Belgium, Canada) exclusively approve funding for bilateral implantation in *children* considering their developmental needs and life expectancy as well as cost-effectiveness of bilateral implantation, compared to that of adults (NHS, 2009; Peters et al., 2010:S25-26). Consequently, most adults in other cochlear implant programmes, other than the Pretoria Cochlear Implant Programme (PCIP), are also only unilateral cochlear implant users (Müller, 2010).
- A further contribution of this study is that it has been conducted on a population of adults with delayed sequential implantations in the South African context - that is, the second implant was done ≥ 5 years after the first implant (Manrique et al., 2007:230-231; Sharma et al., 2002:532-539). This delay is largely ascribed to the fact that state funding in South Africa is limited to only one cochlear implant per adult.
- The tests conducted and results obtained can be utilised by cochlear implant teams to determine and monitor bilateral benefit attainable by sequentially implanted adults and to improve counselling pre- and post-operatively with regards to realistic expectations for bilateral benefit for this population.

Limitations of the research study:

- The number of participants used in this study was limited as a purposive convenient sample was used. Consequently, the population for sound localization as well as speech perception in noise (spatially separated in coincident speech and noise) measures was limited (n=11). This study’s sample was small due to financial and socio-economical restrictions in South Africa which allow only one cochlear implant per candidate. In other South African cochlear implant programmes, other than the PCIP, most adults also have only one cochlear implant (Müller, 2010). Previous international and local research studies on the population of bilaterally implanted adults generally also had small sample sizes, with an average of eight to ten subjects. Furthermore, etiologies and duration of deafness varies greatly among existing studies, causing participant samples to be heterogeneous and not homogenous (Eapen et al., 2009:153; Galvin et al., 2010:368; Litovsky et al., 2009:419-431; Litovsky et al., 2004:648-655; Müller et al., 2002:198-206; Neuman et al., 2007:73-82; Nopp et al., 2004:205-514; Ramsden et al., 2007:988-998; Schön et al., 2002:710-714; Tyler et al., 2007:86-90S; Van Deun et al., 2010: 702-713; Verschuur & Lutman, 2003:13).

- The test setup for sound localization in the horizontal plane may not have been efficient to conduct more in-depth measures to determine the bilateral benefit during sound localization, such as minimal audible angle or root mean square error (RMS: the error for a sound localization response converted into degrees) (Laszig et al., 2004:958-968; Neuman et al., 2007:73-82; Nopp et al., 2004:205-214; Verschuur & Lutman, 2003:13-14). Currently, in South Africa, no such ideal test setup with more than three loudspeakers (as used in this study) is available. This can be ascribed to insufficient funding in the South African context to enable ideal test setups for research purposes. Yet the test setup can be considered as adequate to reach assumptions regarding the extent of bilateral benefit in a broader sense.
- The tests conducted to determine the extent of bilateral processing benefit achieved was performed only once. In order to determine the extent and monitor the development or improvement of bilateral benefit obtained by sequentially implanted adults more effectively, a longitudinal study can be conducted in 3-month intervals for the first year of bilateral implantation or annually for the first four years after bilateral implantation (Eapen et al., 2009:153-159; Ramsden et al., 2005:988-998).

6.5 SUGGESTIONS FOR FURTHER RESEARCH

Increasing volumes of data suggest that bilateral cochlear implantation provides functional bilateral benefit beyond that which is possible with a unilateral implant (Eapen et al., 2009:158). There is also a trend towards increases in measurable bilateral spatial benefits, especially head shadow effect, squelch and summation (Eapen et al., 2009:158). According to Eapen et al. (2009:158) these improvements may be interpreted as reflecting increased ability to use interaural difference cues in sound source segregation and auditory scene analysis. It follows that greater cortical integration of inputs from bilateral cochlear implants may lead to a greater extent of bilateral benefit over a protracted period of time (Eapen et al., 2009:158). Therefore, further studies may be directed at examining the bilateral benefit attained at 3-months intervals for the first year of bilateral implantation or annually for the first four years post-implantation. This will contribute to determine the extent of improvement in bilateral processing benefit over time.

6.6 CLOSING STATEMENT

Cochlear implants are widely recognized as the most successful sensory prosthetic device in the medical world (Wolfe & Schafer, 2010:146). At the same time, unilateral cochlear implant users' loss of bilateral processing and or benefit cannot be considered to be inconsequential. The first White Paper on bilateral cochlear implantation was drafted and published in 2008, namely, the William House Cochlear Implant Study Group: Position Statement on Bilateral Cochlear Implantation. Since 2008, bilateral cochlear implantation is considered the accepted medical practice in clinically suitable adults and children. The paper by Balkany et al. (2008) underscored the importance of bilateral cochlear implantation to enhance bilateral processing benefits for users (Balkany et al., 2008:107). From the results of the current study and findings of previous studies, it is clear that bilateral cochlear implantation is more advantageous than unilateral implantation and that simultaneous implantation is the ideal for enhanced development of bilateral processing abilities. Unfortunately, simultaneous or concurrent implantation is not yet the accepted medical practice in South Africa. Sequentially implanted users do, however, show some extent of bilateral processing benefit. Therefore, determining the extent of bilateral benefit attainable for each sequentially implanted adult to the best of one’s ability by conducting clinically valuable tests that evaluate bilateral processing, namely sound localization in the horizontal plane as well as speech perception in noise tests in dichotic and diotic listening conditions, and enlisting the user as an essential and active component in the process can contribute to more accountable service delivery and optimal satisfaction of the sequentially implanted adult cochlear implant user population. This can be considered as best practice to strive towards in serving cochlear implant users, because “to provide anything than the best we can offer … is to sell them short” (Rossetti, 2001:285).

“A person is born with (a) desire of the
ears,
and a liking for beautiful sounds…”
(Xun Zi, n.d.)

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APPENDIX A

Ethical Clearance from the Research and Ethics Committee of the Department of Communication Pathology, University of Pretoria

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

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E-pos: **petru.woest@up.ac.za**

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESiTHi YAPRETORIA
Fakulteit Geesteswetenskappe

35 Desernber 2008

Me I Davidson
Posbus 58138
KARENPARK
0118

Geagte me Davidson

TITELREGISTRASIE: STUDIERIGTING - MKOMMUNIKASIEPATOLQGIE

Met genoee deel ek u mee dat die volgende goedgekeur is:

ONDERWERP; **Extent of bilateral balancing in sequentially implanted cochlear implant users**

LEIER: **Dr C van Dijk**

MEDELEIER: Me E Groenewald

U aandag word in besonder op die volgende gevestig:

1. TERMYN VAN REGISTRASIE

(a) U moet vir minstens een akademiese jaar as student vir die magistergraad geregistreer wees voordat die graad toegeken kan word.

(b) U registrasie moet jaarliks voor April hernu word totdat u aan al die vereistes vir die magistergraad voldoen het. Geen herregistrasie sal na 31 Maart aanvaar word nie. U sal slegs geregtig wees op die leiding van u leier indien u jaarliks bewys van registrasie aan horn voorte.

2. GOEDKEUR1NG VIR INDIENING

Vir eksamendoeleindes moet u voldoende eksemplare vir elke eksaminator indien, tesame met 'n skriftelike verklaring van u leier dat hy/sy die indiening van die verhandeiing goedkeur sowe! as 'n verklaring deur u, wat voor 'n Kommissaris van Ede geteken word, wat by Studenteadrninistraste ingehandig word.

3. KENNISGEWING VOOR INDIENING

U moet my asseblief ten minste drie maande voordat u beplan om u verhandeling/skripsie in te dien van u voorneme in kennis stel.

4. VOORSKRIFTE IN VERBAND MET DIE VOORBEREIDING VAN DIE VERHANDELING/SKRIPSIE ASOOK DIE SAMEVATTING IS OP DIE KEERSY VAN HIERDIE BRIEF UITEENGESiT.

Die uwe

nms DEKAAN: FAKULTEIT GEESTESWETENSKAPPE

APPENDIX B

Ethical Clearance from the Head of the Pretoria Cochlear Implant Program (PCIP)

100
1908 - 2008

UNIVERSITEIT
UNIVERSITY
YUNiBESiTHI
VAN
PRETORIA
OF
PRETORIA
YA
PRETORIA

Faculty of Humanities
Dept of Communication Pathology
Speech, Voice and Hearing Clinic
Tel: +27124202814
Fax: +27124203517
Email: Catherine.vandijk@up,ac.za

Please complete the form below

Dear Miss llze Davidson,

I hereby give permission to make use of adult clients with bilateral sequentially implanted cochlear implants of the PCIP in the research project described. I also grant permission for you to access the participants' audiological and cochlear implantation records. I will ensure that the participants are aware that participation in the study is on a voluntary basis.

Kind regards,

Professor J. G, Swart Date

Head: PCIP

APPENDIX C

Request for permission:
Letter to the head of the Pretoria Cochlear Implant Program (PCIP):

Professor J. G. Swart

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VAi\ UNIVERSITY
OF YUNIBESiTHI
YA
PRETORIA
PRETORIA
PRETORIA

Faculty of Humanities
Dept of Communication Pathology
Speech, Voice and Hearing Clinic
Tel: +27 12 420 2814
Fax: +27124203517
Email: catherine.vandijk@up.ac.za

Professor J. G. Swart
Head: The Pretoria Cochlear Implant Programme
Department of Communication Pathology
University of Pretoria
Pretoria
0002

25 August 2008

Dear Professor J. G. Swart,

PERMISSION TO CONDUCT A RESEARCH PROJECT THAT INVOLVES ADULT CLIENTS OF THE PRETORIA COCHLEAR IMPLANT PROGRAMME (PCIP) WITH BILATERAL SEQUENTIALLY IMPLANTED COCHLEAR IMPLANTS

I am a Master's student in Communication Pathology at the University of Pretoria. I am requested to conduct a research project in partial fulfilment of my post-graduate degree. The title of my study is: Bilateral Balancing of Sequentially Implanted Cochlear Implant Users. My research project will therefore involve adults with sequential bilateral cochlear implantations.

The purpose of this study is to determine the extent to which bilateral balancing is achieved in sequentially implanted cochlear implant users.

I would like to request permission to involve adult clients with bilateral sequentially implanted cochlear implants of the PCIP in my study. The participants will be requested to participate in a participant selection procedure, including otoscopic examination, tympanometry, aided pure tone air conduction audiometry and speech audiometry, as well as mapping of their cochlear implants and bilateral balancing on the company's (Cochlear™) software. This will form part of a routine follow-up appointment with their current audiologist at the PCIP. Consequently a suitable date and time for the data collection procedures will be arranged between the researcher and participants. These procedures will be conducted at the Hearing Clinic of the Department of Communication Pathology, University of Pretoria. The measurements that will be performed to determine the participant's extent of bilateral balancing include sound localization measures as well as bilateral speech perception measures, specifically spatially separated speech and noise and spatially coincident speech and noise. Permission is also requested to access the participants' cochlear implantation records in order to obtain information on their audiological and cochlear implantation history. This information will be relevant for participant selection, the conduction of the test battery as well as interpretation of results.

The participation in this study is voluntarily and participants have the right to withdraw from the study at any time without negative consequences. Confidentiality will be maintained throughout the course of this study.

The information and results of this research project will be available in the format of a dissertation at the Library of the University of Pretoria as well as in an article publication. All raw data will be stored in hard copy and on CD for 15 years before it will be destroyed. The PCIP may have access to all data obtained in this research project.

Please complete the attached form if you provide permission for conducting the research. Please return the form to the coordinator of the PCIP.

Kind regards,

Ilze Davidson

M. Communication Pathology Student

Dr Catherine van Dijk

Research Supervisor

Professor Brenda Louw

HEAD: DEPT COMMUNICATION PATHOLOGY

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Please complete the form below

Dear Miss lize Davidson,

I hereby give permission to make use of adult clients with bilateral sequentially implanted cochlear implants of the PCIP in the research project described. I also grant permission for you to access the participants' audiological and cochlear implantation records. I will ensure that the participants are aware that participation in the study is on a voluntary basis.

Kind regards,

Professor J. G. Swart

Date

Head: PCIP

APPENDIX D

1. Letter of Informed Consent: English
2. Letter of Informed Consent: Afrikaans

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17 May 2010

Dear sir/madam

REQUEST FOR YOUR PARTICIPATION IN A RESEARCH PROJECT

As a Master's student in Communication Pathology at the University of Pretoria, it is expected of me to conduct a research project in partial fulfilment of the requirements for my degree. The title of my study is: The extent of bilateral and binaural processing in sequentially implanted cochlear implant users. I would appreciate it if you would be willing to participate in this project. Please see details of this research project below.

Purpose of the study:
The purpose of this study is to determine the extent to which bilateral and binaural processing is achieved in sequentially implanted cochlear implant users. Thus, how well both your cochlear implants are functioning together in order to enhance your bilateral and binaural processing abilities. Bilateral and binaural processing abilities refer to your ability to localize a sound (determine from which direction a sound is coming) as well as your speech perception in noise.

Procedure:
You will be requested to participate in participate in a pre-test procedure, based on a routine follow-up appointment at the Pretoria Cochlear Implant Programme. During this procedure programming (mapping) of both your cochlear implants and bilateral balancing thereof will be done. Consequently a suitable date and time for the bilateral and binaural processing test procedures that will be done at the Hearing Clinic of the Department Communication Pathology, University of Pretoria, will be arranged between the researcher and you. The measurements that will be performed to determine the extent of your bilateral and binaural processing include localization measures as well as bilateral speech perception measures, specifically spatially separated speech and noise and spatially coincident speech and noise. The duration of the whole procedure will last about two hours.

Risks and possible discomforts:
There are no risks involved in this study. It will be expected of you to attend the binaural processing test procedure on the arranged date and time.

Value of the study:
By participating in this study, you will contribute to the results that may be used by the researcher and cochlear implant teams to determine the extent of binaural processing that can be achieved by adults with sequentially bilateral cochlear implants. The results of this study could lead to evidence-based recommendations in terms of relevant measures to determine binaural processing as well as enhancing audiologists' insight in post-implantation performance of binaural processing in order to realistically inform prospective candidates. Furthermore, suggestions for adaptation of candidacy considerations, surgery protocols and

motivations for medical schema for funding of simultaneous cochlear implantation could be attained. This information may aid to ensure service delivery that is accountable and optimise bilateral cochlear implant clients' performance and satisfaction.

Participant's rights:
You voluntary participate in this study and accept the fact that you will not receive any reward for your participation. You have the right to withdraw from participation in the study at any time without negative consequences.

Confidentiality:
The information that you will provide will be treated as confidential (only the information that you have provided in the questionnaire will be used for the study and not your name or personal details). It will be assured that the information you have provided would be destroyed should you choose to withdraw from the study.

Dissemination:
The information and results of this research project will be available in the format of a dissertation at the Library of the University of Pretoria as well as in an article publication. All raw data will be stored in hard copy and on CD for 15 years before it will be destroyed.

If you have any questions or concerns, you are welcome to contact me, Ilze Oosthuizen, any time at 072 288 4209.

Kind regards

Ilze Oosthuizen
M. Communication Pathology Student

Dr. Catherine van Dijk
Research Supervisor

Professor Brenda Louw
HEAD: DEPT. COMMUNICATION PATHOLOGY

Please complete the tear slip below

<u>INFORMED CONSENT: Participant</u>

I, ______________________________, am willing to participate in the abovementioned study according to the conditions stipulated in the enclosed letter.

______________________ ____________________

Signature Date

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18 Mei 2010

Geagte heer/dame

TOESTEMMING VIR U DEELNAME AAN ’N NAVORSINGSPROJEK

As ’n Meestersgraad student in Kommunikasiepatologie aan die Universiteit van Pretoria, word daar van my verwag om ’n navorsingsprojek te voltooi ter gedeeltelike vervulling van die vereistes vir my graad. Die titel van my studie is: Die mate van bilaterale en binourale prosessering in opeenvolgend geïnplanteerde koglêere inplanting gebruikers. Ek sal dit hoog op prys stel indien u bereid sou wees om aan hierdie navorsingsprojek deel te neem. Sien asseblief onderstaande inligting rakende hierdie navorsingsprojek.

Doel van die studie:
Die doel van die studie is om te bepaal wat die mate van bilaterale en binourale prosessering is wat koglêere gebruikers met bilateraal, opeenvolgende inplantings kan behaal. Dit wil sê, hoe goed albei u koglêere inplantings funksioneer ten einde u vermoëns tot bilaterale en binourale prosessering te bevorder. Bilaterale en binourale prosesseringsvaardighede verwys na u vermoë om ‘n klankbron te lokaliseer (die rigting waaruit klank kom te bepaal) asook u spraakpersepsie in geraas.

Prosedure:
Daar gaan van u verwag word om aan ’n vooraf-toetsing sessie deel te neem. Dit sal gebaseer word op die prosedures tydens ‘n standaard opvolg-sessie by die Pretoria Koglêere Inplantingsprogram. Daartydens sal albei u inplantings geprogrammeer (“map”) word asook bilateraal gebalanseer word. Gevolglik sal daar met u, as deelnemer, ’n gepaste datum en tyd ooreengekom word vir die bilaterale en binourale prosessering toetsingsprosedure wat by die Gehoor Kliniek van die Departement Kommunikasiepatologie, Universiteit van Pretoria, sal plaasvind. Laasgenoemde sal metings van klanklokalisasie asook spraak persepsie in geraas waar die spraak- en geraassein ruimtelik geskei asook vanuit dieselfde rigting aangebied sal word. Die hele prosedure sal ongeveer twee ure duur.

Risiko’s en moontlike ongerief:
Daar is geen risiko’s aan hierdie studie verbonde nie. Daar sal wel van u verwag word om op die ooreengekomde datum en tyd vir die bilaterale en binourale prosessering toetsprosedure aan te meld.

Waarde van die studie:
U gaan aan die navorser en die koglêere inplanting span waardevolle inligting verskaf wat gebruik kan word om die omvang van bilaterale en binourale prosessering wat volwassenes met bilateraal opeenvolgend geïnplanteerde koglêere inplantings kan behaal, te bepaal. Die resultate kan dus lei tot bewys-gerigte aanbevelings om bilaterale en binourale prosessering te evalueer en ook oudioloë se insig, met betrekking tot gebruikers se post-inplanting funksionering in terme van bilaterale en binourale prosessering, te bevorder ten einde prospektiewe kandidate in te lig met verwysing na realistiese verwagtings. Verder kan aanbevelings in terme van kriteria vir koglêere inplantings kandidate, sjirurgiese protokolle,

en motiverings vir mediese skemas vir befondsing vir gelyktydige bilaterale inplantings behaal word. Hierdie inligting kan moontlik bydra tot meer verantwoordbare dienslewering en optimale bevrediging van die volwassene met bilaterale koglêere inplantings.

Regte van die deelnemer:
U neem vrywillig aan die studie deel en aanvaar dat u geen beloning daarvoor gaan ontvang nie. U het die volle reg om enige tyd, sonder benadeling, aan die studie te onttrek.

Vertroulikheid:
Al die inligting wat van u verkry gaan word, sal baie vertroulik hanteer word (slegs die inligting wat u op die vraelys ingevul het sal vir die studie gebruik word en nie u naam of persoonlike besonderhede nie). Konfidensialiteit van u persoonlike besonderhede sal verseker word. Daar sal onderneem word om alle inligting deur u verskaf te vernietig indien u besluit om aan die studie te onttrek.

Disseminasie:
Die inligting en resultate van hierdie navorsingsprojek gaan in die Biblioteek van die Universiteit van Pretoria in die formaat van ’n verhandeling en ’n artikel beskikbaar wees. Alle rou data sal vir 15 jaar in harde kopie asook op ‘n CD gestoor word voordat dit vernietig word.

Indien u enige verder navrae of bekommernisse het, is u welkom om vir my, Ilze Oosthuizen, enige tyd te skakel by 072 288 4209.

Vriendelike groete

Ilze Oosthuizen
M. Kommunikasiepatologie Student

Dr. Catherine van Dijk
Navorsingsleier

Professor Brenda Louw
HOOF: DEPT. KOMMUNIKASIEPATOLOGIE

Voltooi asseblief die onderstaande skeurstrokie

INGELIGTE TOESTEMMING: Deelnemer

Ek, ________________________________, is bereid om deel te neem aan die bogenoemde studie in ooreenstemming met die inligting verstrek in die meegaande brief.

_________________________	______________________
Handtekening	Datum

APPENDIX E

Biographical Information Form

Participant no: ____________________

BIOGRAPHICAL INFORMATION FORM:
Extent of Bilateral processing in Sequentially Implanted Cochlear Implant Users

1. General Information: (Will be kept strictly confidential)

Name: ______________________________

Surname: ___________________________

Date of Birth: ________________________

Age: ________________________________

Gender: _____________________________

First Language: ______________________

Date of testing: ______________________

2. Audiological History

Cause of hearing loss: ____

Age of hearing loss onset: ____

Type of hearing loss: ____

Degree of hearing loss: ____

Any other significant audiological condition: ___________________________

____

3. Cochlear Implantation History

FIRST IMPLANTATION

Ear implanted first: L/R

Reason for specific ear first implanted: _______________________________

Date of implantation: ____

Age at implantation: ____

Type of cochlear implant: ____

Model of cochlear implant: ____

Model of current speech processor: ____________________________________

SECOND IMPLANTATION

Ear implanted second: L/R

Date of second implantation: ____________________________________

Age at implantation: ____

Type of cochlear implant: _______________________________________

Model of cochlear implant: ______________________________________

Model of current speech processor: _______________________________

Date of last map: ____

Total number of maps: ____

Are both of the participant's cochlear implants balanced on Cochlear™ software? YES/NO

Do you experience one ear to be more dominant than the other? If so, please indicate a reason for your answer.

____

____

Which ear do you experience as to be your dominant ear? L/R

APPENDIX F

Standard Audiogram

Hearing Clinic
Department of Communication Pathology
University of Pretoria

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Universiteit van Pretoria / U a
Kommunikasiepatologie / Communication Pathology

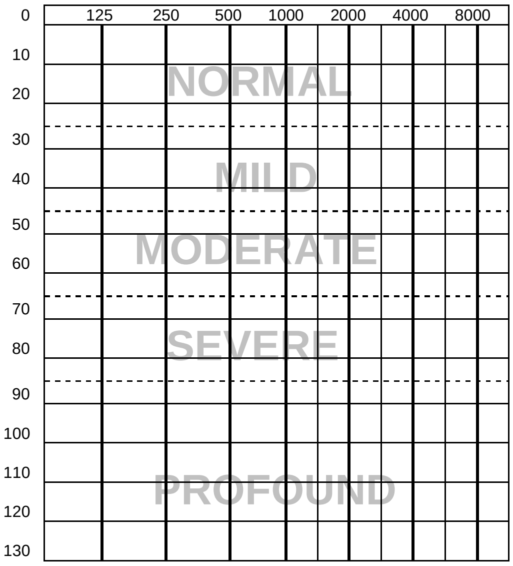
Tel: (012) 420-2816 / (012) 420-2491

Naam / Name: ______________________ **Datum / Date:** ______________________

GEB / DOB: ____________ **Oudioloog / Audiologist:** ____________ **Student / Student:** ____________

Suiwertoonoudiogram / Pure Tone Audiogram

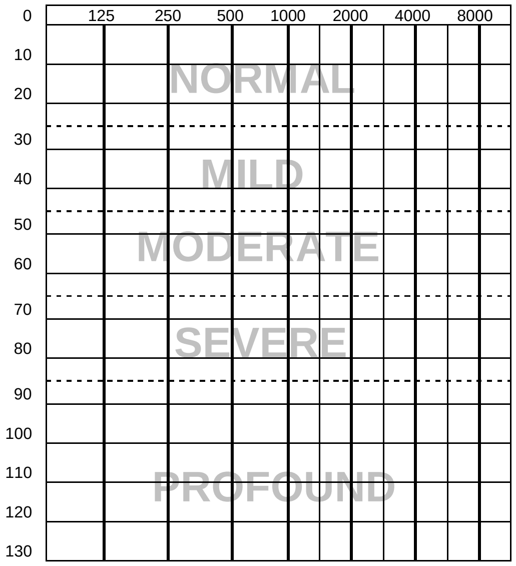
Regteroor / Right Ear



Maskering / Masking

LG/AC							
BG/BC							

Linkeroor / Left Ear



Maskering / Masking

LG/AC							
BG/BC							

Weber

250	500	1000	2000	4000

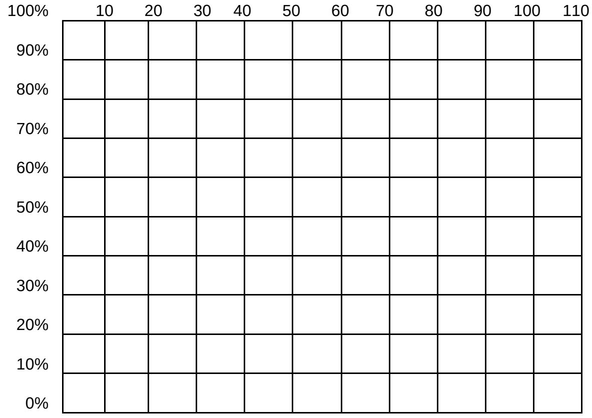
Rinne

R	L

Otoskopiese Ondersoek Otoscopic Examination
R
L

% Gehoorverlies:
% Hearing Loss: R ________ L _________ B _________

Spraakoudiogram / Speech Audiogram



Maskering	L										
Masking	R										

	R	L
STD / PTA		
SOD / SRT		
Disk % Disc.		
MGL / MCL VP / UCL		
Spraakdeteksie Speech Detection		

Akoestiese Immittansie / Acoustic Immittance

	R	L
Timpanogram /Tympanogram		
Middeloordruk / Middle Ear Pressure		
Statiese / Static Compliance		
Oorkanaal Volume / Ear Canal Volume		

Akoestiese Refleks / Acoustic Reflex

Refleks Drempel Reflex Threshold		PTT / STD	Verskil Difference	Refleks Versterwing Reflex Decay	Frekwensie Frequency	Refleks Drempel Reflex Threshold		PTT / STD	Verskil Difference	Refleks Versterwing Reflex Decay
R Kontra Contra	**R** Ipsi					**L** Kontra Contra	**L** Ipsi			
					250 Hz					
					500 Hz					
					1 kHz					
					2 kHz					
					4 kHz					

Ongemaskeerde lug Unmasked Air		Ongemaskeerde Been Unmasked Bone	Gemaskeerde Lug Unmasked Air	Gemaskeerde Been Masked Bone	Geen Respons No Response	Vrye Veld Sound Field	VP / UCL
R	○	<	△	⊏	↓	S	⊓
L	X	>	□	⊐			

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Ouditiewe Prosessering / Auditory Processing

		DD		FP		DP		LPFS		TC		BF
	Oor Ear	R	L	R	L	R	L	R	L	R	L	B
100												
90												
80												
70												
60												
50												
40												
30												
20												
10												

DD = Dichotic Digit Test
FP = Frequency Pattern Test
DP = Duration Pattern Test
LPFS = Low-pass Filtered Speech Test
TC = Time-compressed Speech
BF = Binaural Fusion Test

Maskeringsvlak verskil (MVV) toets Masking level difference (MLD) test			
Stimulus: Suiwertoon Stimulus: Pure tone	Frekwensie Frequency	0º/0º - 0º/180º	MVV-waarde MLD value
Stimulus: Spraak Stimulus: Speech			MVV-waarde MLD value

Simultaneous Binaural Median Plane Localization (SSMPL) Test

Frekwensie Frequency	Int. van R-oor It. of R-ear	Int. van L-oor Int. of L-ear	Interourale verskil Interaural diff.

Buis van Eustachius toetse Eustachian Tube Tests

Toetse Tests	R	L
Inflasie: Inflation:		
Deflasie: Deflation:		
Ander: Other:		

Toonversterwing (binne 60 s) Tone Decay (within 60 s)

Frekwensie: Frequency:	R	L

Otoakoestiese Emissies (OAE) Otoacoustic Emissions (OAE)

Toets / Test:	
Protokol / Protocol:	
Resultate / Results: L	R

Opmerkings / Remarks:

APPENDIX G

1. The *Phonetically Balanced word list* in English

Author: Egan (1948 in Mendel & Danhauer, 1997)

2. The *Afrikaanse Foneties gebalanseerde woordelys*

Authors: Laubscher & Tesner (1966)

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SPEECH,VOICE AND HEARING CLINIC

PHONETICALLY BALANCED WORD LIST

			DATE	
		2	3	4
The first is	ace	me	ail (ale)	move
next is now	ache	mew	air (heir)	new
try listen to	an	none (nun)	and	now
please try	as	not (knot)	bin (been)	oak
next is	bathe	or (car)	by (buy)	odd
listen to now	beels	owl	cap	off
try next is	carve	poor	cars	one
listen to	chew	ran	chest	own
please try	could	see (sea)	die (dye)	pew
now comes	dad	she	does	rooms
let's try	day	skin	dumb	send
listen to	deaf	stove	ease	show
next is now	earn(urn)	them	eat	smart
try listen to	east	there	else	star
please try	felt	thing	flat	tare (tear)
next is let's	give	toe	gave	that
try listen to	high	true	ham	then
now comes	him	twins	hit	thin
please try	hunt	yeard	hurt	two
next is the	isle(aisle)	up	ice	tree
last is	it	us	ill	way
	jam	wet	jaw	well
	knees	what	key	with
	law	wire	knee	yore
	low	you (ewe)	live (verb)	young

Number of words correct				
Percentage of words correct •				
Left (L) , Right. (R) , L & S				
Free field (F)				
Audiometer intensity				
Make of Hearing Aid				
Hearing Aid Volume				
Air/Bone			i	
-r or - lip" reading !"				

AFRIKAANS FONETIES GEBALANSEERDE WOORDELYS

.	LYS 1		LYS 2		LYS 5	!	LYS 4	
	vlieg	brief	brood	vryf	een	vlag	brug	vroeg
	brand	eers	oop	praat	vriend	iets	eet	bril
	OKI	f raai	vroeg	vars	volg	vrag	vel	aand
	diens	vloer	volk	beurt	bleu	bruin	vlam	vleis
	klcnip	drink	blink	dier	broer	droog	breek	draai
	vra	drop	droom	klaar	deur	dank	diep	klaar
	koel	kraal	kiein	druk	klam	klink	krap	dink
	lof	kleur	kry	leer	lyf	les	• loop	kort
	Isngs	lig	lag	krag	kloof	klim	klop	leun
	hy	spring	lief	snaaks	vaal	lank	lag	lomp
	staan	lei	sterf	los	skerp	skrif	swart	stert
	spuit	stoora	stil	hang	groen	skoon	spreek	hoof
	rak	hsar	heel	hand	seep	hok	huis	seit ı
	hulp	reen	huil	noem	haal	rok	hof	hark
	weet	hart	roep	streep	hier	half	roea	res
	reel	ruk	reg	traan	rug	ram	ring	woon
	meet	woes	res	rond	raak	wat	wiel	rant
	werd	weg	mond	mark	wol	merk	meer	werk
	neef	maat	TIOU	grap	maand	tong	wa	mos
	maan	jonk	'teen	trok	was	perd	nog	my
	gras	neus	pas	ja	moes	P^7^{S}	jaar	niks
	trap	groot	pluk	retis	tree	teer	plaas	peer
	tog	trek	groei	wen	' plaat	37	trou	plank
	ple!c	plan	weef	wind	nes	nee	groet	graf
–	berg	paar	waar	erg	prop	golf	treur	trein
Pers. woorde korrek								i
Links (L) of Regs (R)								1
Vryeveld (W)								
Oudiometer intensiteit.								
Tipe Gehoor-at iDaraat		\						_ —
-* Spraaklees — Spraaklees			i					

APPENDIX H

1. The *Central Institute for the Deaf (CID) Everyday Speech Sentences* (English version)

Authors: Davis & Silverman (1970, in Alpiner & McCarthy, 2000)

2. The *Central Institute for the Deaf (CID) Everyday Speech Sentences* (Afrikaans version)

Authors: Müller & De Stadler (1987)

C1D Everyday Sentences

Name' Date: Interval:

Lists A & B (Track 2}

1 Hera are your shoes.
2 Do you want an egq for breakfast?
3 Do.n't try to get out of it this time!.
4 Walking's my favourite exercise.
5 Here v/s go.
3 Come here when I cail you:
7 Move out of the way!
3 Should we let little children go to the moviss by them selves?
9 Someone cleans all Jne flo_p_rs_every night
10 It'siaining. i 1 H®n!l a nice quite piacejo
res_t
12 Whvishouid * ost up so early in the morning?
13 Where are you going?
14 It would be rnt'ch 5":er if everyone would heto.
"15 How do you fed! abCLit beginning work at a different time every';-
16 There isn't, enough oa'nt to finish the room,
17 The water's is too cold for swirnrnjna.
18 Do you think she should stay out so late?
19 Good morning.
20 Open your window before you go to bed.

Total:

	Response
3	
4	
8	
4	
3	
5	
3	
8	
6	
2	
5	
7	
3	
5	
9	
6	
4	
3	
2	
5	
100	

Lists H & G (Track 3)

1 Believe me.
2 it's no trouble at ajl.
3 How do you know?
4 They are not listed in the new.phone book.
5 There was water in the cellar after that heavy rain yesterday.
6 I'll see you right after lunch.
7 If we ...don't get rain soon we'll,have no, grass.
8 Let's get out_of it before it's too late.
9 The phone call's for you.
10 White shoes are awful to keep ciean.
11 There's a big piece of cake left over from dinner.
12 Let's get a cup. of coffee.
13 ShelTonjv be gone a few minutes.
14 I hate driving at night
15 _S_ee you later.
16 Wait for me at the corner in front of the chemist.
17 The morning paper didn't say anything about rain 'this jfternoon or tonight.
18 Hurry up.
19 Chndrenjike sweets.
20 Stand there and don't move until I tell vou.

21

	Resoonse
2	
4	
3	
7	
8	
5	
10	
6	
3	
5	
7	
4	
5	
3	
3	
5	
1 9	
2	
3	
7	
100	

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CiD Everyday Sentences

Name: Date: Interval:

Lists A & B (Track 4)

1 Someone cleans all the floors every night.
2 Open your window before you go to bed.
3 Where are you going?
4 More are your shoes.
5 How do you feel about beginning work at a different time every day?
6 Here's a nice guiet place to rest.
7 Good morning.
8 Do you want an egg for breakfast?
9 Come here when I call you.
10 The water's too cold for swimming.
11 Here we go.
12 It would be much easier if everyone wouid help.
13 Do you think that she should stay out ~.o late?
14 Walking's my favourite exercise;
15 Should we let little children go to the movies by themselves?
16 Don't try to get out of it this time.
17 There isn't enough paint to finish the room.
18 Why should I get up so early in the morning?
19 Move out of the way.
20 It's raining.

21

	Response
6	
5	
3	
3	
10	
5	
2	
4	
5	
4	
3	
5	
8	
=4 •	
8	
8	
6	
7	
3	
2	
100	

Lists G & H (Track 5)

1 The morning paper did'nt say anything about rain this afternoon or tonight.
2 If we don't get rain soon we'll have no grass.
3 Let's get a cup of coffee.
4 Believe me..
5 Stand there and don't move until I tell you.
6 It's no trouble at ajj.
7 Let's get out of here before it is too late.
8 Wait for me at the corner in front of the chemist.
9 They're not listed in the new phone book.
10 Children like sweets.
11 How do you know?
12 White shoes are awful to keep clean.
13 See you later.
14 There was water in the cellar after that heavy rain yesterday.
15 Hurry up.
16 The phone call's for you.
17 I'll see you right after lunch.
18 I hate driving at night.
19 There's a big piece of cake left over from dinner.
20 She'll only be gone a few minutes.

21

	Response
9	
10	
4	
2	
7	
4	
8	
6	
6	
3	
3	
5	
3	
8	
2	
3	
5	
3	
7	
5	
100	

C!D Everyday Sentences

Name: Date: Interval:

Lists G & I (Track 6)

1 I'll see you right after lunch.
2 The show's over.
3 The morning paper didn't say anything about rain this afternoon or tonight.
4 Whi'-B shoes are awful to keep clean.
5 Why don't they paint their walls some other colour?
6 How come I should always be the one to go first?
7 Stand there and don't move until I tell you!
8 Wait for me at the corner in front of the chemist.
9 Wait just a minute!
10 What are you hiding under your coat?
11 You'll get fat eating sweets.
12 It's no trouble at all;
13 I like those big rpd apples we always get in autumn.
14 Thereji a bicL£ieoe of cake left over from dinner. ________________, .
15 Hurray up!
16 See you later
17 What's new?
18 Where can I find a place to park?
19 The phone call's for you.
20 H take sugar and cream in my coffee.

	Response
5	
2	
9	
5	
7	
7	
7	
6	
3	
5	
4	
4	
9	
7	
2	
3	
2	
6	
3	
4	
100	

Lists J & H (Track 7)

1 I don't think I'll have any dessert.,
2 She'll only be gone a few minutes.
3 I don't know what's wrong with the car but it won't start.
4 I'd like some icecream with my pie.
5 Breakfast is ready."
6 I hate driving at night.
7 I haven't read a newspaper since we bought a television set.
8 Let's get a cup of coffee.
9 How are you?
10 Let's get out of here before it's too late.
11 Gail me a little later.
12 If we don't get rain soon we'll have no grass.
13 It sure takes a sharp knife to cut this meat.
14 Believe me.
15 There was water in the cellar after that heavy rain yesterday.
16 Weeds are spoiling the yard.
17 How do you know?
18 They're not listed in the new phone book.
19 Do you have change for a ten rand note?
20 Children like sweets.

21

	Response
5	
5	
7	
6	
2	
3	
7	
4	
2	
7	
4	
10	
7	
2	
8	
4	
3	
6	
6	
3	
1E+06	

CiD Everyday Sentences

Name: Date: Interval:

Lists A, B & J (Track 8)

1 Where are you going?
2 Weeds are spoiling the garden.
3 Should we let little children go to the movies by themselves?
4 Breakfast is ready.
5 Here are you shoes.
6 There isn't enough paint to finish the rcorn.
7 Call me a little later.
8 It's raining.
9 Do you have change for a ten rand note?
10 Come here when I call you.
11 The water's too cold for swimming.
12 I don't know what's wrong with the car but it won't start.
13 How are you?
.". -14 It sure takes a sharp knife to cyt_thj£;nea_l..
15 I don't think I'll have any dessert.
16 I haven't read a newspaper since we've bought a television set.
17 Don't try to get out of it this time.
18 I'd like some icecream with my pie.
19 Do you want an egg for breakfast?
20 Why should I get up so early in the morning?

21

	Response
3	
4	
8	
2	
3	
6	
4	
2	
6	
5	
4	
7	
2	
7 '	i
5	
7	
8	
6	
4	
7	
100	

Lists B & I (Track 9)

1 Where can I find *a place* to park?
2 Do you want an egg for breakfast?
3 Here are your shoes.
4 Should we let little children go to the movies by themselves?
5 Wait just a minute.
6 What are you hiding under your coat?
7 The show's over.
8 Why don't they paint their walls some other colour?
9 The water's too cold for swimming.
10 It's raining.
11 Where are you going?
12 Don't try to get out of it this time.
13 There isn't enough paint to finish the room.
14 Come here when I call you.
15 How come I should always be the one to go first?
16 £[{ take sugar and cream in my coffee.
17 What's new?
18 Why should I get up so early in the morning?
19 You'll get fat eating sweets.
20 I like those big red apples we always get in the autumn.

21

	Response
6	
4	
3	
8	
3	
5	
2	
7	
4	
2	
3	
8	
6	
5	
7	
4	
2	
7	
4	
9	
100	

TYGERBERG HOSPITAAL

CID SINNE AFRIKAANSE VERTALING

NAAM:	DATUM:
PRE INPLANT	dB(KDP):
MND. EVALUASIE	TOTAAL: /50

LYS A

Ek gaan stap graag- vir oefening. Hier's 'n lekker stil plekkie om te rus.

		Wrde	Resp
1.		(5)	( )
2.	Die skoonmaker vee elke daq die vloere.	(5)	( )
3.	Dit sal veel makliker wees as almal wil help	(4)	( )
4.	Goeie more.	(7)	( )
5.	Maak lou venster oop voor iy craan slaap.	(2)	( )
6.	Dink "iv sy moet so laat buite speel?	(6)	( )
7.	Dink jy ons behoort die tyd wat ons beain	(7)	( )
8.	werk te verander?	(9)	( )
9.	Hier craan ons.	(3)	( )
10.	Gee pad.	(2)	( )
	TOTAAL	(50)	( )

[TBH 3]

TYGERBERG HOSPITAAL CID

SINNE AFRIKAANSE VERTALING

NAAM: ____________________________ DATUM:

PRE IMPLANT dB (KDP)

MND. EVALUASIE TOTAAL __________ /50

LYS ..B

1. Die water is te koud om in te swem (5) ( )
2. Waarom moet ek so vroeg .in die more opstaan? (7) ( )
3. Hier is iou skoene. (3) ( )
4. Pit reSn. (2) ( )
5. Waarheen gaan 1y? (3) ( )
6. Kom hier as ek jou roepl (3) ( )
7. Moenie wear probeer om daarmee wecr te kom nie! (6) ( )
8. Behoort ons klein kindertiies alleen te laat gaan fliek? (9) ( )
9. Daar's nie genoeg verf om die kamer klaar te maak nie. (8) ( )
10. Wil jy 'n eier he vir ontbyt. (4) ( )

TOTAAL (50) ( )

[TBH 4]

TYGERBERG HOSPITAAL CID SINNE

AFRIKAANSE VERTALING

NAAM: ____________________________ DATUM:

PRE INPLANT dB (KDP) __

MND. EVALUASIE TOTAAL ____________ /50

LYS C

1. 'n Mens behoort na elke raaaltyd jou tande te borsel. (7) ( )
2. Alles is in die haak. (3) ( )
3. Moenie al die papier, gebruik wanneer jy jou brief skryf nie. (7) ( )
4. Pis reg. (2) ( )
5. ' n Mens behoort een maal per j.aar ' n dokter te besoek. (7) ( )

6 Daardie vensters is so vuil dat ek niks buite kan sien nie. (7) ( )

7. Gee asseblief die brood en hotter aan! (4) ( )
8. Moenie vergeet om jou rekening voor die eerste van die maand te betaal nie. (7) ( )
9. Moenie die hond laat uitgaan nie (3) ( )
10. Daar's 'n rugby-wedstryd vanmiddag. (3) ( )

( )

TOTAAL (50)

[TBH 5]

TYGERBERG HQSPITAAL CID

SINNE AFRIKAANSE VERTALING

NAAM:____________________________ DATUM:

PRE INPLANT dB (KDP)

MND. EVALUASIE TOTAAL __________ /50

LYS D

1. Dis tyd oia te gaan (3) ( )

2. As jy. nie hierdie tydskrifte wil he nie,
moet jy hulle weggooi. ____________________ (7) ( )

3- Wil jy jou hande was? ____________________ (3) ( )

4. Dis recrtig donker vanaand, ry dus versigtig. (5) ( )

5. Ek sal die pakkie vir jou dra. ____________________ (5) ( )

6. Het jj£ vergeet om die kraan toe te draai? (5) ( )

7. Visvang- in 'n bergs-broom is my idee van
plesier. (6) ( )

8. Vaders spandeer nou meer tyd met hulle kinders
as in die verlede> ____________________ (8) ( )

9. Wees versigtig om nie jou bril te breek nie. (6) ( )

10. Ek's jammer. ____________________ (2) ( )

TOTAAAL (50) ( )

[TBH 6]

TYGERBERG HOSPITAA] CID

SINNE AFRIKAANSE VERTALING

DATUM:

NAAM:

dB (KDP)

PRE INPLANT

TOTAAL /50

MND. EVALUASIE

1. en us oorKant die st^aatjiaal- [SI
die bus

Ek kry jou later. ɩar die 2. [5]

Ek sal daaroor dink. 3. [4] [1

4.

5 i>L^i^ie-Vanaand_^a$_m$_m^ **nie.**

As -ioutand so seer is, behoort jy 'n tandarts [6] [']

TOTAAL

te gaan spreek.

7. Sit die koekie terug in die blik. [9] C 3

8. Hou op om gek te skeer. [51 L 1

9. Die tyd is verstreke. [4] C]

10. jy jou_naam? [3] [1

[4] [1

[50] [1

[TBH7]

TYGERBERG HOSPITAAL

CID SINNE AFRIKAANSE VERTALING

NAAM: DATUM:

PRE IMPLANT dB (KDP)

MND. EVALUASIE TOTAAL ______ /50

LYS G

1. Ek sien iou net na middagete. [5] [ ]
2. Sien Iou later.. [3] [ ]
3. Wit skoene is bale rooeilik om skoon te hou. [6] [ ]
4. Staan daar en moenie beweeg voordat ek so se nie. [7] [ ]
5. Daar's 'n groot stuk koek oor na die ete. [7] [ ]
6. Wag vir ray op die hoek voor die apteek. [7] [ ]
7. Pis geen moeite nie. [3] [ ]
8. Maak gou. [2] [ ]
9. Die oggendkoerant net nie. re§n vir vanmiddag of vanaand voorspel nie. [7] [ ]
10. Die telefoon-oproep is vir jou. [3] [ ]

TOTAAL [50] [ ]

[TBH9]

NAAM:

TYGERBERG HOSPITAAL CID

SINNE AFRIKAANSE VERTALING

DATUM:

PRE INPLANT dB (KDP) __

MND. EVALUASIE TOTAAL ___

Y50

1. Glo my. [2] [1
2. Kom ons drink 'n koppie koffie. [5] [1
3. Ons moet hier uitkom voordat dit te laat is. [5] [ ]
4. Ek hou nie daarvan om in die nag te bestuur [6] [1

nie

die telder na

5. Daj3jrLJwa^_-WS-!=i^=- [7] [1 r 1

in Daarminute_weg_JZees.

6 SY_sai net Hasi [6]

[

[J

•"» T

> 3] L J

7 Hoe wei3tL i£? [3] [1

^^H^r-c: hou van iekkers n.

Q K1 nClGJ-^^* i-f-^1-*- ——

cai daar vaniaar 3e^

AS dit nie igou ireiin me sal da.

y ^\t3 vt-i» «*• ~~A "*•~~ [8] [1

oes__wees nie.

[-1

ip in die telefoongids nie.

TT,Ti Q no-mmer is nie in ^j-1^ js ---- [5]]

3_0. Hulie noiiuuti-i- — ±^2 ---- [50] [

TOTAAL

[TBH 10]

TYGERBERG HOSPITAAL

CID SINNE AFRIKAANSE VERTALING

DATUM: ____________

NAAM: ________________________

________ PRE INPLANT

dB (KDP) __________

TOTAAL __________/50

________ MND. EVALUASIE

sny.

Ek lees nooit meer koerant vandat ons 'n televisiestel gekoop het nie.

Onkruid maak die agterplaas onooglik.

Bel my 'n bietjie later.

Het jy kleingeld vir vyf rand?

Hoe gaan dit?

Ek sal hou van room by my appeltert.

Ek dink nie ek sal nagereg neem nie.

TOTAA

DATUM:

NAAM:

PRE INPLANT dB (KDP)

EVALUASir, TOTAAL _/50

_

[3] [1

1 «n

groot rooi appels wat ons altyd

2

[9] [1

Jy sal vet word

[1

Die vergadering is verby.

e

Waarom verf hulle nie

C]

Waar_J«n

34 E K ^^ die leKKers^t

in die

herfs_JcrY

[3]

Wat is die nuus?

7. Wat_steek jy onder jou

3. ias_weg?

Waarom meet

9·

e)c_altYd_^erste_^aan?

10

TOTAAL [50]

Ek neem suiker en melk

Wagi_net 'n oombUk.

rTBHJLU.

APPENDIX I

Adapted Audiogram: Bilateral Processing Benefit

Universiteit van Pretoria / University of Pretoria
Kommunikasiepatologie / Communication Pathology

Deelnemer kode nr		**Datum**	
Participant code nr:		**Date:**	
GEB		**Oudioloog**	
DOB:		**Audiologist:**	
Oor 1e geïnplanteer	**R**	**L**	
Ear 1st implanted:	**R**	**L**	

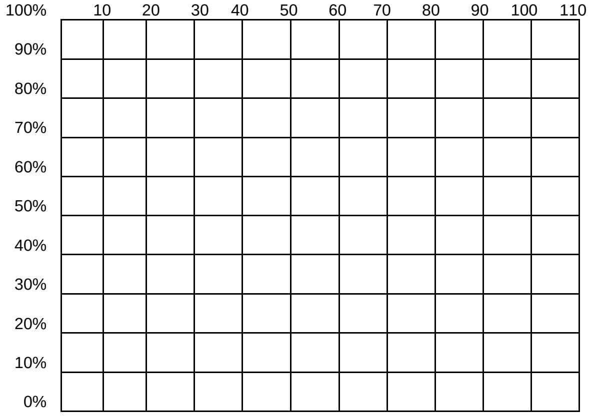
Bilateral Processing Benefit

1. Sound localization (horizontal plane)

Stimuli **Speech weighted noise (SWN)**	**% Correctly localized** **(10 SWN presentations)**
First cochlear implant switched on	
Second cochlear implant switched on	
Both cochlear implants switched on	

2. Aided speech perception in spatially separated speech and noise

a. Noise directed to the participant's CI 1

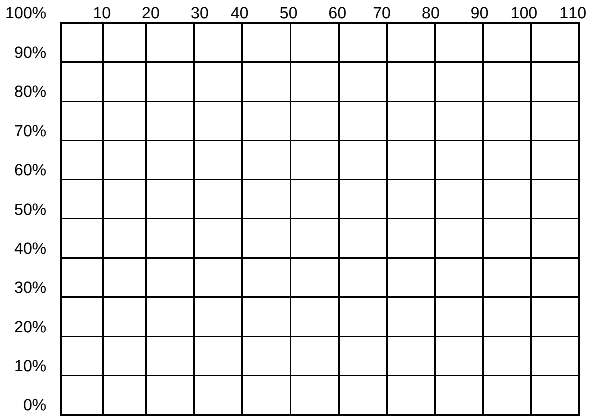


	CI 1	**CI 2**	**Bilateral**
SNR value			
Disc %			

CI 1 = First cochlear implant
CI 2 = Second cochlear implant

2. Aided speech perception in spatially separated speech and noise

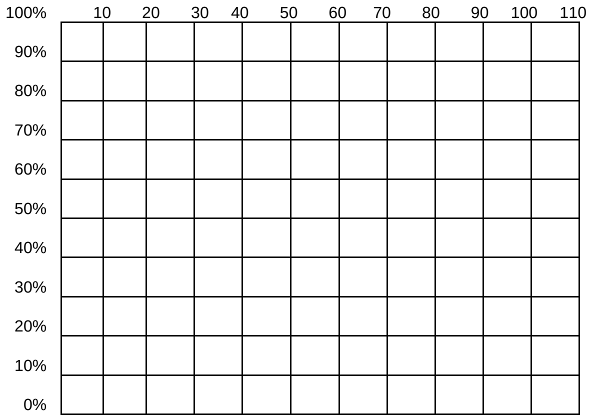
b. Noise directed to the participant's CI 2



	CI 1	**CI 2**	**Bilateral**
SNR value			
Disc %			

CI 1 = First cochlear implant
CI 2 = Second cochlear implant

3. Aided speech perception in spatially coincident speech and noise



	CI 1	**CI 2**	**Binaural**
SNR value			
Disc %			

CI 1 = First cochlear implant
CI 2 = Second cochlear impant

Opmerkings / Remarks:

Appendix J

Instructions to participants and audiometer settings for tests of sound localisation and speech perception in noise

Instructions to Participants for the Procedures for Evaluating the Bilateral Processing Benefit

1. Sound localisation

Instructions to participant:

- For this test you will put your head against the headrest. This is to ensure that you keep your head still during the test.
- Face the centre Loudspeaker, numbered 2, with your head against the headrest.
- Loudspeaker 1 is on your left hand side and Loudspeaker 3 is situated on your right.
- You will hear short bursts of sound coming through anyone of the three Loudspeakers.
- Call out the number of the Loudspeaker through which you think the sound came.
- You will now hear a burst of sound coming through all three Loudspeakers to familiarize you with the setup, starting at Loudspeaker 1 and continuing to the right to Loudspeaker 3.
- Three trials will be done, first with only your first cochlear implant switched on, then with only the second implant switched on and finally with both your implants switched on simultaneously.

2. Bilateral speech perception in spatially separated speech and noise

a. *Instructions to participant to determine the speech perception in noise abilities where the noise is directed to the participant's right ear:*

- You will face the centre Loudspeaker, numbered 2.
- Ten sentences will be presented from Loudspeaker 2 and a noise will be presented from Loudspeaker 3 at the same time.
- Please repeat each sentence to the best you can. If you are not sure of a word, you may guess.
- Please select the map you prefer to listen to speech in a noisy environment.

- Three trials will be done, first with only your first cochlear implant switched on, then with only the second implant switched on and finally with both your implants switched on simultaneously.

b. Instructions to participant to determine the speech perception in noise abilities where the noise is directed to the participant's left ear:

- You will face the Loudspeaker number 3.
- Ten sentences will be presented from Loudspeaker 3 and a noise will be presented from Loudspeaker 2 at the same time.
- Please repeat each sentence to the best you can. If you are not sure of a word, you may guess.
- Please select the map you prefer to listen to speech in a noisy environment.
- Three trials will be done, first with only your first cochlear implant switched on, then with only the second implant switched on and finally with both your implants switched on simultaneously.

3. Bilateral speech perception in spatially coincident speech and noise

Instructions to participant:

- You will face the centre Loudspeaker, numbered 2.
- Ten sentences will be presented from Loudspeaker 2 and at the same time noise will also be presented from Loudspeaker 2. Thus, the sentences and the noise will come from the same loudspeaker.
- Please repeat each sentence to the best you can. If you are not sure of a word, you may guess.
- Please select the map you prefer to listen to speech in a noisy environment.
- Three trials will be done, first with only your first cochlear implant switched on, then with only the second implant switched on and finally with both your implants switched on simultaneously.

Audiometer and Toggle Switch Settings for the Procedures for Evaluating the Bilateral Processing Benefit

1. SOUND LOCALISATION

The order in which the stimuli, speech-weighted noise (SWN), are presented in a randomised order across the loudspeakers. The order for the randomisation was calculated according to a statistic standarised random number table (The Rand Corporation, 1955).

Audiometer settings – NB: Set channel 2 first

	Channel 1	**Channel 2**
Stimulus	Speech-noise	Microphone
Transducer	Speaker	Speaker
Intensity	70 dB HL	0 dB HL

Routing and toggle switch settings

To select speaker number:	**Routing on channel 1**	**Toggle switch setting**
1	Left	Left
2	Left	Centre
3	Right	Centre

2. BILATERAL SPEECH PERCEPTION IN NOISE

The testing is conducted with initially only the first cochlear implant switched on (CI 1), then with only the second implant switched on (CI 2) and finally with both implants switched on simultaneously (BiCI) in the spatially separated speech and noise conditions (with noise first from the right (NR) and then with noise from the left (NL)) as well as in the spatially coincident speech and noise conditions. Thus, there are 9 possible listening configurations.

Firstly, a calibration tone, as stored and selected through the ipod and connected to the audiometer, is played. Concurrently, the *External A* knob on the audiometer is turned until the VU meter on Channel 1 of the audiometer is set on 0. This is done at an intensity level of 70 dB HL.

2.1 Bilateral speech perception in spatially separated speech and noise

a. *Settings to determine the speech perception in noise abilities where the noise is directed to the participant's right ear:*

The participant will face Loudspeaker 2, situated in the centre. The speech signal will presented from Loudspeaker 2 and the noise signal from Loudspeaker 3.

Audiometer settings

	Channel 1	**Channel 2**
Stimulus	External A	Speech noise
Transducer	Speaker	Speaker
Routing	Left	Right
Starting Intensity	55 dB HL	55 dB HL

Toggle switch setting

Centre

b. *Settings to determine the speech perception in noise abilities where the noise is directed to the participant's left ear:*

The participant will face Loudspeaker 3, situated on the right. The speech signal will presented from Loudspeaker 3 and the noise signal from Loudspeaker 2.

Audiometer settings

	Channel 1	**Channel 2**
Stimulus	External A	Speech noise
Transducer	Speaker	Speaker
Routing	Right	Left
Starting Intensity	55 dB HL	55 dB HL

Toggle switch setting

Centre

2.2 Bilateral speech perception in spatially coincident speech and noise

The participant will face Loudspeaker 2, situated in the centre. The speech and noise signals will presented from Loudspeaker 2 simultaneously.

Audiometer settings

	Channel 1	**Channel 2**
Stimulus	External A	Speech noise
Transducer	Speaker	Speaker
Routing	Left	Left
Starting Intensity	55 dB HL	55 dB HL

Toggle switch setting

Centre

APPENDIX K

Lists of randomised presentation orders for the sound localisation test

SOUND LOCALIZATION SCORE SHEET

Participant number: 1

CI 1 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	L		
3	L		
4	L		
5	R		
6	R		
7	L		
8	L		
9	R		
10	R		

Percentage correct: ________________

CI 2 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	R		
2	R		
3	R		
4	L		
5	C		
6	L		
7	C		
8	C		
9	C		
10	C		

Percentage correct: ________________

Both CI switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	R		
3	L		
4	L		
5	C		
6	C		
7	R		
8	C		
9	L		
10	L		

Percentage correct: ________________

Keys:
L: ***Left*** loudspeaker, numbered as ***1*** to participant
C: ***Centre*** loudspeaker, numbered as ***2*** to participant
R: ***Right*** loudspeaker, numbered as ***3*** to participant

SOUND LOCALIZATION SCORE SHEET

Participant number: 2

CI 1 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	L		
3	C		
4	L		
5	C		
6	R		
7	C		
8	C		
9	C		
10	L		

Percentage correct: ________________

CI 2 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	R		
3	C		
4	R		
5	R		
6	C		
7	C		
8	C		
9	L		
10	C		

Percentage correct: ________________

Both CI switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	R		
3	R		
4	C		
5	L		
6	C		
7	L		
8	R		
9	C		
10	C		

Percentage correct: ________________

Keys:
L: ***Left*** loudspeaker, numbered as ***1*** to participant
C: ***Centre*** loudspeaker, numbered as ***2*** to participant
R: ***Right*** loudspeaker, numbered as ***3*** to participant

SOUND LOCALIZATION SCORE SHEET

Participant number: 3

CI 1 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	R		
2	R		
3	L		
4	L		
5	R		
6	R		
7	R		
8	R		
9	C		
10	C		

Percentage correct: ________________

CI 2 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	L		
3	L		
4	C		
5	C		
6	R		
7	L		
8	L		
9	C		
10	C		

Percentage correct: ________________

Both CI switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	C		
2	C		
3	R		
4	R		
5	R		
6	R		
7	L		
8	R		
9	L		
10	C		

Percentage correct: ________________

Keys:
L: ***Left*** loudspeaker, numbered as ***1*** to participant
C: ***Centre*** loudspeaker, numbered as ***2*** to participant
R: ***Right*** loudspeaker, numbered as ***3*** to participant

SOUND LOCALIZATION SCORE SHEET

Participant number: 4

CI 1 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	R		
3	L		
4	C		
5	C		
6	C		
7	L		
8	R		
9	C		
10	C		

Percentage correct: _______________

CI 2 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	C		
2	C		
3	L		
4	R		
5	L		
6	L		
7	L		
8	L		
9	L		
10	L		

Percentage correct: _______________

Both CI switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	C		
2	L		
3	C		
4	R		
5	R		
6	R		
7	L		
8	C		
9	L		
10	C		

Percentage correct: _______________

Keys:
L: ***Left*** loudspeaker, numbered as ***1*** to participant
C: ***Centre*** loudspeaker, numbered as ***2*** to participant
R: ***Right*** loudspeaker, numbered as ***3*** to participant

SOUND LOCALIZATION SCORE SHEET

Participant number: 5

CI 1 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	C		
2	R		
3	R		
4	C		
5	C		
6	R		
7	L		
8	L		
9	L		
10	C		

Percentage correct: ________________

CI 2 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	L		
3	C		
4	C		
5	C		
6	L		
7	C		
8	R		
9	R		
10	R		

Percentage correct: ________________

Both CI switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	C		
2	L		
3	C		
4	L		
5	R		
6	C		
7	C		
8	C		
9	L		
10	L		

Percentage correct: ________________

Keys:
L: ***Left*** loudspeaker, numbered as ***1*** to participant
C: ***Centre*** loudspeaker, numbered as ***2*** to participant
R: ***Right*** loudspeaker, numbered as ***3*** to participant

SOUND LOCALIZATION SCORE SHEET

Participant number: 6

CI 1 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	C		
2	R		
3	C		
4	R		
5	R		
6	L		
7	C		
8	L		
9	R		
10	R		

Percentage correct: _______________

CI 2 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	C		
2	L		
3	R		
4	R		
5	R		
6	R		
7	R		
8	L		
9	C		
10	R		

Percentage correct: _______________

Both CI switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	L		
3	C		
4	R		
5	C		
6	C		
7	R		
8	C		
9	L		
10	C		

Percentage correct: _______________

Keys:
L: ***Left*** loudspeaker, numbered as ***1*** to participant
C: ***Centre*** loudspeaker, numbered as ***2*** to participant
R: ***Right*** loudspeaker, numbered as ***3*** to participant

SOUND LOCALIZATION SCORE SHEET

Participant number: 7

CI 1 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	R		
2	L		
3	L		
4	L		
5	R		
6	C		
7	C		
8	L		
9	C		
10	L		

Percentage correct: ________________

CI 2 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	C		
3	R		
4	L		
5	C		
6	L		
7	R		
8	C		
9	C		
10	C		

Percentage correct: ________________

Both CI switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	R		
2	R		
3	L		
4	L		
5	R		
6	L		
7	C		
8	L		
9	C		
10	R		

Percentage correct: ________________

Keys:
L: ***Left*** loudspeaker, numbered as ***1*** to participant
C: ***Centre*** loudspeaker, numbered as ***2*** to participant
R: ***Right*** loudspeaker, numbered as ***3*** to participant

SOUND LOCALIZATION SCORE SHEET

Participant number: 8

CI 1 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	C		
3	C		
4	L		
5	R		
6	L		
7	C		
8	C		
9	C		
10	R		

Percentage correct: ________________

CI 2 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	R		
2	R		
3	L		
4	C		
5	L		
6	L		
7	L		
8	R		
9	R		
10	R		

Percentage correct: ________________

Both CI switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	C		
2	R		
3	C		
4	C		
5	C		
6	L		
7	C		
8	L		
9	C		
10	L		

Percentage correct: ________________

Keys:
L: ***Left*** loudspeaker, numbered as ***1*** to participant
C: ***Centre*** loudspeaker, numbered as ***2*** to participant
R: ***Right*** loudspeaker, numbered as ***3*** to participant

SOUND LOCALIZATION SCORE SHEET

Participant number: 9

CI 1 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	R		
2	L		
3	R		
4	R		
5	R		
6	C		
7	L		
8	R		
9	C		
10	C		

Percentage correct: ________________

CI 2 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	C		
2	R		
3	C		
4	R		
5	C		
6	C		
7	R		
8	R		
9	R		
10	C		

Percentage correct: ________________

Both CI switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	C		
2	C		
3	L		
4	L		
5	L		
6	L		
7	C		
8	R		
9	R		
10	C		

Percentage correct: ________________

Keys:
L: ***Left*** loudspeaker, numbered as ***1*** to participant
C: ***Centre*** loudspeaker, numbered as ***2*** to participant
R: ***Right*** loudspeaker, numbered as ***3*** to participant

SOUND LOCALIZATION SCORE SHEET

Participant number: 10

CI 1 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	R		
2	R		
3	R		
4	L		
5	C		
6	R		
7	C		
8	C		
9	L		
10	C		

Percentage correct: ________________

CI 2 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	C		
3	R		
4	L		
5	L		
6	C		
7	R		
8	C		
9	R		
10	L		

Percentage correct: ________________

Both CI switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	R		
2	L		
3	C		
4	R		
5	L		
6	C		
7	C		
8	L		
9	L		
10	L		

Percentage correct: ________________

Keys:
L: ***Left*** loudspeaker, numbered as ***1*** to participant
C: ***Centre*** loudspeaker, numbered as ***2*** to participant
R: ***Right*** loudspeaker, numbered as ***3*** to participant

SOUND LOCALIZATION SCORE SHEET

Participant number: 11

CI 1 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	C		
3	C		
4	C		
5	L		
6	C		
7	L		
8	R		
9	R		
10	R		

Percentage correct: _______________

CI 2 switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	R		
2	C		
3	R		
4	R		
5	R		
6	L		
7	R		
8	L		
9	L		
10	C		

Percentage correct: _______________

Both CI switched on

Stimulus number	Target loudspeaker	Identified loudspeaker	Correct: √ Incorrect: x
1	L		
2	C		
3	L		
4	C		
5	L		
6	C		
7	R		
8	L		
9	R		
10	C		

Percentage correct: _______________

Keys:
L: ***Left*** loudspeaker, numbered as ***1*** to participant
C: ***Centre*** loudspeaker, numbered as ***2*** to participant
R: ***Right*** loudspeaker, numbered as ***3*** to participant

APPENDIX L

Data Summary:

Results of sound localisation responses

Sound localization Data sheet: Participant 1

	CI 1 switched on: Right		CI 2 switched on: Left		Both CI switched on	
Presentation	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker
1	L	R	R	L	L	C
2	L	C	R	L	R	R
3	L	C	R	C	L	L
4	L	R	L	L	L	C
5	R	R	C	C	C	C
6	R	R	L	R	C	C
7	L	R	C	L	R	R
8	L	C	C	L	C	L
9	R	R	C	C	L	C
10	R	C	C	C	L	L
TOTAL CORRECT		**3**		**4**		**6**

Sound localization Data sheet: Participant 2

	CI 1 switched on: Left		CI 2 switched on: Right		Both CI switched on	
Presentation	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker
1	L	L	L	R	L	L
2	L	L	R	R	R	C
3	C	L	C	C	R	C
4	L	L	R	R	C	R
5	C	L	R	R	L	L
6	R	L	C	R	C	C
7	C	C	C	R	L	L
8	C	L	C	C	R	R
9	C	C	L	C	C	C
10	L	L	C	R	C	R
TOTAL CORRECT		**6**		**5**		**6**

Sound localization Data sheet: Participant 3

	CI 1 switched on: Right		CI 2 switched on: Left		Both CI switched on	
Presentation	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker
1	R	R	L	L	C	R
2	R	R	L	L	C	C
3	L	R	L	L	R	R
4	L	R	C	L	R	R
5	R	R	C	L	R	R
6	R	R	R	L	R	R
7	R	R	L	L	L	C
8	R	R	L	L	R	R
9	C	R	C	L	L	C
10	C	R	C	L	C	C
TOTAL CORRECT		**6**		**5**		**7**

Sound localization Data sheet: Participant 4

	CI 1 switched on: Right		CI 2 switched on: Left		Both CI switched on	
Presentation	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker
1	L	R	C	L	C	R
2	R	R	C	L	L	L
3	L	C	L	C	C	L
4	C	R	R	L	R	L
5	C	R	L	L	R	C
6	C	R	L	L	R	R
7	L	R	L	L	L	L
8	R	R	L	L	C	C
9	C	C	L	L	L	L
10	C	R	L	L	C	C
TOTAL CORRECT		**3**		**6**		**6**

Sound localization Data sheet: Participant 5

	CI 1 switched on: Right		CI 2 switched on: Left		Both CI switched on	
Presentation	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker
1	C	C	L	L	C	R
2	R	R	L	L	L	C
3	R	R	C	L	C	C
4	C	R	C	L	L	L
5	C	R	C	L	R	C
6	R	R	L	L	C	L
7	L	R	C	L	C	L
8	L	R	R	L	C	L
9	L	R	R	L	L	L
10	C	R	R	L	L	L
TOTAL CORRECT		**4**		**3**		**4**

Sound localization Data sheet: Participant 6

	CI 1 switched on: Right		CI 2 switched on: Left		Both CI switched on	
Presentation	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker
1	C	R	C	L	L	L
2	R	R	L	L	L	C
3	C	R	R	C	C	L
4	R	L	R	L	R	R
5	R	C	R	R	C	C
6	L	R	R	C	C	C
7	C	C	R	C	R	R
8	L	L	L	L	C	L
9	R	R	C	R	L	C
10	R	R	R	L	C	C
TOTAL CORRECT		**5**		**3**		**6**

Sound localization Data sheet: Participant 7

	CI 1 switched on: Left		CI 2 switched on: Right		Both CI switched on	
Presentation	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker
1	R	C	L	R	R	R
2	L	L	C	C	R	C
3	L	L	R	R	L	L
4	L	C	L	L	L	C
5	R	C	C	C	R	R
6	C	R	L	R	L	L
7	C	C	R	C	C	L
8	L	L	C	L	L	L
9	C	C	C	R	C	C
10	L	C	C	C	R	R
TOTAL CORRECT		**5**		**5**		**7**

Sound localization Data sheet: Participant 8

	CI 1 switched on: Right		CI 2 switched on: Left		Both CI switched on	
Presentation	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker
1	L	R	R	L	C	R
2	C	R	R	L	R	R
3	C	R	L	L	C	C
4	L	C	C	C	C	R
5	R	R	L	L	C	R
6	L	R	L	L	L	C
7	C	C	L	L	C	C
8	C	R	R	L	L	L
9	C	R	R	L	C	R
10	R	C	R	L	L	L
TOTAL CORRECT		**2**		**5**		**5**

Sound localization Data sheet: Participant 9

	CI 1 switched on: Left		**CI 2 switched on: Right**		**Both CI switched on**	
Presentation	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker
1	R	L	C	R	C	L
2	L	L	R	R	C	L
3	R	L	C	R	L	C
4	R	L	R	C	L	L
5	R	L	C	R	L	L
6	C	C	C	C	L	L
7	L	L	R	C	C	C
8	R	L	R	R	R	R
9	C	L	R	C	R	R
10	C	L	C	R	C	C
TOTAL CORRECT		**3**		**3**		**7**

Sound localization Data sheet: Participant 10

	CI 1 switched on: Left		**CI 2 switched on: Right**		**Both CI switched on**	
Presentation	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker
1	R	L	L	R	R	R
2	R	L	C	R	L	L
3	R	L	R	C	C	C
4	L	C	L	L	R	R
5	C	L	L	L	L	L
6	R	C	C	R	C	C
7	C	L	R	C	C	C
8	C	C	C	R	L	L
9	L	L	R	L	L	L
10	C	C	L	C	L	L
TOTAL CORRECT		**3**		**2**		**10**

Sound localization Data sheet: Participant 11

	CI 1 switched on: Left		**CI 2 switched on: Right**		**Both CI switched on**	
Presentation	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker	Target loudspeaker	Identified louspeaker
1	L	L	R	R	L	L
2	C	L	C	R	C	L
3	C	C	R	R	L	C
4	C	L	R	R	C	L
5	L	C	R	C	L	L
6	C	L	L	L	C	C
7	L	R	R	L	R	R
8	R	L	L	L	L	R
9	R	C	L	R	R	C
10	R	R	C	R	C	C
TOTAL CORRECT		**3**		**5**		**5**

APPENDIX M

Data Summary:

Bilateral spatial benefits calculations

HEADSHADOW 90° LEFT EAR (difference in SRT left ear in NF vs NR)

Participant	NF	NR	Effect
1:L = CI 2	18 dB	17 dB	1dB
2: L = CI 1	23 dB	28.67 dB	(-5.67 dB)
3: L = CI 2	9.67 dB	9.67 dB	0 dB
4:L = CI 2	20 dB	13 dB	7 dB
5:L = CI 2	22.67dB	23 dB	(-0,33 dB)
6:L = CI 2	22 dB	26 dB	(-4 dB)
7:L = CI 1	18.33 dB	9 dB	9 dB
8:L = CI 2	20 dB	9 dB	11 dB
9:L = CI 1	22.33dB	27.33 dB	(-5 dB)
10:L = CI 1	18.33 dB	13 dB	5 dB
11:L = CI 1	23 dB	29 dB	(-6 dB)

HEADSHADOW 90° CI 1 (Accepted values: ≥ 3 dB)

Participant	Effect
1	0 dB
2	(-6 dB)
3	(-3 dB)
4	(-5 dB)
5	**4 dB**
6	**4 dB**
7	**9 dB**
8	0 dB
9	(-5 dB)
10	**5 dB**
11	(-6 dB)
Median	0 dB

HEADSHADOW 90° RIGHT EAR (difference in SRT right ear in NF vs NL)

Participant	NF	NL	Effect
1:R = CI 1	20 dB	20.33 dB	(-0.33 dB)
2:R = CI 2	22.33 dB	28.67 dB	(-6.34 dB)
3:R = CI 1	18.67 dB	21.67 dB	(-3 dB)
4:R = CI 1	23 dB	28.33 dB	(-5 dB)
5:R = CI1	22 dB	17.67 dB	4 dB
6:R = CI 1	22.67 dB	18.33 dB	4 dB
7:R = CI 2	22.67 dB	20.33 dB	2 dB
8:R = CI 1	20.67 dB	20.33 dB	0.34 dB
9:R = CI 2	21.67 dB	23.67 dB	(-2 dB)
10:R = CI 2	16.33 dB	19 dB	(-3 dB)
11: R = CI 2	20.33 dB	25.67 dB	(-5.34 dB)

HEADSHADOW 90° CI 2 (Accepted values: ≥ 3 dB)

Participant	Effect
1	1 dB
2	(-6 dB)
3	0 dB
4	**7 dB**
5	0 dB
6	(-4 dB)
7	2 dB
8	**11 dB**
9	(-2 dB)
10	(-3 dB)
11	(-5 dB)
Median	0 dB

HEADSHADOW 180° LEFT EAR (difference in SRT in NL vs NR)

Participant	NL	NR	Effect
1:L = CI 2	27.67 dB	17 dB	10.67 dB
2:L = CI 1	29 dB	28 dB	1 dB
3: L = CI 2	17 dB	9.67 dB	7 dB
4:L = CI 2	20.33 dB	13 dB	7 dB
5:L = CI 2	24.67 dB	23 dB	2 dB
6:L = CI 2	27.67 dB	26 dB	2 dB
7:L = CI 1	19 dB	9 dB	10 dB
8:L = CI 2	25.67 dB	9 dB	16.67 dB
9:L = CI 1	28.5 dB	27.33 dB	1 dB
10:L = CI 1	19.67 dB	13 dB	7 dB
11:L = CI 1	27.33 dB	29 dB	(-1.67 dB)

HEADSHADOW 180° CI 1 (Accepted values: ≥ 3 dB)

Participant	Effect
1	**4 dB**
2	1 dB
3	**5 dB**
4	1 dB
5	**11 dB**
6	**9 dB**
7	**10 dB**
8	1 dB
9	1 dB
10	**7 dB**
11	(-2 dB)
Median	**4 dB**

HEADSHADOW 180° RIGHT EAR (difference in SRT in NR vs NL)

Participant	NR	NL	Effect
1:R = CI 1	24.67 dB	20.33 dB	4.34 dB
2:R = CI 2	28 dB	28.67 dB	(-0.67 dB)
3: R = CI 1	26.67 dB	21.67 dB	5 dB
4: R = CI 1	29 dB	28.33 dB	1 dB
5:R = CI 1	28.67 dB	17.67 dB	11 dB
6:R = CI 1	27.33 dB	18.33 dB	9 dB
7:R = CI 2	26 dB	20.33 dB	6 dB
8:R = CI 1	21.33 dB	20.33 dB	1 dB
9:R = CI 2	26.67 dB	23.67 dB	3 dB
10:R = CI 2	24 dB	19 dB	5 dB
11: R = CI 2	26.33 dB	25.67 dB	0.66 dB

HEADSHADOW 180° CI 2 (Accepted values: ≥ 3 dB)

Participant	Effect
1	**11 dB**
2	(-1 dB)
3	**7 dB**
4	**7 dB**
5	2 dB
6	2 dB
7	**6 dB**
8	**17 dB**
9	**3 dB**
10	**5 dB**
11	1 dB
Median	**5 dB**

SQUELCH LEFT EAR (difference in SRT for left ear and BiCI in NR)

Participant	Left	BiCI	Effect
1:L = CI 2	17 dB	15 dB	2 dB
2: CI 1 = L	28.67 dB	28.33 dB	0.34 dB
3: CI 2 = L	9.67 dB	3.67 dB	6 dB
4: CI 2 = L	13 dB	14.33 dB	(-0.67 dB)
5: L = CI 2	23 dB	16.33 dB	7 dB
6:CI 2 = L	26 dB	22 dB	4 dB
7:CI 1 = L	9 dB	17.67 dB	(-9 dB)
8:L = CI 2	9 dB	9 dB	0 dB
9:L = CI 1	27.33 dB	17 dB	10 dB
10:L = CI 1	13 dB	9 dB	4 dB
11:L = CI 1	29 dB	23.67 dB	5 dB

SQUELCH RIGHT EAR (difference in SRT for right ear and BiCI in NL)

Participant	Right	BiCI	Effect
1: CI 1 = R	20.33 dB	23 dB	(-2.67 dB)
2: CI 2 = R	28.67 dB	28 dB	0.67 dB
3: CI 1 = R	21.67 dB	16.33 dB	5 dB
4: CI 1 = R	28.33 dB	24.33 dB	4 dB
5:R = CI1	17.67 dB	18.33 dB	(-0.66 dB)
6:CI 1 = R	18.33 dB	22.33 dB	(-4 dB)
7:CI 2 = R	20.33 dB	23 dB	(-3 dB)
8:CI 1 = R	20.33 dB	20.33 dB	0 dB
9:R = CI 2	23.67 dB	23 dB	1 dB
10:R = CI 2	19 dB	14.33 dB	5 dB
11: R = CI 2	25.67 dB	26.5 dB	(-0.83 dB)

SQUELCH CI 1 (Accepted values: Negative up to 2dB)

Participant	Effect
1	(-3 dB)
2	**0 dB**
3	5 dB
4	4 dB
5	**(-1 dB)**
6	**(-4 dB)**
7	**(-9 dB)**
8	**0 dB**
9	10 dB
10	4 dB
11	5 dB
Median	**0 dB**

SQUELCH CI 2 (Accepted values: Negative up to 2 dB)

Participant	Effect
1	**2 dB**
2	**1 dB**
3	6 dB
4	**(-1 dB)**
5	7 dB
6	4 dB
7	**(-3 dB)**
8	**0 dB**
9	**1dB**
10	5 dB
11	**(-1 dB)**
Median	**1 dB**

SUMMATION CI 1 added (CI 2 - BiCI in NF) (Accepted values: Negative up to 6 dB)

Participant	CI 2	BiCI	Effect
1:CI 1 = R	18 dB	17.67 dB	**0 dB**
2: CI 1 = L	22.33 dB	22.67 dB	**0 dB**
3: CI 1 = R	9.67 dB	12.33 dB	**(- 3 dB)**
4:CI 1 = R	20 dB	20.67 dB	**0 dB**
5:CI 1 = R	22.67 dB	18.33 dB	**4 dB**
6:CI 1 = R	22 dB	22.33 dB	**0 dB**
7:CI 1 = L	22.67 dB	20.33 dB	**2 dB**
8:CI 1 = R	20 dB	15 dB	**5 dB**
9:CI 1 = L	21.67 dB	22 dB	**0 db**
10:CI 1 = L	16.33 dB	12.33 dB	**4 dB**
11:CI 1 = L	20.33 dB	22.33 dB	**(-2 dB)**
Median			**0 dB**

SUMMATION C2 added (CI 1 - BiCI in NF) (Accepted values: Negative up to 6 dB)

Participant	CI 1	BiCI	Effect
1: CI 2 =L	20 dB	17.67 dB	**2 dB**
2: CI 2 = R	23 dB	22.67 dB	**0 dB**
3: CI 2 = L	18.67 dB	12.33 dB	**6 dB**
4: CI 2 = L	23 dB	20.67 dB	**2 dB**
5: CI 2 = L	22 dB	18.33 dB	**4 dB**
6:CI 2 = L	22.67 dB	22.33 dB	**0 dB**
7:CI 2 = R	18.33 dB	20.33 dB	**(-2 dB)**
8: CI 2 = L	20.67 dB	15 dB	**6 dB**
9:CI 2 = R	22.33 dB	22 dB	**0 dB**
10:CI 2 = R	18.33 dB	12.33 dB	**6 dB**
11:CI 2 = R	23 dB	22.33 dB	**1 dB**
Median			**2 dB**

SRM for Noise on CI 1 (BiCI NF - BiCI Noise on CI 1) (Accepted values: 0 - 4dB)

Participant	BiCI NF	BiCI Noise on CI 1	Effect
1:CI 1 = R	17.67 dB	15 dB	**3 dB**
2: CI 1 = L	22.67 dB	28 dB	(-5 dB)
3: CI 1 = R	12.33 dB	3.67 dB	9 dB
4:CI 1 = R	20.67 dB	14.33 dB	6 dB
5:CI 1 = R	18.33 dB	16.33 dB	**2 dB**
6:CI 1 = R	22.33 dB	22 dB	**0 dB**
7:CI 1 = L	20.33 dB	23 dB	(-3 dB)
8:CI 1 = R	15 dB	9 dB	6 dB
9: CI 1 = L	22 dB	23 dB	(-1 dB)
10:CI 1 = L	12.33 dB	14.33 dB	(-2 dB)
11:CI 1 = L	22.33 dB	26.5 dB	(-4 dB)
Median			**0 dB**

SRM for Noise on CI 2 (BiCI NF - BiCI Noise on CI 2) (Accepted values: 0 - 4 dB)

Participant	BiCI NF	BiCI Noise on CI 2	Effect
1:CI 2 = L	17.67dB	23 dB	(-5 dB)
2: CI 2 = R	22.67 dB	28.33 dB	(-6 dB)
3: CI 2 = L	12.33 dB	16.33 dB	(-4 dB)
4:CI 2 = L	20.67 dB	24.33 dB	(-4 dB)
5:CI 2 = L	18.33 dB	18.33 dB	**0 dB**
6:CI 2 = L	22.33 dB	22.33 dB	**0 dB**
7:CI 2 = R	20.33 dB	17.67 dB	**3 dB**
8:CI2 = L	15 dB	20.33 dB	(-5 dB)
9:CI 2 = R	22 dB	17 dB	5 dB
10:R = CI 2	12.33 dB	9 dB	**3 dB**
11: CI 2 = R	22.33 dB	23.67 dB	(-1 dB)
Median			(- 1 dB)

BETTER SNR ear added to LEFT EAR (difference between SRT for left ear and BiCI in NL)

Participant	Left CI	BiCI	Effect
1:L = CI 2	27.67 dB	23 dB	4.67 dB
2:L = CI 1	29 dB	28 dB	1 dB
3: L = CI 2	17 dB	16.33 dB	1 dB
4: L = CI 2	20.33 dB	24.33 dB	(-4 dB)
5:L = CI 2	24.67 dB	18.33 dB	6 dB
6:L = CI 2	27.67 dB	22.33 dB	5 dB
7L = CI 1	19 dB	23dB	(-4 dB)
8: L = CI 2	25.67 dB	20.33 dB	5 db
9:L = CI 1	28.5 dB	23 dB	6 dB
10: L = CI 1	19.67 dB	14.33 dB	5 dB
11: L = CI 1	27.33 dB	26.5 dB	1 dB

BETTER SNR added to CI 1

Participant	Effect
1	10 dB
2	1 dB
3	23 dB
4	15 dB
5	12 dB
6	5 dB
7	(-4 dB)
8	12 dB
9	6 dB
10	5 dB
11	1 dB
Average	9 Db

Better SNR ear added to RIGHT EAR (difference between SRT for right ear and BiCI in NR)

Participant	Right CI	BiCI	Effect
1:R = CI 1	24.67 dB	15 dB	9.67 dB
2:R = CI 2	28 dB	28.33 dB	(-0.33 dB)
3:R = CI 1	26.67 dB	3.67 dB	23 dB
4: R = CI 1	29 dB	14.33 dB	15 dB
5:R = CI 1	28.67 dB	16.33 dB	12 dB
6:R = CI 1	27.33 dB	22 dB	5 dB
7:R = CI 2	26 dB	17.67 dB	8 dB
8:R = CI 1	21.33 dB	9 dB	12 dB
9: R = CI 2	26.67 dB	17 dB	10 dB
10:R = CI 2	24 dB	9 dB	15 dB
11:R = CI 2	26.33 dB	23.67 dB	3 dB

BETTER SNR added to CI 2

Participant	Effect
1	5 dB
2	0 dB
3	1 dB
4	(-4 dB)
5	6 dB
6	5 dB
7	8 dB
8	5 dB
9	10 dB
10	15 dB
11	3 dB
Average	5 Db