# A comparison of bilateral cochlear implantation and bimodal aiding in severely-profoundly hearing-impaired adults: head movements, clinical outcomes, and cost-effectiveness

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# Abstract

Under current guidelines in the UK, eligible adults can receive a single cochlear implant through the National Health Service. Should they wish to aid their non-implanted ear they can either use an acoustic hearing aid and have ‘bimodal aiding’ or elect to pay for a second cochlear implant and have ‘bilateral cochlear implants’. The experiments reported in this thesis sought to inform this choice by establishing which option provides the greater benefit. It was found that both options offered listening and self-reported benefits over listening with a single cochlear implant. However a greater clinical benefit was found from bilateral cochlear implantation, with better localisation and speech perception in noise abilities. A series of experiments investigated whether head movements could improve listening performance. It was found that cochlear implant users made more complex head movements than normally hearing listeners. Whilst head movements by bilateral cochlear implant users improved localisation performance by reducing the number of front back confusions made, users of a single cochlear implant were unable to accurately locate sounds when head movements were permitted. Finally experiments demonstrated that current generic health related quality of life instruments are limited in their sensitivity to binaural hearing benefits. These instruments are used to inform the ‘effectiveness’ component in cost-effective analyses. Therefore a new questionnaire sensitive to benefits in binaural hearing was developed and its validity and sensitivity were demonstrated. Using this self-report instrument, bimodal aiding and bilateral cochlear implantation were shown to have the potential to be a cost-effective use of resources resulting in improvements to ‘hearing-related quality of life’ compared to a single cochlear implant.

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# Declaration

This thesis comprises the candidate's own original work and has not, whether in the same or different form, been submitted to this or any other University for a degree. All experiments were designed by the candidate with assistance from the supervisors. As part of an undergraduate project that was co-supervised by the candidate, Rhian Bardsley, Sarah-Louise Buggins, Danielle Dickinson, and Rachel Williamson collected data from normally hearing adults in the study reported in Chapter 8. Leah Glover and Padraig Kitterick assisted with data collection for the studies reported in Chapters 5 and 6. The remaining testing and all analyses were conducted by the candidate.

## Conference presentations

Goman, A.M., Kitterick, P.T. & Summerfield, A.Q. (2014). Cochlear implant users make more complex head movement trajectories than normal hearing listeners when locating sources of sound. Talk presented at the Moving Sounds, Moving Listeners workshop, Glasgow, UK.

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Goman, A.M., Bardsley, R., Buggins, S., Dickinson, D., Williamson, R.J., & Summerfield, A.Q. (2014). Development and validation of a measure of "Hearing-related quality of life" sensitive to binaural hearing in adults. Poster presented at the Association for Research in otolaryngology 37th Annual Midwinter Meeting, San Diego, CA, USA.

Goman, A.M., Kitterick, P.T., & Summerfield, A.Q. (2013). Contribution of head movements to sound localisation in the horizontal plane by normally hearing adults: accuracy and effort. Poster presented at the British Society for Audiology 4th Annual Conference and Experimental and Clinical Papers Short Meeting, Nottingham, UK.

Goman, A.M., Kitterick, P.T. & Summerfield, A.Q. (2012). Binaural advantages from a contralateral hearing aid or a second implant for UK adult cochlear-implant users. Poster presented at the British Society for Audiology 3rd Annual Conference and Experimental and Clinical Papers Short Meeting, Nottingham, UK.

## Overview of thesis

Hearing impairment affects over 300 million people worldwide (World Health Organisation, 2012). In the UK, 16% of adults are estimated to have a hearing loss of at least 25dB HL and 1% have at least a severe (with a hearing loss greater than 65dB) bilateral impairment (Davis, 1989). One option for individuals with a profound loss of hearing is to receive a cochlear implant (CI). Under current guidelines (National Institute of Health and Care Excellence (NICE), 2013), with a few exceptions, adults in the UK may receive one CI from the National Health Service (NHS). Should individuals wish to aid their other ear they have two options: one is to use a contralateral acoustic hearing aid which can be obtained free from the NHS and have 'bimodal aiding'; the other is to pay for a second CI themselves and have 'bilateral CIs'. In this thesis, a second CI, or an acoustic hearing aid, in the ear contralateral to an implant is referred to as a 'second device'.

The purpose of this thesis was to investigate the clinical and cost-effectiveness of a second device for profoundly deafened UK adults. This thesis has addressed this issue from three perspectives (see Figure 0.1). The first (A) is a comparison of bimodal and bilateral CI users on a variety of listening tasks and self-report measures. This comparison is reported in chapters 5 and 6. Performance on listening tasks that benefitted from binaural hearing was investigated further by studying the role of head movements (B). These experiments are reported in chapter 7. Finally chapters 4 and 8 consider the cost-effectiveness (C) of a second device by studying the impact which a second device has on the quality of life of patients.

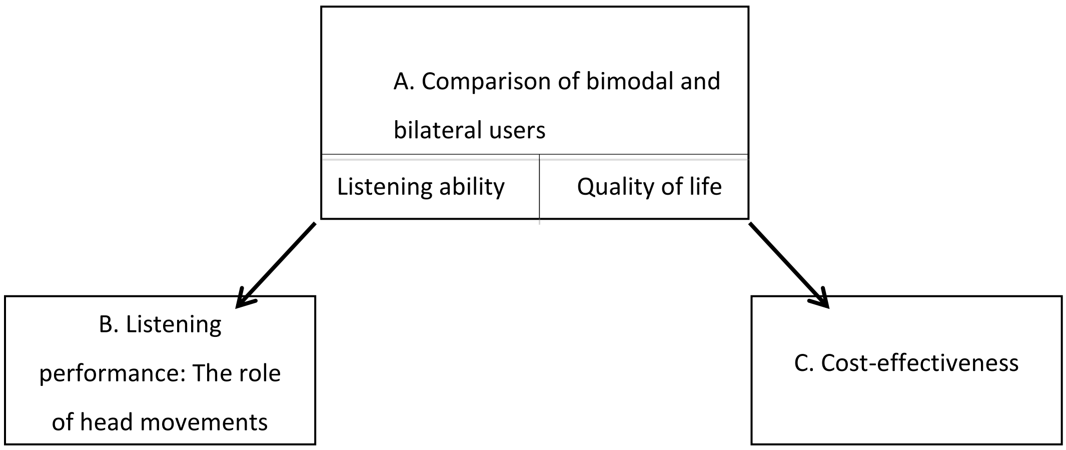


**Figure 0.1. Structure of thesis: The clinical- and cost-effectiveness of a second device was investigated from three perspectives.**

## Chapter 1: Introduction

This chapter describes the auditory pathway and explains how a normally-hearing listener perceives sounds. Next, the prevalence of hearing loss and the impact it can have on an individual's life and society as a whole are discussed. Then, an overview of hearing aids and CIs is provided with evidence of who may benefit from a hearing aid and what the candidacy requirements to receive a CI are. This chapter demonstrates that if a CI user has residual hearing remaining in their non-implanted ear, and they wish to aid it, they can choose to either use a contralateral acoustic hearing aid or receive a second CI.

## Chapter 2: Bimodal aiding or bilateral cochlear implantation: Clinical effectiveness

This chapter first presents evidence that demonstrates that binaural listening provides advantages over monaural listening. Advantages include better spatial listening and speech perception, which are reflected in both performance tests and in self-report measures. Secondly, this chapter investigates the potential trade-offs made when opting for either a contralateral acoustic hearing aid or a second CI. It is argued that greater overall benefit is obtained from a second CI, but this comes at a cost both financially, and at the expense of pitch perception. A contralateral hearing aid on the other hand, costs less than a CI, and has been argued to have the potential to provide more pitch information which might be used in segregating talkers and understanding emotion. This chapter evaluates these issues further and suggests that the evidence is inconclusive on which option, a second CI or a contralateral acoustic hearing aid, is better for profoundly deafened adults.

## Chapter 3: Contribution of head movements to sound localisation

This chapter discusses the acoustic and psychoacoustic rationale for the potential of head movements to assist both normal-hearing and hearing-impaired listeners when locating sound sources. It is argued that whilst head movements have been shown to help both normal-hearing and hearing-impaired listeners, it is less clear whether CI users can receive similar benefits.

## Chapter 4: Cost-effectiveness of a second device for adult users of a single cochlear implant

This chapter describes existing generic instruments for measuring health-related quality of life. The chapter discusses the strengths and limitations of these instruments – in particular their limited sensitivity to hearing-specific difficulties and interventions. In addition the chapter outlines how responses to these instruments are used in analysing the cost-effectiveness of interventions. Finally studies which have used generic instruments to measure the cost-effectiveness of a second CI are reviewed. This chapter demonstrates that existing research suggests that bilateral cochlear implantation is not a cost-effective intervention although bimodal aiding is likely to be cost-effective.

## Chapter 5: Binaural advantages from a contralateral hearing aid or second cochlear implant

This chapter reports an experiment comparing the listening ability of UK adult CI users on a battery of listening tasks. The test battery consisted of localisation tasks, speech perception tasks in quiet, in noise, and in the presence of other talkers, vocal emotion perception and melody recognition. The experiment compares performance on these tasks by users of bimodal aiding, users of bilateral CIs, and users of a unilateral CI. This study demonstrates that spatial listening ability is improved from a contralateral acoustic hearing aid. Bilateral cochlear implantation provided improvements in spatial listening, speech perception in noise and speech perception in speech. Overall, a greater clinical benefit was obtained from a second CI.

## Chapter 6: Self-reported advantages from a contralateral hearing aid or second cochlear implant

This chapter reports results from an experiment comparing self-reported listening ability among unilateral and bilateral CI users and individuals using bimodal devices. In addition, the association between self-reported ability and actual listening ability as measured and reported in chapter 5 is discussed. This study demonstrates that self-reported listening ability and overall quality of life is improved from both bimodal aiding and bilateral cochlear implantation compared to unilateral cochlear implantation. Bilateral CIs provided a greater benefit in self-reported listening ability compared to bimodal aiding.

## Chapter 7: The role of head movements: Sound localisation, listening effort and speech perception in noise

This chapter reports three experiments investigating the role of head movements on listening performance. The first experiment examined the ability of unilateral and bilateral CI users to orient their heads towards a sound that was either short or long in length. In the second experiment a sound localisation task was completed where head movements were either permitted or not permitted. This experiment investigated the role of head movements in reducing front-back confusions. The third experiment investigated what head orientation strategies listeners adopt when listening to speech in noise. These studies demonstrated that unilateral CI users are poor at localising sound sources and are unable to orient towards a sound even when it is continuous in duration. When a stimulus is long enough, bilateral CI users are as accurate as NH listeners in orienting to a sound although they make more complex head movements to achieve the same level of accuracy. Bilateral CI users benefit from head movements as the number of front-back confusions is reduced. In addition, listeners orient their heads so as to maximise the level of a target talker irrespective of where background noise is presented from.

## Chapter 8: Development and validation of a measure of "hearing related quality of life" sensitive to binaural hearing in adults.

This chapter addresses the limitations of current generic quality of life instruments outlined in chapter 4 by developing a new questionnaire, the York Hearing Related Quality of Life questionnaire (YHRQL). This chapter outlines the development of the questionnaire, from identifying areas in which binaural hearing provides benefits, to gathering valuations from members of the public using the time-trade-off technique. Then the chapter describes an experiment which validated the YHRQL by using it to elicit responses from a group of CI users which were then compared with other measures of quality of life, and measures of listening performance obtained from the same patients. This chapter demonstrates that the YHRQL is sensitive to binaural hearing and can detect differences between clinically distinct groups who use different combinations of devices. Furthermore, using this instrument bilateral cochlear implantation has the potential to be considered a cost-effective intervention at a willingness-to-pay threshold of £30,000 per quality adjusted life year when compared to unilateral CI listening.

## Chapter 9: Summary and general discussion

This chapter summarises the main findings and conclusions from the four experimental chapters. It offers recommendations for which option (bilateral CIs or bimodal devices) should be chosen and suggests options for measuring the cost-effectiveness of a second device. Finally, directions for future research are proposed and discussed. This chapter demonstrates that whilst both bimodal aiding and bilateral CIs offer clinical advantages over using a unilateral CI, a greater clinical benefit is obtained from a second CI.

# 1 Introduction

## 1.1 Normal hearing

When an object vibrates, it causes changes in the air pressure level around it. This pressure change causes air molecules to move resulting in sound waves emanating from the object. The auditory pathway enables changes in sound pressure in the air to be converted to neuronal impulses to be sent to the brain. The human auditory system can be divided into four parts; the outer ear, the middle ear, the inner ear (shown in Figure 1.1) and the central auditory nervous system.

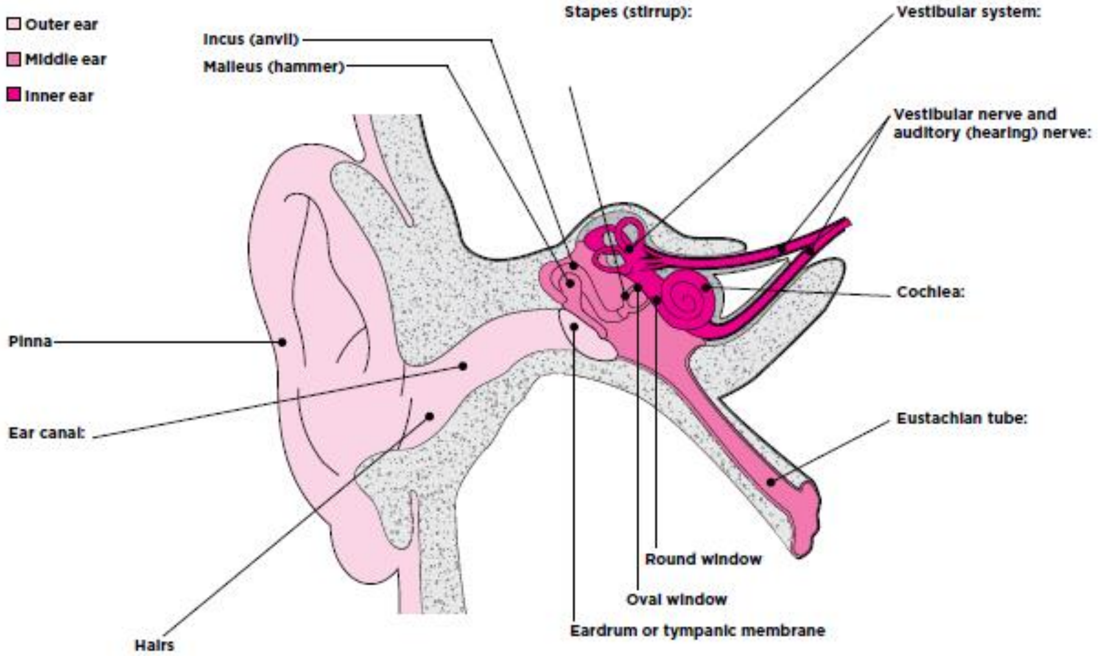


**Figure 1.1. Diagram of the human auditory system. Adapted from (Action on Hearing Loss, n.d.).**

Sound waves enter the ear canal both directly as well as indirectly by reflecting off the pinna. The waves reach the tympanic membrane, causing it to vibrate. These vibrations cause the ossicles (the malleus, incus and stapes) to move transmitting the sound through the middle ear. This process, known as ossicular coupling, is the main way in which sound is transmitted through the middle ear to the inner ear (Rosowski, 2010). The innermost ossicle, the stapes, is positioned on top of the oval window, a membrane that covers an opening to the cochlea. The cochlea is a rigid spiral-shaped structure containing fluid and if it were to be unravelled it would be 35mm long (Yost, 2000). The base of the cochlear is closest to the oval window whereas the apex is furthest from the oval window. The cochlea has three main sections: the scala vestibuli, scala tympani and scala media (see Figure 1.2).

The scala vestibuli and scala media are separated by Reissner's membrane. When the stapes moves, fluid in the scala vestibuli vibrates. Between the scala media and the scala tympani lies the basilar membrane. Vibration of the scala vestibuli causes the basilar membrane to vibrate. The movement of the membrane appears like a 'travelling wave' with high-frequency sounds resulting in maximum displacement at the basal end of the cochlear whereas low frequency sounds result in maximum displacement near the apical end of the cochlear (Moore, 2012). The organ of corti is positioned along the basilar membrane and contains approximately 3,500 inner- and 12,000 outer hair cells and each hair cell has approximately 140 (outer hair cells) or 40 (inner hair cells) stereocillia attached (Moore). Displacement of the basilar membrane can cause the stereocillia to deflect. If the deflection is large enough, ion channels are opened resulting in the generation of neuronal impulses. Larger deflections lead to a greater neuronal impulse which leads to increased auditory cortex activity (Plack, 2014).

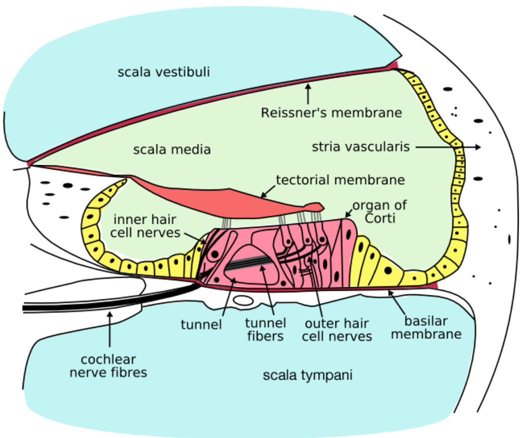


**Figure 1.2. Cross-section of cochlea. Image from Ropshkow (2004).**

## 1.2 Hearing impairment

### 1.2.1 Types

Peripheral hearing loss can either be conductive, sensorineural or mixed. In conductive hearing loss, the damage is in the outer/middle ear whereas with sensorineural hearing loss, damage is present in the inner ear. Congenital hearing loss is present from birth and may be hereditary and genetic in origin, or it may have arisen as a result of problems arising during pregnancy or childbirth. Acquired hearing loss may occur due to excessive noise exposure. Excessive noise exposure can damage the stereocilia or even the tympanic membrane disrupting the normal auditory pathway (Yost, 2000). As individuals age, hearing impairment becomes more common

(Davis, 1989; Stevens et al., 2011). This age-related hearing loss known as presbyacusis, initially adversely affects hearing of the highest frequencies but over time, it gradually affects lower frequencies as well (Yost). The ability to control the electrical potential needed for effective neural transmission is reduced in older adults, which whilst impacting all frequencies, has the most impact on higher frequencies (Plack, 2014). Furthermore, damage or missing hair cells predominantly in the basal end of the cochlear can contribute to the larger loss at high frequencies (Liu & Yan, 2007). Furthermore, ototoxic drugs, infections or diseases such as meningitis or even a head injury can cause hearing impairment and in some cases the cause of the loss may be unknown.

### 1.2.2 Severity and prevalence

Estimating the prevalence of hearing impairment is a challenging task, with some individuals unaware or unwilling to accept that they have a hearing impairment lowering estimations. Recent worldwide prevalence rates vary. Using 42 population based studies, the World Health Organisation (WHO, 2012) estimated that 328 million individuals over the age of 15 worldwide have a hearing loss greater than 40dB in their better ear. In a cross-sectional survey randomly selecting participants from electoral registers in four large UK cities, Davis (1989) estimated the prevalence of hearing loss of at least 25dB HL in UK adults to be 16%. Using audiometric data, they demonstrated that the prevalence of hearing loss was much higher among older adults (60% of adults aged 71 to 80 years had a loss of more than 25dB HL in their better ear) than younger adults.

The severity of hearing loss can be measured using pure-tone audiometry, which measures the minimum level at which individuals can detect a sound. It is performed for both ears across a number of different frequencies. An average threshold is then calculated for each ear, which is used to describe the level of hearing loss. The WHO (n.d.) uses the average threshold of the better-hearing ear to determine hearing loss severity. For adults, under the definitions described by the WHO, an average four-frequency (0.5, 1, 2, and 4 kHz) threshold between 26 and 40dB HL indicates a slight impairment. A moderate impairment exists if the threshold is between 41 and 60dB HL, whereas a threshold between 61 and 80dB HL defines a severe impairment. A threshold at 81dB HL or greater indicates a profound impairment. However, the classification of hearing loss severity commonly adopted in the UK uses the definitions described by the British Society of Audiology (BSA, 2004). A five-frequency pure tone average is taken for each ear using the thresholds at 0.25, 0.5, 1, 2, and 4 kHz. The BSA defines a mild hearing impairment as an average hearing threshold between 20 and 40 dB HL, while an average threshold between 40 and 70 dB HL indicates a moderate hearing loss. An average threshold between 70 and 95 dB HL indicates a severe loss, and thresholds greater than 95 dB HL indicate a profound loss.

### 1.2.3 Impact of hearing loss

Hearing loss results in a reduction in audibility. This can make it difficult for hearing impaired individuals to understand and follow conversations or detect potential hazards around them (e.g. an approaching car). Damage to the inner hair cells can result in a reduction in sensitivity and also result in problems with phase-locking, where temporal information is coded (Plack, 2014). Whereas damage to the outer hair cells can reduce the amplitude of the basilar membrane vibration, reduce frequency selectivity (the ability to resolve constituent frequencies in a complex sound), and impair pitch perception (Plack, 2014). These impairments can make it difficult for individuals to adequately understand speech and segregate concurrent sounds perceptually.

#### *Psycho-social*

Hearing loss can have a substantial social and emotional impact upon an individual. Communication is an important part of social interaction and not being able to hear adequately what someone is saying can result in misunderstandings. Not only is communication an important social aspect, it can also be important in many work settings, for example talking on the telephone, following instructions in noisy environments and attending meetings with others. Hearing impaired individuals may perceive stigma from others regarding their hearing loss, which can lead some individuals to pretend to understand conversations when in fact they cannot hear what is being said (Wallhagen, 2010).

Perceived stigma may result in individuals being less inclined to acknowledge and accept they have difficulties with their hearing (Hétu, Jones, & Getty, 1993). Furthermore, hearing impaired individuals may withdraw from social situations due to embarrassment or difficulties in following group conversations leading to feelings of isolation (Hétu et al.). Hearing loss may prevent an individual from partaking in their usual activities, however, if the hearing loss occurs gradually over time, it may allow the individual to adapt in order to cope with their reduced hearing abilities. Hearing loss also has a substantial impact upon relationships with others. Partners of hearing impaired individuals can often feel frustrated, stressed and angry, feelings which can arise as a consequence of the hearing impairment, such as having to tolerate excessively loud television, continuously repeat things to the hearing impaired individual and being faced with many misunderstandings (Hétu et al.).

***Financial***

Not only does hearing impairment have an impact upon the individual and their family, it also has a financial impact upon society. Mohr et al. (2000) used incidence rates of hearing loss to estimate the cost to society that severe-to-profound hearing impairment has in the USA. After considering medical, education and rehabilitation costs as well as productivity losses across the lifespan, Mohr et al. demonstrated that severe-to-profound deafness costs society on average USD $297,000 per individual. The cost was substantially greater when the age of onset was 0-2 years old with an estimated total cost of over $1 million, with about half of that cost concerning special education. When the age at onset was greater than three years the greatest societal cost arose from productivity losses over the lifetime. Mohr et al. argued that early identification of hearing loss and early intervention with hearing aids and CIs could reduce these costs in the future.

## 1.3 Hearing aids

A hearing aid includes a microphone to detect sounds whose intensity is amplified before they are delivered through a loudspeaker to the ear canal. This enables sounds to be more audible to the listener whilst at the same time not being too loud so as to be uncomfortable. Despite having elevated hearing level thresholds, the threshold for tolerating loud sounds does not become elevated for individuals with sensorineural hearing loss (B. C. J. Moore, 2012). Thus simply amplifying all sounds in the environment could cause discomfort to listeners. Therefore, hearing aids are able to compress the amplitude of sounds in the environment into a smaller dynamic range by using automatic gain control. This means that quieter sounds are amplified more than loud sounds.

A microphone on the hearing aid picks up sounds in the environment. These sounds are converted into electrical signals using digital signal processing before being passed to an amplifier that applies automatic gain control, so the sounds are made audible but not excessively loud. A receiver then converts the electrical signals back to acoustic signals that are then presented to the ear canal. A battery also provides power. Modern hearing aids are available in a variety of designs, including ones that are positioned in the ear canal as well as ones that are positioned behind the ear. However, whilst hearing aids improve audibility, they do not restore normal hearing. For instance, hearing impaired individuals have limited frequency resolution due to broader auditory filters (Wang, Xu, & Mannell, 2011), which cannot be restored through the use of a hearing aid.

### 1.3.1 Hearing aid use

In order to benefit from a hearing aid the individual needs to have a sufficient amount of residual hearing remaining meaning that there needs to be a sufficient number of undamaged inner hair calls. Plomp (1978) demonstrated that hearing aids provide benefits in speech perception when hearing loss is at or greater than 35dB HL. Chien and Lin (2012) used a representative of the USA population to estimate the prevalence of hearing loss and hearing aid use. They estimated that less than 15% of older hearing impaired individuals in the USA use hearing aids (Chien & Lin, 2012). Prevalence of hearing aid use differed depending upon the severity of the hearing impairment, with more individuals utilising hearing aids for moderate-to-severe hearing impairment than mild hearing impairment. In the UK, estimates are similar to that of the USA, suggesting that only 15% of individuals who report having a hearing difficulty actually use a hearing aid (Stephens, Lewis, Davis, Gianopoulos, & Vetter, 2001). However, more recent estimates suggest that the number of hearing impaired older adults (aged 55-74) utilising a hearing aid may be closer to 25% (Davis, Smith, Ferguson, Stephens, & Gianopoulos, 2007).

Estimating hearing aid use in populations is a challenging task. Indeed a recent systematic review of the literature, incorporating studies from 16 countries, including the UK and USA, was unable to estimate the prevalence of hearing aid use in adults over fifty years of age due to vast differences in the methodologies employed (Perez & Edmonds, 2012). Despite this uncertainty, a number of individual differences related to hearing aid use or non-use have been shown. In a review of 22 studies, Meyer and Hickson (2012) found that compared to hearing impaired individuals who did not use hearing aids, hearing aid users were often older, had a greater hearing loss, perceived there to be more advantages than disadvantages from using hearing aids, and also perceived their significant others to be supportive of the use of hearing aids.

Based on the available prevalence estimates cited above, it would appear that there are many individuals worldwide who do not use hearing aids, who may be likely to benefit from their use. If someone who does not have sufficient residual hearing wishes to aid their ear, then they may be interested in obtaining a CI.

## 1.4 Cochlear Implants

A CI is an electronic device that directly stimulates the auditory nerve fibres. A CI consists of both an external part and an internal part (see Figure 1.3). The key components of the external part are a microphone, speech processor and transmitter coil. The internal part consists of a magnet, receiver coil, stimulator, and a microelectrode array. The external microphone picks up sounds in the environment and the signals are then passed to the processor. The processor converts the input into digital signals which are then coded as radio frequency signals (Zeng, Rebscher, Harrison, Sun, & Feng, 2008). These signals are then passed to the transmitter coil, which is held in place by a magnet implanted under the skin. The radio-frequency signals are transmitted to the receiver coil. The signals provide power for the stimulator, which converts the radio-frequency signal into electrical bi-phasic charge balanced impulses that are then passed to the microelectrode array. The electrodes then directly stimulate the auditory nerve fibres.

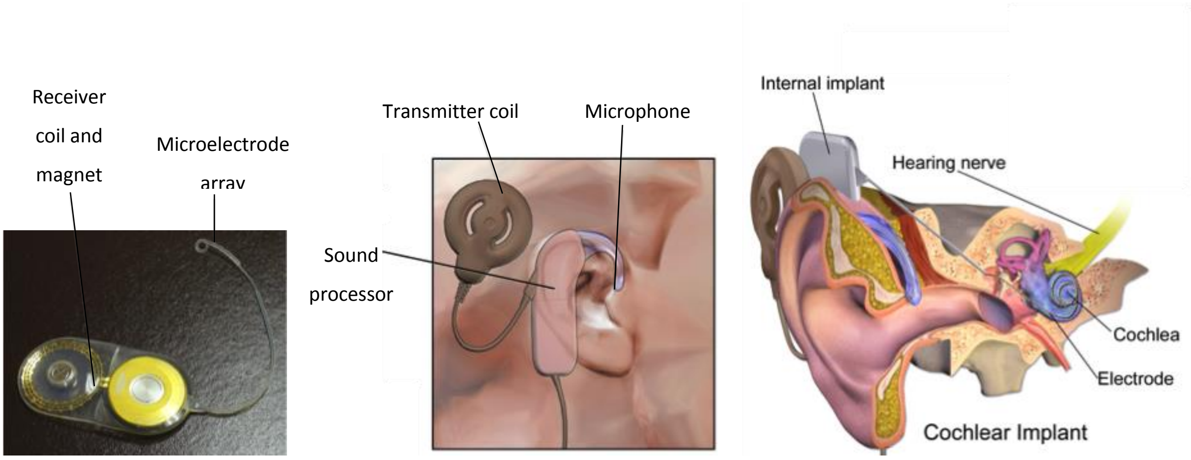


**Figure 1.3. Internal (left image) and external (middle image) parts of a CI with key components labelled. Rightmost image shows the components in relation to the cochlea. Left image adapted from (Tabercil, 2009), middle and right images adapted from (Blaus, 2013).**

The microelectrode array is positioned in the cochlea. The intended location of the array is within the scala tympani, although the array may pass into the scala vestibuli due to the delicate nature of the cochlea and the 'invisible' aspect of surgery (see Finley & Skinner, 2008). During cochlear implantation the microelectrode array is not fully inserted into the cochlea because there is a potential risk of cochlea damage with a full insertion. The width of the cochlea is wider at the basal end than the apical end and the spiral turns of the cochlea become tighter. As such there is a risk that a deep electrode insertion can damage the apical end of the cochlea. Within the normal cochlea there is a tonotopic arrangement, with high frequencies being encoded at the base of the cochlea and low frequencies being encoded at the apex of the cochlea, as such low frequency information is not well represented by CIs.

### 1.4.1 Candidacy

Candidacy requirements for a CI are continuously being updated and revised as evidence demonstrates that even individuals who perform reasonably well with a hearing aid perform much better with a CI (Gifford, 2011). Gifford, Dorman, Shallop and Sydlowski (2010) tested 22 participants with severe-to-profound hearing loss on a speech perception in quiet task and they found that individuals performed significantly better with one CI (mean: 67% correct) than they did with bilateral hearing aids (mean: 41% correct). With candidacy for a CI being relaxed, many individuals are being implanted with considerable levels of residual hearing in their non-implanted ear (Gifford). Candidacy for a CI is not uniform and differs between and, in some cases, within countries. In the UK, under current guidelines (see Table 1.1) severe-to-profoundly deafened adults are eligible to receive a CI if they have tried using a hearing aid for at least three months and they are not achieving functional hearing from it (NICE, 2009). To assess whether individuals are achieving functional hearing with the use of a hearing aid, a speech perception test in quiet is conducted. The stimuli used are context rich sentences spoken in a clear voice. If an individual fails to identify 50% of the keywords in the sentences when presented at 70dB SPL without lipreading, they are judged not to be achieving functional hearing with their hearing aid and are therefore eligible for a CI (NICE).

In the USA, candidacy for a CI is more variable (see Table 1.1). The centers for Medicare and Medicaid have more relaxed criteria than the UK, specifying that cochlear implantation should be for individuals with moderate to profound hearing loss (Phurrough, Jacques, Ulrich, Spencer, & Sheridan-Moore, 2005). The Food and Drug administration has approved CIs for use with slightly different criteria depending upon the device (see Table 1.1).

**Table 1.1. Candidacy requirements for a CI for adults.**

| Criteria specification | Severity of loss | Stimuli | % correct | Which ear is the decision based on? |
|---|---|---|---|---|
| UK: | | | | |
| NICE (2009) | Severe-to-profound deafness defined as only hearing sounds above 90dB HL at 2 and 4 kHz unaided. | Bamford-Kowal-Bench recorded sentences at 70 dB SPL | <50% | Bilateral |
| United States of America: | | | | |
| Centers for Medicare and Medicaid services in the USA (Phurrough et al., 2005) | Bilateral moderate-to-profound hearing loss | Recorded sentences | <40% | Best-aided |
| FDA indicators: | | | | |
| Cochlear Americas Nucleus device (Cochlear, 2010) | Moderate to profound loss in the low frequencies and profound loss (≥90dB HL) in mid to high frequency regions | Sentence recognition (type not specified) | ≤ 50% in the ear to be implanted (≤60% in the best aided condition) | Bilateral |
| Advanced Bionics HiRes device (Advanced Bionics, n.d.) | Bilateral severe-to-profound (pure tone average ≥ 70dB HL. | Hearing in noise test (HINT) sentences | ≤ 50% | Not specified |
| Med-El Combi 40+ device (US Food and Drug Administration, 2002) | Bilateral severe-to-profound (pure tone average ≥ 70dB HL. | HINT sentences | ≤ 40% | Best aided |

### 1.4.2 Prevalence

Approximately 324,000 individuals worldwide have received CIs (Food and Drug Administration, 2012 as cited in the National Institute on Deafness and Other Communication Disorders, n.d.). There are approximately 11,000 CI users in the UK (British CI Group, 2012; The Ear Foundation, 2011). The majority are adults, and the British CI Group highlights that there were 6088 adults with CIs in the UK in March 2012, and only 244 had bilateral CIs. Furthermore 675 adults were implanted in the UK between April 2011 and March 2012 with 96% receiving a single CI. The relatively few numbers of bilateral CI users in the UK can be explained by considering the current guidelines issued by NICE (2009) on bilateral cochlear implantation. In the UK, the NHS will pay for an eligible adult to receive *one* CI. The NHS will not pay for an individual to receive two CIs as bilateral cochlear implantation is not deemed to be a cost effective intervention for adults (Bond et al., 2009; Crathorne et al., 2012; Summerfield, Marshall, Barton, & Bloor, 2002). However, clinical specialists outlined that deaf-blind individuals and deaf individuals with other disabilities (who rely more heavily on hearing for spatial awareness than solely deaf individuals) will receive a greater quality of life from bilateral CIs than other CI candidates. As such, NICE guidelines specify that deaf-blind individuals and deaf individuals with other disabilities can receive a second CI paid for through the NHS. Otherwise, if an adult in the UK wishes to obtain a second implant they have to pay for it themselves. The finances needed would have to cover the cost of the CI itself and also the cost of the surgery and rehabilitation, which amounts to about £25,000 (Nottingham University Hospitals, n.d.). Add to that a yearly cost for audiology appointments and maintenance and it is clear that the finances required for a second CI are not available to many individuals.

### 1.4.3 Advantages and disadvantages of cochlear implantation

Cochlear implantation can enable profoundly deafened individuals to understand speech without the need to lipread. Although there is variability in listening performance following implantation, most individuals benefit, with mean speech perception performance for monosyllabic words above 50% correct (Finley & Skinner, 2008; Holden et al., 2013; United Kingdom CI Study Group, 2004; Wilson & Dorman, 2008) and even higher performance when contextual cues are present in the form of sentences (United Kingdom CI Study Group, 2004; see Wilson & Dorman, 2008 for a review). In a systematic review Berrettini et al. (2011) found cochlear implantation improved listening ability and quality of life in adults, even those with pre-lingual deafness. Furthermore, cochlear implantation can result in improved job opportunities which has been shown to result in an increase to personal income with economic benefits to society (Monteiro, Shipp, Chen, Nedzelski, & Lin, 2012).

Despite substantial benefits from CIs, there are some drawbacks. Cochlear implantation involves a surgical procedure and therefore it comes with the risks which surgery poses. The facial nerve may become damaged during surgery, however this is a small risk affecting less than 1% of patients (Fayed, Wanna, Micheletto, & Parisier, 2003). Cochlear implantation is also an irreversible option. As the procedure can damage the remaining hair cells, patients cannot decide to return to using a hearing aid should they dislike using the CI. As with hearing aids, a CI does not restore hearing to normal levels of function. Whilst speech perception in quiet may be good (Carroll, Tiaden, & Zeng, 2011; Yoon, Li, Kang, & Fu, 2011) performance deteriorates abruptly with decreasing signal to noise ratios (Ricketts, Grantham, Ashmead, Haynes, & Labadie, 2006; Yoon et al., 2011), and the quality of sounds, particularly musical sounds, is poor (Looi, McDermott, Mckay, & Hickson, 2007). Sounds may appear unnatural and it may take time for an individual to associate these unfamiliar sounds with their source.

Nevertheless, if an individual chooses to receive a CI they have two options should they wish to aid their non-implanted ear: use an acoustic hearing aid (and be aided bimodally) or obtain a second CI (bilateral implantation). The next chapter will consider the advantages and disadvantages of these options.

## 1.5 Summary of main points

- The auditory pathway of a normal hearing listener converts changes in air pressure to neuronal impulses enabling them to perceive sound.
- Hearing impairment arises as a result of damage to the auditory pathway; the most common form of hearing loss is presbyacusis that occurs in older age.
- Hearing impairment can have a substantial functional, social, and economical impact.
- Hearing aids improve audibility for hearing impaired listeners who have sufficient residual hearing remaining, but they do not restore normal hearing.
- Cochlear implantation is an irreversible surgical procedure that enables the great majority of users to understand speech without the need to lipread.
- For the majority of users, listening ability and quality of life are improved following cochlear implantation.

# 2 Bimodal aiding or bilateral implantation for adult users of a single cochlear implant: Clinical-effectiveness

As a result of the relaxation of criteria of candidacy for cochlear implantation over the last 25 years (Gifford, 2011), many patients are being implanted whilst still having residual hearing in their non-implanted ear. Should these individuals wish to aid their non-implanted ear, they have two options. One option is to receive a contralateral acoustic hearing aid and have 'bimodal aiding'; the other option is to receive a second CI and have 'bilateral CIs'. The aim of this chapter was to (1) assess the benefits and drawbacks of each option compared with using a single CI, and (2) compare the relative benefits of the two options in terms of clinical effectiveness. As will be demonstrated, both options offer advantages over a single CI both in behavioural and self-reported measures. However, due to differing methodologies in the research studies it is unclear as yet, which option is better for individuals with one CI.

## 2.1 Why two ears are better than one

Listening with two ears rather than one has a number of benefits. These include the ability to localise sound sources more effectively, an important issue for safety, and understand speech in more adverse conditions such as in the presence of noise. The binaural cues that enable listeners to benefit from a second device are reviewed in the next sub-sections.

### 2.1.1 Interaural differences

A sound originating on the right hand side of an individual reaches the right ear before it reaches the left ear, because the right ear is closer to the sound source. This interaural time difference (ITD) is one cue which can be used for locating sound sources. The length of the ITD is dependent upon the angle of the sound source in relation to the listener's head. When a sound source is directly in front of the listener (0°azimuth) it reaches the left and right ears at the same time so there is no ITD. However, as the location of a source increases in azimuth, the ITD increases, reaching a maximum ITD of about 709µs when the sound is at ±90° azimuth, although there are individual differences depending upon the size of the head (Middlebrooks, 1999). Listeners can detect differences in the ITD of pure tones at lower frequencies but for pure tones with frequencies greater than 1500Hz, individuals are unable to discriminate differences between ITDs due to phase ambiguity (Klump & Eady, 1956, as cited in Akeroyd, 2006; Colburn, Shinn-Cunningham, Kidd, & Durlach, 2006).

A sound originating on the right hand side of an individual is also more intense at the right ear compared to the left ear creating an interaural level difference (ILD). The amount of ILD depends upon the frequency of the sound and the distance between the sound source and the ears (Shaw, 1974). Normal hearing listeners are able to detect differences in ILD as small as 0.5 dB across frequencies (Durlach & Colburn, 1978; as cited in Colburn et al., 2006). Rayleigh (1907) proposed that the use of ILD and ITD cues was dependent upon frequency which was later known as the duplex theory, As the phase of high frequency tones can be ambiguous, the main cue listeners used to localise low-frequency pure tones is ITD. However, for pure tones at high frequencies listeners judge location using ILDs as the head acts as a barrier to the shorter waveforms and shadowing occurs (Macpherson & Middlebrooks, 2002; Plack, 2014).

### 2.1.2 Head shadow

Should a sound be presented to either side of an individual, the head will act as an acoustic barrier, attenuating the transmission of the sound to the further ear. Listeners can take advantage of this head shadow effect when listening to speech in the presence of spatially separated maskers. If a target talker is presented from 0° azimuth and noise is simultaneously presented from either +90° or -90° this will result in a less intense representation of the target at the ear closer to the noise (compared to the other ear) and a less intense representation of the masker at the ear furthest from the noise (compared to the other ear; Akeroyd, 2006). Therefore the listener can use the ear which has a better target-to-masker ratio to hear out the target speech. Although a monaural effect, listeners have an advantage when listening with two ears as they can obtain the benefit from the head shadow when noise is presented to either their right or to their left.

### 2.1.3 Binaural summation

Sounds are perceived as being louder when listening with two ears compared to one ear (Hirsh, 1948). Also referred to as binaural redundancy, binaural summation refers to the fact that listening with two ears results in information being represented twice, once at each ear. Thus there is some redundant information that listeners can use which may help them in tasks of speech perception in the presence of spatially concurrent noise or speech (Schafer, Amlani, Paiva, Nozari, & Verret, 2011).

### 2.1.4 Binaural squelch

Inputs received at each ear are combined enabling a suppression of some of the signal (Carhart, 1965; Koenig, 1950). Speech perception in the presence of spatially separated noise can benefit from binaural squelch (Dunn, Tyler, & Witt, 2005). This effect arises when inputs to each ear have different signal-to-noise ratios. Listeners are able to use interaural differences to listen with the ear that has the better signal-to-noise ratio (Balkany & Zeitler, 2013).

### 2.1.5 Auditory deprivation

Adult users of a single CI who do not aid their non-implanted ear risk the effects of auditory deprivation (O'Neil, Connelly, Limb, & Ryugo, 2011; Silman, Gelfand, & Silverman, 1984). Silman et al. (1984) examined pure-tone thresholds and speech perception performance in a group of 67 adults with bilateral hearing impairment in two sessions; once at a hearing-aid evaluation and again 4 to 5 years later. At the evaluation 44 individuals were fitted with bilateral hearing aids and 23 were fitted with a single hearing aid. Pure-tone thresholds were similar between the two groups at the hearing aid valuation and whether the participant received one or two hearing aids depended upon the view of the audiologist whom they had seen. For the bilaterally aided participants, speech recognition performance with just the left ear decreased from a mean of 87.5% at hearing-aid fitting to a mean of 85.9% four to five years later. Similar results were found with the right ear (89.8% to 87.9%). When listening with their aided ear, monaurally aided listeners also demonstrated a similar slight worsening on speech recognition scores (mean score of 86.2% to 83.6%). However, when listening with their unaided ear, performance dropped from 84.9% to 66.4%. Despite the potential implications of not aiding a hearing-impaired ear for some time, opting to aid an auditory deprived ear later on can result in recovery for some individuals (see Palmer, Nelson, & Lindley, 1998 for a review). Opting to not aid an ear is detrimental, even is some recovery of function can occur following later aiding.

## 2.2 Bimodal aiding

There are an increasing number of individuals with a single CI who have aidable residual hearing in their non-implanted ear who could benefit from using a contralateral acoustic hearing aid. Whilst there have been reports that some users experience difficulty integrating the inputs from the two different devices (Fitzpatrick & Leblanc, 2010; Fitzpatrick, Séguin, Schramm, Chenier, & Armstrong, 2009; Mok, Grayden, Dowell, & Lawrence, 2006), for the most part a positive complementarily has been reported from using bimodal devices (Ching, 2005; Ching, van Wanrooy, & Dillon, 2007; Ching, Incerti, & Hill, 2003; Fitzpatrick et al., 2009; Incerti et al., 2011; van Hoesel, 2012). The use of a hearing aid in conjunction with a CI can give rise to a positive complementarity as it enables access to a broader frequency range than a CI alone because the hearing aid can provide access to the low-frequency range that is not conveyed by a CI.

### 2.2.1 Localisation

However, mixed findings have been reported regarding localising sound sources in the frontal horizontal plane with bimodal devices. In an influential, yet small sampled study, Tyler et al. (2002) found that two out of three individuals benefitted from using a hearing aid in conjunction with a CI for localising sound. However, Dunn, Tyler, and Witt (2005) found that localisation ability varied widely among a group of twelve bimodal users. Although three of the participants could localise fairly well with bimodal devices, the majority of participants were unable to locate the source of the sounds accurately. Indeed the mean root-mean-square (RMS) error for these participants was 42.7°, which was similar to performance by unilateral CI users who did not aid their contralateral ear (seeTable 2.1; Dunn, Tyler, Oakley, Gantz, & Noble, 2008). Similar findings were reported by Noble, Tyler, Dunn, & Bhullar (2008b, see Table 2.1). Further discrepant findings have been found by Seeber, Baumann, & Fastl (2004) who tested a group of eleven bimodal users each of whom were fitted with the same model of hearing-aid a week prior to testing. Prior to the study, six participants regularly used hearing aids, whereas five participants did not. On each trial white noise was presented from one of eleven loudspeakers (from ±50°, separated by 10°), hidden from participants' view. In comparing accuracy of localisation with bimodal devices to when using one CI alone, four of the participants did not benefit significantly from a hearing aid. In another study, 19 unilateral CI users were fitted with a contralateral hearing aid (Potts, Skinner, Litovsky, & Strube, 2009). Monosyllabic words (lasting 1 to 2 seconds) were presented from one of ten loudspeakers separated by 15° in the frontal horizontal plane (±70°). Participants completed the task using their CI alone, and their CI and hearing aid together. The RMS error was calculated for each listening condition. Performance was significantly better with bimodal devices than with a CI alone. The results of these studies are summarised in Table 2.1.

**Table 2.1. Summary of mean localisation performance by bimodal and unilateral CI listening. Also shown is the measure of variance reported in the study. CIHA = bimodal, CI = CI. SD = standard deviation, SE = standard error.**

| Study | Participants | CIHA | CI only |
|---|---|---|---|
| Tyler et al. (2002) | 3 CIHA | Did not report RMS error data | Did not report RMS error data |
| Dunn, Tyler, and Witt (2005) | 12 CIHA | 43° (range 27° to 49°) | n/a |
| Dunn et al. (2008) | 12 unilateral CI users | n/a | 44° (SE = 2°)† |
| Noble, Tyler, Dunn, & Bhullar (2008b) | 16 CIHA<br>14 CI only | 38° (SD = 7°) | 43° (SD = 6°) |
| Seeber, Baumann, & Fastl (2004) | 11 CIHA | 22.° (SE = 2.°) | 25° (SE = 1°) |
| Potts, Skinner, Litovsky, & Strube (2009) | 19 CIHA | 39.° (range 21.° to 66°) | 54° (range 30° to 80°) |

† Mean and SE inferred from figure.

Whilst localisation ability is improved for some users of bimodal devices, for others it is not. The reason for these individual differences are unclear and further research using larger samples is needed to identify whether there are any participant characteristics that can account for this difference.

### 2.2.2 Speech perception

An additional advantage from using a contralateral acoustic hearing aid is that low frequency information contains cues to consonant voicing and manner of articulation which is useful for speech perception (Rosen, 1992). A signal can be broken down into an envelope and temporal fine structure (TFS) information using the Hilbert Transform (B. C. J. Moore, 2008). The envelope contains information about the slow changes in amplitude of the signal, whereas the TFS information is the rapid changes over time whose amplitude defines the envelope (see Figure 2.1). Fine structure information contained in the low-frequencies is important in conveying cues to the voicing and manner of consonants (Rosen, 1992). CI processing extracts the envelope of a signal but the temporal fine structure is not well represented (Rubinstein, 2004).

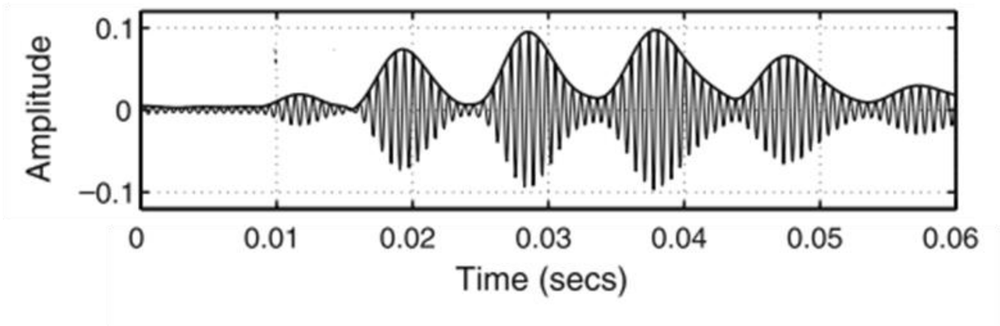


**Figure 2.1. Example waveform showing the slowly varying envelope (thick black line), and the rapidly changing TFS over time. Image from (Moore, 2008).**

Advantages of combining low-frequency acoustic stimulation with the stimulation provided by a CI include improved speech perception in quiet (Incerti et al., 2011; Zhang, Dorman, & Spahr, 2010), as well as improved speech perception in the presence of noise (Carroll, Tiaden, & Zeng, 2011; Ching, Incerti, & Hill, 2004; Ching, van Wanrooy, Hill, & Dillon, 2005; Zhang et al., 2010). Adult users of bimodal devices can also benefit from binaural redundancy when listening to speech in noise (Ching et al., 2005). However, the bulk of the benefit has been shown to arise as a result of having access to information around the fundamental frequency (f0) region (Carroll et al., 2011; Zhang et al., 2010). This will be discussed in the next section.

#### *2.2.2.1 How much low-frequency information is needed to improve the accuracy of speech perception?*

Zhang et al. (2010) demonstrated that combining a CI with a limited amount of low-frequency acoustic input (125 Hz low-pass filtered signal) can improve word recognition in quiet and sentence recognition in noise compared to unilateral CI listening. The improvement was about 20 percentage points in quiet and about 30 percentage points in noise. This was despite the fact that speech perception performance was at zero percent correct with the 125 Hz low-pass filtered acoustic signal alone. When Zhang et al. (2010) increased the low frequency information conveyed up to 250Hz, 500Hz, or 750Hz, and combined it with electrical information, performance was not significantly different to performance with a CI and low-frequency information up to 125Hz. Thus the majority of benefit obtained arose from the low frequency region containing the fundamental frequency.

A similar super-additive effect of combining low-frequency information with electric information has been found by Cullington and Zeng (2010). Electrical information was presented directly to the CI and acoustic information was filtered and presented to the non-implanted ear via an inset ear phone. The acoustic signal was low pass filtered at 150, 250, 500, and 1000Hz or was high pass filtered at 2000, 4000, and 6000 Hz. One participant was tested on speech perception in noise with their CI alone, acoustic information alone, and combined CI and acoustic information. Performance was poor with their CI alone (3% correct). Similar to Zhang et al. (2010), performance with acoustic information only at 250Hz was at floor. However when combined with the electrical information, performance was about 35% (an increase of 32 percentage points compared to electric information alone). Thus despite performance with a CI alone being different from that achieved by Zhang et al.'s participants, a similar increase in performance from bimodal aiding was found in both studies. These results demonstrate that whilst low-frequency information may not provide much benefit on its own, in combination with electrical information conveyed by a CI a substantial benefit in speech perception can be obtained.

However, the findings reported by Cullington and Zeng (2010) were achieved by a single listener who used a CI in one ear but who had near normal hearing in the non-implanted ear (pure tone thresholds ≤ 20dB HL at 0.25 – 8 kHz with the exception of 4kHz which was at 35 dB HL). The bimodal participants in the study by Zhang et al. (2010) also had relatively good low-frequency hearing with thresholds ≤ 60 dB HL at 500 Hz and below. Under current guidelines from NICE (2009) these hearing levels are better than a typical UK candidate for a CI would have and as such UK users may not benefit from the addition of low frequency-information in the same way as these studies have demonstrated. Indeed, Neuman & Svirsky (2013) investigated how hearing aid bandwidth affected speech perception in quiet and in noise for listeners with *severe-to-profound hearing loss* in their non-implanted ear. They tested participants in five conditions; CI alone, CI and acoustic information up to 500Hz, CI and acoustic information up to 1000Hz, CI and acoustic information up to 2000Hz, and CI and wideband acoustic information. Neuman and Svirsky (2013) found that the mean sentence understanding was about 65% correct in quiet and 70% correct in noise with a CI alone. Despite the potential to improve, combining stimulation from a CI with low-frequency acoustic information below 500Hz, did not result in a significant benefit in performance either in quiet or in noise. However, significant benefits were observed when stimulation from a CI was combined with low-frequency information up to 2000Hz or wideband acoustical stimulation. In those conditions, performance improved to about 80% correct.

Both Zhang et al., (2010) and Neuman and Svirsky (2013) tested intelligibility with AzBio sentences presented in noise at +10dB SNR. However, there were some potentially important methodological differences between the two studies. Zhang et al. presented stimuli directly to the participant's CI and low-pass filtered acoustic stimuli were pre-generated and presented to participants through an insert ear-phone with real-ear insertion gain applied. Neuman and Svirsky on the other hand, adopted a more ecologically valid approach by presenting stimuli in the free field and setting programs on the hearing aid to achieve different bandwidths. The National Acoustic Laboratories, Revised Profound prescriptive procedure (Byrne, Dillon, Ching, & Katsch, 2001) was used to set the wideband condition as this was designed for individuals with severe to profound hearing loss. However, Neuman and Svirsky point out that this prescription does not provide much gain at frequencies below about 200Hz which is the region which Zhang et al. identified as providing the most benefit. Thus, individuals with severe to profound hearing loss would typically have reduced access to acoustic information in the low-frequency region even when using a hearing aid. Therefore suggesting that more than a limited amount of low-frequency acoustic information is required to benefit from bimodal devices. In order to receive maximum benefit from bimodal devices, users should have access to low-frequency acoustic information up to at least 2000Hz.

##### 2.2.2.1.1 Cues conveyed in low-frequency information

Thus far it has been argued that when low-frequency information is combined with electric information there is a super-additive benefit for some individuals. However it is less clear why this is the case. One possibility is that it is cues to the f0 that provide the benefit. The f0 can convey phonetic information useful for speech perception such as manner of articulation and consonant voicing as well as lexical information such as prosody and lexical boundaries (Brown & Bacon, 2009; Sheffield & Zeng, 2012). Kong, Stickney, and Zeng (2005) tested four bimodal users on a speech in noise task. Sentences spoken by a male talker were presented in the presence of a competing talker at +20, +15, +10, +5 and 0dB SNR. The competing talker was either a different male talker or a female talker. Participants were tested with their hearing aid alone, their CI alone, and the two devices together. Whilst performance with the hearing aid alone was at floor across all SNRs, combining the hearing aid with the CI resulted in better performance than the CI alone, particularly in the more favourable listening conditions (+15 and +20dB SNR). The authors argued that the temporal envelope alone (CI listening) did not provide sufficient pitch information to separate the two talkers. However, periodicity conveyed in the temporal envelope together with TFS at low-frequencies in the acoustic information (which are correlated) could be used to improve performance.

However, the lead author later argued that the benefit may arise from voicing or glimpsing (using the temporal envelope changes to know when to listen) cues in the signal rather than from the correlation between temporal envelope periodicity cues and the f0. In a simulation study using vocoded speech, Kong and Carlyon (2007) first replicated the super-additive benefit from combining electric information with low-frequency acoustic information found from Kong et al. (2005) by testing speech perception of a target talker in the presence of a masker. In a follow up experiment phonetic cues were removed from the low-frequency stimuli but f0 cues, glimpsing, and voicing cues remained. This was achieved by frequency-and amplitude-modulating a harmonic complex with the same f0 contour as the voiced sections of the target speech. When participants were tested at 5dB SNR, a significant superadditive benefit from bimodal listening was found. In a further follow up experiment the f0 cues were also removed by replacing the f0 contour with a harmonic complex with a fixed f0. The envelope of the voiced sections of the target speech was used to amplitude modulate the monotonic harmonic complex. Thus voicing and glimpsing cues remained in the stimulus but f0 cues were removed. Again, when participants were tested at 5dB SNR, a significant superadditive benefit from bimodal listening was found. This finding demonstrated that the benefit could not have arisen solely from the ability to use f0 cues to segregate the target from the masker. As the super-additive effect remained without the f0 the authors argued that the effect most likely resulted from glimpsing or voicing cues.

However, Visram, Azadpour, Kluk, and McKay (2012) argued that f0 cues may be useful but not sufficient on their own for bimodal benefit to occur. The non-implanted ear of seven bimodal listeners was presented with different types of low-pass filtered stimuli: unprocessed speech , vocoded stimuli (which maintained spectral shape information but not f0), or modulated tones (which maintained f0 and amplitude information but removed spectral shape information). When a CI was combined with the unprocessed speech, speech perception performance was significantly better than with the CI alone. However no significant difference was found between using their CI alone and using their CI combined with the other low-pass filtered stimuli.

Brown and Bacon (2009) also suggested that a combination of low-frequency cues resulted in the greatest benefit, however they also demonstrated that voicing alone can improve performance.

Brown and Bacon (2009) simulated electro-acoustic information within the same ear. This differs to traditional bimodal users who have a long electrode insertion in one ear and a contralateral acoustic hearing aid in the other ear. ‘Hybrid’ implant systems which use a short electrode array and maintain residual acoustic low-frequency information in the ear that is being implanted are used by some individuals with good low-frequency thresholds (no hearing loss to moderate hearing loss) but profound hearing loss at high frequencies (Gantz, Turner, Gfeller, & Lowder, 2005). 25 normal hearing listeners completed a speech in noise task with a female target talker. The masker was either a male talker or a female talker, 4-talker babble or speech shaped noise. Stimuli were vocoded to achieve the electrical simulation. Simulated low-frequency information was either the target speech low-pass filtered at 500Hz or a tone (mean f0 = target mean f0). Changes in f0 over time were either present or not in the tone stimuli. Results showed that performance with low-pass filtered speech at 500Hz alone was 20% correct and with a vocoder alone was about 25% correct. However, when combined, performance was around 85% correct. The addition of voicing information (conveyed in the tone) to vocoded stimuli resulted in an average of an 11 percentage point improvement. When changes in f0 and voicing cues were present an average 25 percentage point improvement compared to vocoder alone was observed. When voicing and glimpsing cues were available (by modulating the tone to the envelope of low pass speech) performance was also 25 percentage points better on average than with the vocoder alone. When the vocoder was combined with an amplitude and frequency modulated tone performance was on average 31 percentage points better than with the vocoder alone. In the male background the greatest benefit arose from the voicing cue (with no significant additional benefit from the other cues) however, in the other backgrounds the other cues did provide a significant additional benefit.

The f0 has been shown to be an important contributor to the benefit obtained in a number of simulation studies (Brown & Bacon, 2009; Carroll et al., 2011; Qin & Oxenham, 2006; Turner, Gantz, Vidal, Behrens, & Henry, 2004) and patient studies (Carroll et al., 2011; Kong et al., 2005; Turner et al., 2004; Zhang et al., 2010). Whether or not the f0, voicing, or glimpsing cues are the primary reason behind the benefit warrants further investigation. However, the overarching conclusion from these studies is that a benefit in speech perception is obtained from combining low-frequency acoustic information with electric information.

### 2.2.3 Pitch perception

Access to fine structure information conveyed in the low frequencies has also been shown to improve melody recognition when changes in pitch are made to be the only cue to identification (Kong et al., 2005). Furthermore, self-reports have shown that users rate sound quality and listening to music better with bimodal devices than a CI alone (Flynn & Schmidtke, 2004). The ability to perceive changes in pitch is also important for detecting changes in intonation and vocal emotion recognition because pitch is one cue that indicates emotion in addition to intensity and duration (Pittam & Scherer, 1993). Indeed, Most, Gaon-Sivan, Shpak, and Luntz (2012) found that performance was significantly higher with bimodal devices than a single CI for emotion identification and intonation recognition.

### 2.2.4 Self-reported benefits

The Speech, Spatial and Qualities of hearing questionnaire (SSQ; Gatehouse & Noble, 2004) considers a wide range of listening scenarios across three broad topics: speech perception, spatial listening, and other aspects of hearing. Scores can be obtained for each of the three sections, or the questionnaire can be divided into ten sub-sections (speech perception in quiet, speech perception in noise, speech perception in the presence of other speech, multiple speech stream processing and switching, sound localisation, perceiving distance and movement, sound quality and naturalness, identification of sound and objects, segregation of sounds, and listening effort) resulting in ten scores (Gatehouse & Akeroyd, 2006). Noble et al. (2008b) found no significant differences between unilateral CI users and bimodal users on any of the 10 sub-sections. This result will be discussed in more detail in Chapter 6, which reports an experiment comparing self-reported listening ability by unilateral, bimodal, and bilateral CI users. Noble, Tyler, Dunn, and Bhullar (2008a) administered the Hearing Handicap Inventory for the Elderly and the Hearing Handicap Questionnaire to 40 bimodal users and 71 unilateral CI users. Both questionnaires measure the impact of hearing loss on social activities (social restriction) and emotional wellbeing (emotional distress). The Hearing Handicap for the Elderly also contains questions related to specific hearing difficulties (e.g. “Does a hearing problem cause you difficulty when listening to TV or radio?”). On neither questionnaire was there a significant difference between unilateral or bimodal listeners on any of the sub-sections.

### 2.2.5 Effectiveness of bimodal aiding

As bimodal aiding has been shown to provide some binaural benefits (for instance speech perception improvements), Ching et al. (2004; Ching, 2005) recommended that users of a single CI use a contralateral hearing aid as a matter of standard practice. In a systematic review assessing the effectiveness of bimodal aiding, Olson and Shinn (2008) demonstrated that the majority of bimodal patients receive benefit from using a contralateral hearing aid in conjunction with a CI. However, they did point out that some participants did not benefit, with some even showing a worsening in performance from using a contralateral hearing aid. They suggested that this outcome might be a result of the short amount of time for which these participants had experienced bimodal aiding. Nevertheless, on the whole, benefits were found for speech perception in quiet, but a greater benefit was found for speech perception in noise. Olson and Shinn discussed four studies that had assessed localisation abilities, but found that localisation ability was quite varied between participants and studies. The review discussed two studies that had utilised self-report measures. The two studies had each created a questionnaire which showed preference for listening with bimodal devices over a CI alone. Olson and Shinn concluded that although the evidence for bimodal aiding was limited by studies with small samples, an adequate body of evidence existed to support the clinical effectiveness of bimodal aiding.

## 2.3 Bilateral implantation

### 2.3.1 Localisation

One well established advantage of bilateral CIs over unilateral CI listening is improved localisation for sounds presented in the frontal horizontal plane (Dunn, Tyler, Oakley, Gantz, & Noble, 2008; Kerber & Seeber, 2012; Litovsky, Parkinson, & Arcaroli, 2009; van Hoesel & Tyler, 2003). Bilateral CI users have good access to ILDs however, they have a  limited ability to use ITDs due to restricted temporal information encoded by CIs (Laback, Majdak, & Baumgartner, 2007; van Hoesel, Ramsden, & O'Driscoll, 2002). Dunn et al. (2008) compared localisation performance between twelve bilateral CI users and twelve unilateral CI users. They demonstrated that although the average RMS error of the bilateral CI users was about 18°, this was 25° better than the RMS error of the unilateral CI users which was 43°. In a within-subjects design, a group of 17 bilateral CI users completed a localisation task using one or both of their CIs and a similar amount of benefit from bilateral devices was also found (Litovsky et al., 2009).

### 2.3.2 Speech perception

Bilateral advantages have also been observed for speech perception in the presence of multiple spatially separated competing talkers (Dunn et al., 2010; Loizou et al., 2009). With two CIs, a patient can listen with the ear that has the better signal-to-noise ratio (Loizou et al., 2009). Furthermore, bilateral CI users can benefit from the head shadow, binaural squelch and binaural redundancy when listening to speech in noise (Müller, Schön, & Helms, 2002; Schafer et al., 2011; Schleich, Nopp, & D’Haese, 2004) although the head shadow has been shown to account for the majority of the benefit (Müller et al., 2002; Schleich et al., 2004).

### 2.3.3 Pitch perception

Cochlear implants do have some limitations. One limitation is that they do not convey the temporal fine structure of sounds very well (Nie, Stickney, & Zeng, 2005) and they also do not provide access to low frequency information due to a risk of cochlear damage from a deep insertion of the electrode array.  Although there will be differences between recipients and speech processors, cochlear implants intend to convey information between about 300Hz and 7000Hz (Başkent & Shannon, 2004). As a result CI users find pitch-related tasks difficult (Gfeller et al., 2007) such as vocal emotion recognition (Luo, Fu, & Galvin, 2007) and music perception (e.g. Cullington and Zeng, 2010).

### 2.3.4 Self-reported benefits

Research has shown better self-ratings for two CIs compared to one CI across the three sections of the SSQ (Noble, Tyler, Dunn, & Bhullar, 2009; Summerfield et al., 2006). Furthermore, Noble, Tyler, Dunn, and Bhullar (2008) compared self-reported ratings on the ten sub-sections of the SSQ between users of a single CI and users of bilateral cochlear implants. They found higher (greater self-rated ability) ratings for the bilateral CI users on the spatial sub-sections but no significant difference on the speech sub-sections. This finding was consistent with the participants' behavioural performance. The participants completed a speech perception in quiet task with monosyllabic words and a localisation task where a stimulus was presented from one of eight loudspeakers in the frontal horizontal plane. Consistent with the SSQ results, there was no significant difference in performance between the bilateral CI users and the unilateral CI users on the speech in quiet task. However the bilateral CI users performed significantly better on the localisation task than the unilateral CI users.

Unlike bimodal listeners described in Section 2.2.4, Noble et al. (2008a) did find that bilateral CI users reported less difficulty in hearing than unilateral CI users as measured on the Hearing Handicap Inventory for the Elderly. Furthermore, bilateral CI users reported less restriction on social activities than unilateral CI users as measured with both the Hearing Handicap Inventory for the Elderly and the Hearing Handicap Questionnaire. However, similar to the bimodal users there was no significant difference in emotional distress between bilateral and unilateral CI users. Out of a maximum of four with higher values indicating greater distress, bilateral CI users had a mean emotional distress of 0.85 (SD = .09) and unilateral CI users had a mean of 1.31 (SD = 1.1). Thus the bilateral CI users were not at floor but were numerically lower than unilateral CI users.

### 2.3.5 Quality of life

There is limited evidence to suggest that there are differences in quality of life between using one and two CIs. In one study, four different measures were administered to 28 CI users to determine quality of life values for unilateral and bilateral cochlear implantation (Summerfield et al., 2006). Both within-subject and between subjects comparisons were made. No significant differences in quality of life were found with between-group comparisons for any of the four measures. One measure used was the Glasgow Health Status Inventory (MRC Institute of Hearing Research, 1998) which assesses psychosocial aspects of quality of life. In a within-subjects comparison, this measure showed a significantly greater quality of life with two CIs after nine months compared to one CI. However, contrasting results were found with a generic health-related quality of life questionnaire, the EuroQol (Brooks, 1996), which showed a significantly poorer quality of life with two CIs compared to one CI after nine months of bilateral CI use. These contradictory results may be due to the fact that the EuroQol focuses on health aspects of quality of life, rather than psychosocial aspects. However, the researchers also administered another measure which focuses on health aspects of quality of life, the Health Utilities Index Mark III (HUI3, Boyle, Furlong, Feeny, Torrance, & Hatcher, 1995). Results from this measure showed no significant differences in quality of life between bilateral and unilateral CI listening. Furthermore a measure that assessed overall quality of life by asking participants to indicate their overall quality of life on a 100-point scale where 0 indicated the worst imaginable quality of life and 100 indicated the best imaginable quality of life also showed no difference between the groups. The researchers suggested that the lack of a positive benefit from two devices was due to worsening tinnitus among some individuals upon receiving a second CI. The impact of a second device on quality of life will be discussed in greater detail in Chapter 4.

### 2.3.6 Effectiveness of bilateral cochlear implantation

A recent systematic review assessing the effectiveness of bilateral CIs demonstrated that, compared to a single CI, bilateral CIs improve localisation ability and speech perception performance in the presence of background noise, but quality of life gains vary depending upon the measure used (Crathorne et al., 2012). Although an advantage of bilateral cochlear implantation is that the more physiological responsive ear is guaranteed to be implanted, undergoing two operations (as in sequential implantation) increases the risks which surgery poses.

In a review considering papers published up to July 2007, Bond et al. (2009) assessed five studies comparing bilateral to unilateral cochlear implantation in adults. Two studies investigated spatial hearing; one was self-reported spatial hearing as measured with the SSQ and the other was performance on a sound localisation task. Both studies found a significant benefit from bilateral cochlear implantation. Three studies investigated speech perception in quiet and in noise. All three studies found a bilateral advantage for speech in noise, and two out of three found a bilateral advantage for speech in quiet. This review has been followed up by van Schoonhoven et al. (2013) who reviewed the literature for studies published between October 2006 and March 2011. The five studies which were included in the review by Bond et al. (2009) and 14 more recent studies were assessed. Scores on performance measures were standardized to enable comparisons between listening configurations. The main findings echoed those of Bond et al.

(2009) in that there was a clear advantage of bilateral CIs compared to a unilateral CI in spatial listening ability.

## 2.4 Bimodal aiding or bilateral implantation

Whilst it has been demonstrated that using a second device, whether it be a CI or a hearing aid, provides advantages over one CI alone, it is less clear which option is the better choice. Each option offers different benefits suggesting there is a trade-off (van Hoesel, 2012). Although, as will be discussed in Chapter 4, bilateral cochlear implantation is not currently considered a cost-effective intervention (Bond et al., 2009; Crathorne et al., 2012; Summerfield et al., 2006), there is interest amongst individuals in obtaining a second device. Therefore it is important that unilateral CI users are aware of what can be achieved with each option in order to make an informed choice.

In a meta-analysis assessing speech perception in the presence of background noise (where noise included speech, other talkers, babble and broadband noise), the benefit of a second CI and a contralateral hearing aid were compared (Schafer et al., 2011). Effect sizes were calculated in order to compare studies on three aspects of potential benefit: binaural squelch, binaural summation and the head-shadow effect. The results of the meta-analysis showed that both options provided a significant benefit for users in terms of binaural summation and the head shadow effect. Whereas only a second CI provided significant benefit for binaural squelch. These results led Schafer et al. to conclude that a second CI offers only a slight advantage over a contralateral hearing aid. Noble et al. (2008b) found no significant difference between bilateral CI users and bimodal listeners on perception of monosyllabic words in quiet. Noble et al. also asked participants to indicate the location of everyday sounds presented in the frontal horizontal plane from eight loudspeakers separated by 15.5°. In this case they found a bilateral advantage. Bimodal users had a mean RMS error of 38° (see Table 2.1) whereas a group of 12 bilateral CI users had a mean RMS error of about 22° which was significantly less than the bimodal users. In a further study Cullington and Zeng (2011) compared performance by bimodal and bilateral CI users on four different pitch related tasks. Each task had a number of sub-tasks resulting in sixteen tests, so a Bonferonni correction was applied to correct for multiple comparisons. It was expected that bimodal users would perform better than bilateral CI users due to the fact that they had access to low-frequency information. Although bimodal performance was numerically better than bilateral CI users on the majority of the tasks, no differences were found to be significant. Thus adding to the uncertainty about which option is better for adult users of a single CI.

Comparisons between bimodal devices and bilateral CIs have also been made using self-report measures. Noble et al. (2008) compared ratings on the SSQ between 16 bimodal and 18 bilateral CI users (of a similar age and with similar lengths of CI experience) and found few differences. Without correction for multiple comparisons, a significant advantage was found for bilateral cochlear implantation over bimodal listening in three of the ten sub-sections (speech in speech, distance and movement, and listening effort), whereas the other seven sub-sections showed no significant differences. Furthermore, Noble et al. (2008a) found that self-reported difficulty in hearing, emotional distress and restriction of social activities was reduced for users of bilateral CIs compared to bimodal aiding. These findings suggest that there may be a slight advantage for bilateral cochlear implantation compared to bimodal aiding.

In a review of the literature comparing listening performance and self-rated sound quality, Ching, van Wanrooy, and Dillon (2007), highlighted advantages and disadvantages of each option. However, based on the available evidence, they were unable to conclude that one option was better than the other. A more recent review considering research published between 2006 and 2010 focussed on  speech perception, localisation and self-reported ability (Sammeth, Bundy, & Miller, 2011). The review showed that bimodal aiding provided speech perception benefits, and binaural advantages from the head shadow effect and binaural redundancy, whereas mixed results were found for localising sounds. On the other hand, localisation ability with two CIs was shown to be much better than with one CI. Furthermore, bilateral CIs provided advantages for speech perception in quiet and in noise. Both options were found to have some self-reported benefits with bimodal users reporting a more natural sound over a single CI. However, although the authors were able to conclude that each option provides benefits over a single implant alone, they too were unable to reach a conclusion as to which option is better. Problems in drawing a conclusion stemmed from the limited amount of research directly comparing the two options, small samples sizes limiting statistical power, and varying methodologies. In a review by Bond et al. (2009), no studies comparing bimodal aiding to bilateral cochlear implantation in adults were found. In a more recent review, van Schoonhoven et al. (2013) highlighted that the limited number of studies investigating this comparison restricted the ability to draw firm conclusions. Indeed, in their review of the literature from 2006-2011, only three studies compared bimodal aiding to bilateral CI use and there was an overlap in the patients tested between the three studies. One study Noble et al. (2009) only analysed the effect of age on performance. The other two (Noble et al., 2008a, 2008b) have been discussed above.

### 2.4.1 Literature search

Against the background of the conclusions reached in the previous section, a literature search was conducted in PubMed (National Center for Biotechnology Information, n.d.) in August 2014 using the search terms ''cochlear implant*' AND 'bilateral' AND (bimodal OR "hearing aid"). When the search was limited to publications in English between January 2009 and August 2014 there were 97 results. To be included in the following review the paper must have been reporting a comparison between bimodal aiding and bilateral CI use in adults and not be a review. Titles and abstracts were assessed to determine if they met the inclusion criteria. If uncertainty remained the full text was reviewed to assess whether the article met the inclusion criteria. 13 articles were excluded due to being review papers and 21 articles were excluded because they focused on children. 10 articles concerned a different topic (e.g. tinnitus and ageing), 13 papers concerned other devices (including unilateral cochlear implantation and auditory brainstem implants), 19 studies focussed on just bimodal listening, 8 papers focused on just bilateral cochlear implantation, and four further studies did not compare performance between bimodal and bilateral listeners (two investigated the effect of age on the benefit obtained and two used the use of a contralateral hearing aid or bilateral CIs as predictors on performance on music tasks but did not directly compare overall performance). Thus 9 papers remained; summaries of these papers are displayed in Table A1. Two papers covered the same study and have been summarised together.

There was a hint from the results from Yoon, Shin, and Fu (2012) that the amount of residual hearing remaining may be important in the benefit obtained from a contralateral hearing aid for speech perception. They divided a group of 13 bimodal users into a 'good group' (n = 7) and a 'poor group' (n=5) based on their audiometric thresholds. Good users had pure tone average thresholds less than 55dB HL (over 250, 500, 750 & 1000 Hz) whereas the poor group had loses greater than 55dB HL. They found that the benefit obtained from the hearing aid was significantly greater for the good group than the poor group for speech perception in quiet and noise.

#### 2.4.1.1 Comparison of studies

Similar to van Schoonhoven et al. (2013) effect sizes for the difference between bimodal and bilateral performance were calculated as:

$$Effect\ size = \frac{(Bilateral\ mean - Bimodal\ mean)}{\text{Pooled SD}}$$

In the case of speech in noise tasks with SRT as a measure, where a lower value indicates better performance, the result was multiplied by minus one. 95% confidence intervals were calculated as follows:

$$95\%\ CI = Effect\ size\ \pm (1.96\ x\ SE)$$

The results are shown in Figure 2.2.

##### 2.4.1.1.1 Localisation

Only one study (Potts & Litovsky, 2014) compared localisation ability between bimodal aiding and bilateral CI use. They did not report a measure of variance for performance by each group and therefore are not included in this analysis.

##### 2.4.1.1.2 Speech in quiet

Five papers included in the review investigated speech perception in quiet. Two studies could not be included in the analysis: Potts and Litovsky (2014) did not report a measure of variance for overall performance by each group. Yoon et al. (2012) reported overall performance graphically but the mean and SD could not be inferred from their figures. Kong et al. (2012) plotted mean performance and SE on graphs, the mean was extracted and the SD was calculated from the SE. Three out of four results showed the effect size did not differ significantly from zero. One finding (Sasaki, Yamamoto, Iwaki, & Kubo, 2009) had an effect size significantly smaller than zero indicating an advantage from bimodal aiding compared to bilateral CIs on speech perception of monosyllabic words.

##### 2.4.1.1.3 Speech in noise

Four studies reported speech in noise performance. Similar to the speech in quiet results Yoon et al. (2012) presented performance on the task graphically. The mean and SD could not be extracted from these figures and therefore they are not included in the analysis. Gifford et al.

(2014) presented percentiles as a measure of variability. As it was unclear from the report whether the data were normally distributed, the results are not included in this analysis. Cullington and Zeng (2011) reported three measures of speech in noise performance and Kokkinakis and Pak (2014) also presented three measures. Across these six measures, effect sizes did not differ significantly from zero demonstrating no difference between the two options. It is important to note that in binaural listening to speech in noise when the noise was presented ipsilateral to the first (or only) CI, the effect size showed a trend of better performance with bilateral CIs but this was not significant.

#### 2.4.1.1.4 Self-reported ability

Two studies compared self-reported listening ability. One study (Potts & Litovsky, 2014) did not report mean performance or a measure of variability for either group and therefore is not included. Results showed that the effect size of Perreau et al. (2014) was significantly greater than zero indicating a significant advantage from bilateral CIs compared to bimodal aiding.

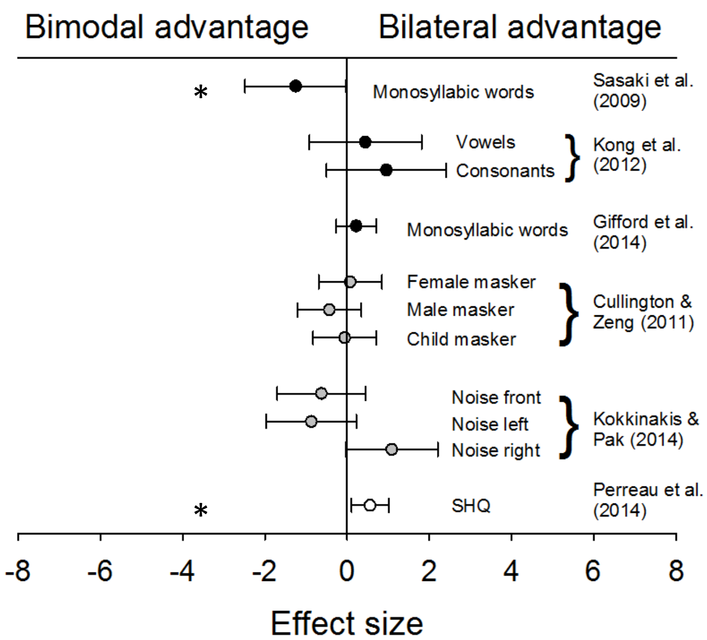


**Figure 2.2. Effect sizes and 95% confidence intervals from studies included in the review. Black circles indicate speech in quiet tasks. Grey circles indicate speech in noise task. The white circle indicates a self-report measure the Spatial Hearing Questionnaire (SHQ). Asterisks indicate that the effect size is significantly different from zero. For bimodal users in the study reported by Kokkinakis & Pak (2014) 'Noise left' was on the side of their acoustic hearing aid and 'Noise right' was on the side of the cochlear implant.**

Consistent with the earlier reviews discussed in this chapter (Ching et al., 2007; Sammeth et al., 2011; van Schoonhoven et al., 2013) this review found the following. (1) Only a limited number of studies have directly compared bimodal aiding with bilateral CI use in adults. (2) Of those studies that did include a comparison, varying methodologies were employed. (3) When results were standardized, for the most part there was no difference in performance. In summary, this review found no clear advantage of one option over the other.

## 2.5 Conclusion

Whilst the literature has demonstrated advantages of both bimodal aiding and bilateral cochlear implantation over using a single CI, there is a lack of certainty about which option is more advantageous to patients. Few studies have directly compared bimodal aiding to bilateral CI use and of those that have, differences in methodology restrict clear conclusions from being drawn. There are hints of a trade-off in listening abilities, with bilateral CIs offering greater spatial listening abilities but with reduced ability to use pitch information, and bimodal aiding offering a more natural sound quality and improved speech perception but minimal advantage in spatial listening skills. Much of the research has shown intersubject variability, with some individuals displaying great benefit from a second device, whilst others show minimal benefit. It would be of interest to identify why some individuals perform well whilst others do not. Small sample sizes make this task challenging and at present a clear explanation for these differences is lacking. The inconclusive findings highlight the need for a randomised control trial to be conducted to compare bimodal aiding to bilateral cochlear implantation on a variety of different behavioural and self-report measures. Thus, whilst the evidence suggests that a second device should be used by users of a single CI, whether it would be better to use a second CI or a contralateral acoustic hearing aid, remains at present unresolved.

# 3 Contribution of head movements to sound localisation

## 3.1 Introduction

It has long been known that rotations of the head can aid in locating sources of sound (Wallach, 1940). Specifically changes in yaw (head movement from left to right) can aid localisation of sources in the horizontal plane. Changes in pitch (head movement up and down) and roll (rolling the head from side to side so that one ear becomes closer to one shoulder) can help determine where in elevation a sound is located. Head movements alter the interaural differences between the ears. For instance, should a sound be presented from straight ahead, there will be no ILD or ITD (see Chapter 2). However, rotating the head to the left will mean that the sound will reach the right ear earlier than it reaches the left ear. Furthermore the sound will be louder at the right ear. This chapter will summarise the role head movement have been shown to play in helping normally-hearing and hearing-impaired listeners (including CI users) locate a sound.

## 3.2 Normally-hearing listeners

Table B1 summarises findings from studies that have investigated head movements by normally-hearing adults. Head movements have been shown to improve horizontal localisation (Mueller, Meisenbacher, Lai, & Dillier, 2014; Perrett & Noble, 1997a; Pollack & Rose, 1967) and vertical localisation (Perrett & Noble, 1997b; Wightman & Kistler, 1999). Furthermore, permitting head movements has been shown to reduce the number of front-back confusions made in the horizontal (Mueller et al., 2014; Perrett & Noble, 1997a) and vertical (Perrett & Noble, 1997b; Wightman & Kistler, 1999) planes.

### 3.2.1 Localisation accuracy

Perrett and Noble (1997a) found that when participants were instructed to rotate their head to the left by 45° while a sound stimulus was presented, horizontal localisation accuracy improved compared to when head movements were not permitted. Allowing participants to make natural head movements during the presentation of a three second stimulus, improved horizontal localisation accuracy significantly compared to when head movements were not permitted. When the stimulus was only 0.5 seconds long this effect was not found. The authors commented that the onset of a natural head movement was unlikely to have been achieved before this short stimulus ceased. Thus in order for normally-hearing listeners to benefit from head movements the stimulus needs to be sufficiently long for a head movement to be made whilst the stimulus is being presented.

This effect of duration was also noted by Pollack and Rose (1967) who found participants were more accurate locating a one second stimulus than a 15ms stimulus. However they found mixed results on the effect of head movement. In one experiment localisation error increased when the rate of head movement increased. In this experiment participants were instructed to locate a brief click (15ms) presented from one of 19 loudspeakers in the horizontal plane. One participant was instructed to move their head from left to right (or right to left) at two speeds: 120°/s or 40°/s. At 120°/s the average localisation error was 5.1° but the average error reduced to 3.7° at 40°/s. In a follow up experiment, a light was presented to pace head movements at 120°/s and at 40°/s. This time the average localisation error was similar across fast (10.75° error) and slow (10.70° error) movement speed conditions. However, this was significantly higher than the error obtained when no head movement was permitted (3.1°). In three further experiments, participants were permitted to move their heads as if “searching for an auditory target”. In two out of the three experiments, localisation accuracy was better when head movements were permitted. However, in each of the five experiments reported by Pollack and Rose, no more than three participants were tested, which limits the generalizability of the findings.

In a more recent study with eleven normally-hearing listeners, Mueller et al. (2014) found that head movement improved localisation accuracy if the stimulus was long enough. Participants located a target sentence in the presence of background noise in the horizontal plane. The sentence was either short (503ms), medium (2.18s), or long (4.45s) in duration. The average RMS error was significantly reduced when head movements were allowed for the medium and long stimuli. Consistent with Perrett and Noble (1997a), no benefit from head movements was found for the short stimuli, suggesting that half a second is not long enough for listeners to make a beneficial head movement.

### 3.2.2 Front-back confusions

Perrett and Noble (1997a) compared performance in three conditions: forced head movement where participants turned 45° to the left following stimulus onset, natural head movements permitted after stimulus onset, or no head movement permitted. In the forced head movement condition, very few front-back confusions occurred (about 2% of trials with a 3s stimulus and about 4% of trials with a 0.5s stimulus). With a 0.5 second stimulus the number of front-back confusions made when participants rotated their heads was significantly less than when participants kept their heads still (about 25% of trials) and significantly less than when they could move their heads as they wished (about 17% of trials). However, when the stimulus was longer at three seconds, the number of front-back confusions made when participants could move their heads as they wished was similar to the forced head rotation condition at about 1% of trials, which was significantly less than the number of front-back confusions made when participants kept their heads still (about 30% of trials). Further support for the notion that head movements can reduce front-back confusions comes from Perrett and Noble (1997b). They found that when participants oscillated their heads between ±30° there were no front-back confusions for sources in the upper vertical plane. However, when head movements were not permitted, front-back confusions were made on 27% of trials. It is important to note that each participant completed just 7 trials per condition. When the number of trials was increased and the possible locations were extended by using 17 loudspeakers across the full 360° of the vertical plane, just 0.4% of trials resulted in a front-back confusion. As there were 22 participants completing 34 rotation trials each, this was just three errors across the whole data set. When head movements were not permitted, 35% of trials resulted in a front-back confusion.

Mueller et al. (2014) found that the effect of head movement on the number of front-back confusions was dependent upon the duration of the stimulus. Although not significant, numerically fewer front-back confusions were made with a 503ms stimulus when head movements were permitted than when they were not permitted. When the stimulus was 2.18 seconds of longer, permitting head movements resulted in no front-back confusions.

### 3.2.3 Head movement trajectories

Wightman and Kistler (1999) recorded the yaw, pitch and roll made by listeners during a sound localisation task. A visual inspection of the head movements made revealed that participants tended to turn their heads in the direction of the target. This finding is consistent with Mueller et al. (2014). Interestingly, Wightman and Kistler found that those individuals who made many front-back confusions when head movements were not permitted, made large head movements when head movements were permitted. Conversely those individuals who made few to no front-back confusions when head movements were not permitted made few head movements when they were permitted. The authors argued that individuals who do make front-back errors use head movements to take advantage of the cues available to reduce the confusion. Conversely those who do not make front-back errors do not require head movements to perform well.

In an earlier study Thurlow, Mangels, and Runge (1967) presented a five second noise stimulus from one of 10 loudspeakers located in the horizontal and vertical planes. Participants were instructed to move their head as much as they liked (but not their bodies) after the onset of the stimulus. Changes in yaw, pitch and roll greater than 3° were used to categorize the pattern of movement a participant made. They found that maximal changes in yaw were greater than changes in pitch and roll, and, consistent with the later findings of Wightman and Kistler (1999) and Mueller et al. (2014), the majority of participants turned towards the target source. Whilst 23 participants were included in the analyses, a number of other participants were tested but excluded due to no head movements being made. Despite not measuring localisation accuracy the authors excluded the participants from the analysis as *they "[felt] that these subjects found the problem of localizing in three dimensions very difficult, and they did not really know how to go about it"* (pp. 90). However, this may not have been accurate as when the findings from Wightman and Kistler (1999) are considered it may have been that these participants chose not to move because they did not need to in order to perform well. As localisation accuracy was not measured by Thurlow et al., it is not possible to confirm this speculation.

## 3.3 Hearing-impaired listeners

Previous research has demonstrated that hearing-impaired listeners make more complex head movements when attempting to orient to an auditory target. For instance, Brimijoin et al. (2010) instructed participants to orient towards an auditory stimulus or a visual stimulus presented from one of 11 loudspeakers in the frontal horizontal plane (-75° to +75°). They found that while a group of 17 normally-hearing adults undershot both auditory and visual targets to the same degree (see Table B1), a group of 14 hearing-impaired adults undershot auditory targets less than visual targets (see Table B2). Furthermore, hearing-impaired listeners made more complex head movements in orienting to auditory stimuli than normally-hearing listeners. Brimijoin and colleagues fitted increasingly higher order polynomial functions to the trajectories made until the head movement was accurately fitted. The lowest order of polynomial which did this was taken as an index of the complexity of the head movement. It was found that, for every 20dB increase in four-frequency-average hearing loss the mean polynomial order increased by about 1. The hearing-impaired listeners were also slower to orient to auditory stimuli than the normally-hearing listeners. Whilst the normally-hearing listeners took 0.9 seconds on average to orient to the target location, the hearing-impaired listeners needed on average 1.3 seconds, which was the duration of the stimulus itself.

Other research has demonstrated that hearing-impaired listeners may use head orientation as a strategy for coping with their loss in adverse listening environments. For instance, Brimijoin, McShefferty, and Akeroyd (2012) investigated the head orientation strategies used by hearing-impaired listeners during a speech in noise task. 36 listeners with asymmetrical hearing impairment participated. A target sentence was presented from one of five locations in the horizontal plane and noise was presented from one of five separations from the target. It was found that individuals who had better hearing in their left ear, oriented their heads to the right of the target, and individuals with better hearing in their right ear oriented their heads to the left of the target. This strategy maximised the level of the signal. However the strategy was the same regardless of the location of the noise suggesting that listeners did not seek to maximise the signal-to-noise ratio.

### 3.3.1 CI users

Buhagiar, Lutman, Brinton, and Eyles (2004) tested localisation performance in the frontal-horizontal plane by a group of 18 unilateral CI users using seven types of stimuli (including speech, noise and tones, see Table B2). It was not their primary objective to investigate the role of head movements on sound localisation but in one condition participants were permitted to move their heads. In all other conditions participants were instructed to keep their heads still. It was found that when head movements were not permitted localisation accuracy was significantly better for sound presented on the side ipsilateral to the CI than sounds presented on the contralateral side. However, when head movements were permitted performance improved (although still remained poor with an average RMS error of 49°) and there was no difference in accuracy performance for sources presented on either side of the listener.

This finding is somewhat discrepant to that found by Tyler, Noble, Dunn, and Witt (2006). They found that even when head movements were permitted, unilateral CI users were unable to localise sounds when they were presented from the side of the horizontal plane (exact target locations were not reported). The position of the loudspeakers could account for this difference in finding. Whereas Bulagiar et al. (2004) positioned loudspeakers in the frontal horizontal plane from -90° to +90°; the results from Tyler et al. were from a condition where all loudspeakers were reported to be positioned to the side of the listener. Tyler et al. also tested bilateral CI users and found that when head movements were not permitted and the loudspeakers were positioned to the side, the bilateral CI users were unable to accurately locate the source of the sound. This was likely due to the inability of listeners to judge the location of a sound on the ‘cone of confusion’. The ‘cone of confusion’ refers to the fact that for a given ITD there are a number of possible locations (Plack, 2014), which can result in front-back and up-down confusions as discussed in section 3.2.2. When head movements were permitted, localisation accuracy by bilateral CI users was near perfect. This demonstrates that bilateral CI users can make use of head movements to alter the ITD and ILD and resolve where the sound is located. These findings demonstrate that whilst head movements can help improve localisation accuracy by bilateral CI users, they do not help unilateral CI users to locate sounds very well.

Head movements can also help improve speech perception performance in adverse listening conditions. For instance, in their model, Culling, Jelfs, Talbert, Grange, & Backhouse (2012) predicted that if speech is presented at 0° azimuth and noise is presented at +90° azimuth bilateral CI users could increase their spatial release from masking (SRM) from 3.5dB to 7dB if they rotated their head from 0° azimuth to 20° azimuth. In addition, a further 1.25dB of SRM could be achieved if the bilateral CI users turned to 30° azimuth. Furthermore, head movements can help bilateral CI users reduce the number of front-back confusions made during a localisation in noise task. For instance, Mueller et al. (2014) measured the localisation accuracy of seven bilateral CI users in the presence of background noise. In the same set-up described in section 3.2.1 for normally-hearing adults, head movement was either permitted or not permitted and the target stimulus was either short (503ms), medium (2.18s) or long (4.45s) in duration. Although angular accuracy did not improve from permitting head movements, the number of front-back confusions was significantly reduced when head movements were permitted for the medium and long stimuli, from about 24% of trials when head movements were not permitted to about 8% of trials when head movements werepermitted. Permitting head movements did not reduce the number of front-back confusions for short stimuli. Mueller et al. monitored the head movements made by the bilateral CI users. They found that listeners tended to make search-like movements, which were more complex and longer in duration than the head movement trajectories made by normally-hearing listeners (see Table B2).

## 3.4 Conclusion

Both normally-hearing and hearing-impaired-listeners can benefit from head movements for improving localisation accuracy. When head movements are permitted, normally-hearing adults tend to orient their heads towards the source of the target and few to no front-back confusions occur. There are suggestions in the literature that some normally-hearing adults opt not to move their heads when permitted to do so because they perform well even when head movements are not permitted. Hearing-impaired individuals take longer than normally-hearing adults to orient their head to a target source. Furthermore when localising, they make more search-like movements resulting in longer and more complex head movement trajectories than normally-hearing listeners.

When head movements are permitted localisation accuracy in the frontal-horizontal plane by unilateral CI users remains. When the sources of sound are moved to the side of the listener in the horizontal plane, unilateral CI users do not benefit from head movements. However, bilateral CI users do benefit from head movements in this configuration, demonstrating that they are able to make use of the changes in ITD and ILD that are afforded by making head movements, to reduce the number of front-back confusions. For both normally-hearing and hearing-impaired individuals the duration of the stimulus had an influence on the effect of head movements. When the stimulus is short (about 0.5 seconds or less) performance is not better when head movements are permitted. This is likely due to insufficient time available to begin a head movement, with the target sound ceasing before a head movement has begun or been completed.

In conclusion, if the sound is long enough, head movements can improve localisation performance for both normally-hearing and hearing-impaired listeners. Furthermore, whilst users of bilateral CIs can benefit from making head movements to alter the ITD and ILD, unilateral CI users do not have access to these cues to help them.

## 3.5 Summary

- Head movements can improve angular accuracy and reduce front-back confusions for normally-hearing adults if the sound is long enough for a head movement to be made.
- Normally-hearing adults typically orient their heads towards the target sound during tasks of localisation.
- Hearing-impaired listeners make longer, more complex head movements than normally-hearing listeners when attempting to locate a sound.
- Like normally-hearing adults, hearing-impaired listeners can benefit from head movements in reducing front-back confusions if the sound is long enough for a head movement to be made.

# 4 Cost-effectiveness of a second device for adult users of a single cochlear implant

With limited resources available to fund healthcare, policy makers must prioritise the treatments to which they allocate funding. Cost-effectiveness analyses can inform the setting of priorities by ranking treatments in terms of the cost of gaining increments in health-related quality of life. This chapter will first outline what health-related quality of life (Health Utility) is and how it can be measured. The chapter will then discusses the strengths and limitations of existing self-report systems (i.e. questionnaires and methods for scoring them) for measuring health-related quality of life for hearing-impaired individuals. Next, how measures of health utility are used in calculations of incremental cost-effectiveness ratios will be explained before the existing literature on the cost-effectiveness of a second device for users of a single CI is evaluated.

## 4.1 Health-related quality of life (Health Utility)

With any disorder it is important to know the impact it has on people and the effectiveness of available treatments. When multiple treatments are available, it is important to ascertain which treatment is most effective. Policy makers need to measure the impact of disorders and the effectiveness of treatments on generic scales that are applicable to all disorders and interventions. This enables comparisons to be made between disorders and treatments. Measures of health-related quality of life address this requirement and can be obtained either directly or indirectly. Using the direct approach, an individual is asked to use either the standard gamble technique or the time-trade-off method to value their current health state or value a description of a hypothetical health state which they are instructed to imagine applies to them. These methods (discussed in detail below) are used to indicate a respondent's preference for a health outcome. Whilst the standard gamble produces 'utilities' and the time-trade-off technique produces 'values' the terms are frequently used interchangeably to indicate preference (Drummond, O'Brien, Stoddart, & Torrance, 2000). This thesis will use the term 'utility' to indicate preference.

Using the indirect approach, an individual completes a questionnaire to indicate what their current health state is. For the indirect approach, a utility value for that health state is assigned from valuations provided by a group of informants who used the direct approach to value some or all of the possible combinations of states which the questionnaire can define. This is the preferred method for assigning a value of health utility to a patient's health state. The standard gamble and time-trade-off techniques are conceptually demanding and also invoke the concept of early death and as such are not appropriate methods to use directly with patients. Furthermore, guidelines from NICE (2013) state that health-related quality of life valuations should be obtained from a large, representative sample of the UK population.

### 4.1.1 Standard gamble

In the standard gamble technique, participants are faced with a scenario in which they have to weigh up the risks of receiving a particular treatment. If the treatment is successful they would have perfect health for the rest of their life. If the treatment fails then they would die an immediate yet painless death. The task for the participant is to consider the risks of receiving a treatment and determine a probability of success for which they would be indifferent between taking the gamble and remaining in their current health state for the rest of their life (Drummond et al., 2000). This probability is taken as the utility value for that health state. The standard gamble is widely regarded as the 'gold standard' of utility valuations because it requires a decision under conditions of uncertainty and risk (Drummond et al., 2000; van Osch & Stiggelbout, 2008). However, the standard gamble is sensitive to loss aversion in which people value potential losses greater then they value potential gains. van Osch and Stiggelbout (2008) asked participants to think aloud whilst completing a standard gamble exercise with six rheumatioid arthritis health state descriptions. The researchers coded the number of times participants mentioned (together with the probability of it happening) the good outcome from the gamble, the bad outcome from the gamble, and the certain outcome. The most frequently mentioned outcome was determined to be the focus of attention. It was found that when attention was focused on the negative outcomes higher utility values were observed, whereas when participants focused on the positive outcomes a lower utility value was obtained. Attention was not directly manipulated by the experimenters, therefore results could be due to individual differences (e.g. individuals who focus on the negatives may also be more likely to give lower utility values) rather than a causal inference. Future research could manipulate attention by changing the wording in the instructions.

### 4.1.2 Time-trade-off technique

With the time-trade-off method, a health state is described and the respondent evaluates how many years (f) in perfect health they judge is equal to living a number of further years (y) with the health difficulties described. Health utility is calculated as f/y. The time-trade-off technique is a convenient method using hypothetical scenarios, which therefore avoids the need to question patients directly. However, there is wide variation among studies in the number of further years that have been used with this technique (Arnesen & Trommald, 2005). Heintz, Krol, and Levin (2013) used actuarial life expectancy based on the age and gender of the participant. However, many other studies have used a fixed number of years with the aim of levelling the playing field for all respondents. Some studies have used 10 years (Dolan, Gudex, Kind, & Williams, 1996; van Nooten, Koolman, & Brouwer, 2009; van Nooten, Koolman, Busschbach, & Brouwer, 2013), or other fixed amounts of time from one month to fifty years (Attema & Brouwer, 2012; Perez, McGee, Campbell, Christensen, & Williams, 1997; Summerfield, Lovett, Bellenger, & Batten, 2010). Other studies have used participant specific durations from current age to a specified age (Summerfield, Marshall, Barton, & Bloor, 2002; van Nooten & Brouwer, 2004).

The study reported in Chapter 8 used the time-trade-off technique rather than the standard gamble as it is less conceptually demanding. Furthermore responses using the time-trade-off technique have been demonstrated to be reliable in test-retest investigations (Dolan et al., 1996). Therefore the following discussion focuses on the time-trade-off technique.

### *Limitations of the time-trade-off technique*

The concept of constant proportional trade off suggests that individuals should be willing to trade the same proportion of life regardless of the time horizon used. For example, if they were willing to trade one year in a 10-year time horizon, they should be willing to trade 5 years in a 50-year time horizon. However, in a review of the literature, Attema & Brouwer (2010) found constant proportional trade-off is not always evident and that the time horizon can have an influence on utility values. They highlight that with long time horizons participants may be unwilling to trade beyond a certain number of years (maximum trade) whereas with shorter durations participants may be unwilling to live less than a certain amount of time (minimum life remaining).

Numerous demographic variables have been shown to impact the willingness of a participant to trade life years; therefore it is important that studies seeking valuations of health states use a large, representative sample. One such variable that has been shown to impact valuations is subjective life expectancy. For instance, if a respondent is asked to imagine that they will live until they are 80 years old but they expect that they will live until they are 83 years old they may feel they are being cheated out of three years of life and will trade less. Whereas those who have a subjective life expectancy less than 80 may feel they have bonus years and are therefore likely to trade more. This effect has been shown in several studies (van Nooten & Brouwer, 2004; van Nooten et al., 2009, 2013). Indeed, even when actuarial life expectancies are used for each participant, subjective life expectancy can have an influence, with those expecting to live longer willing to trade fewer years, and those expecting to live a shorter period of time trading more years (Heintz et al., 2013). Age and educational level have also been shown to impact willingness to trade, with older adults less willing to trade, and those with higher education more willing to trade (van Nooten et al., 2009, 2013). Furthermore, the time-trade-off technique is sensitive to differences in the way the task is explained. van Nooten et al. (2013) developed two questionnaires that asked participants to value three health states using the time-trade-off technique with a ten-year time frame. One questionnaire explicitly made the ten-year time horizon clear to participants by asking them how old they would be in ten years' time before each question. The other questionnaire was identical to the first one, except the ten-year time horizon was not made explicitly clear. It was found that when the amount of time was made explicit, 42% of respondents were unwilling to trade any life compared to only 21% who completed the implicit questionnaire. Furthermore, those who completed the explicit questionnaire and did choose to trade life traded fewer years than those in the implicit condition.

Despite the limitations surrounding the time-trade-off technique, it is widely used in the valuation of health states. However, no widely agreed guidance exists on how the time-trade-off method should be structured (e.g. time horizon, response method, instructions, etc., Attema, Edelaar-Peeters, Versteegh, & Stolk, 2013).

## 4.2 Generic measures of health-related quality of life

In addition to the direct measures highlighted above, indirect measures can also be used to measure quality of life. Generic health-related quality of life instruments can be used to measure the effectiveness component for use in a cost-effectiveness analysis. By using instruments that result in a common metric, comparisons between treatments can be made to ascertain which treatment provides the greatest benefit. Responses to generic health-related quality of life instruments are converted to a utility score where 1 corresponds to perfect health and 0 corresponds to being dead. Scores less than zero indicate that the health state is considered to be worse than being dead.

The EuroQol questionnaire (EQ5D, Brooks, 1996; The Euroqol Group, 1990) is a generic instrument assessing health-related quality of life. It contains five multiple choice questions. Each question focuses on a domain of health (mobility, self-care, usual activities, pain/discomfort, and anxiety/depression) with three levels of difficulty (no difficulty, some difficulty, and extreme difficulty). Users of the instrument are instructed to select the level of difficulty which best describes how they function in each domain. There are 243 possible combinations of difficulties. A subset were valued by a representative sample of 2997 adults in the United Kingdom using the time-trade-off technique allowing an algorithm to be derived which assigns a value of health utility to any combination of difficulties (Dolan, Gudex, Kind, & Williams, 1995). Similar valuation exercises have been conducted in other countries (Lamers, Mcdonnell, Stalmeier, Krabbe, & Busschbach, 2006; Shaw, Johnson, & Coons, 2005; Tsuchiya et al., 2002; Weijnen, Nieuwenhuizen, Ohinmaa, & de Charro, 2003; Wittrup-Jensen, Lauridsen, Gudex, & Pedersen, 2009).

The EQ5D is quick to complete and uses straightforward terminology. From a UK perspective it also has the advantage of being valued by a UK sample and it is the preferred instrument for measuring health-related quality of life by NICE (2013). However, the EQ5D does not include any questions related to hearing or listening, nor speech understanding. Furthermore, for many individuals, hearing loss develops sufficiently gradually that they accommodate their 'usual activities' to their loss. As a result, they may indicate that they do not have any difficulties in this domain, despite being restricted in the range of activities with which they can engage. These limitations make the EQ5D relatively insensitive to hearing-related difficulties (e.g. Grutters et al., 2007). Indeed, many hearing-impaired individuals are assigned a utility score of 1 ('perfect health') by the EQ5D (Barton, Bankart, & Davis, 2005; Grutters et al., 2007).

The Health Utilities Index Mark 3 (HUI3, Boyle, Furlong, Feeny, Torrance, & Hatcher, 1995; Feeny et al., 2002; Torrance, Furlong, Feeny, & Boyle, 1995) is another widely used generic instrument measuring health-related quality of life. This instrument covers eight domains (vision, hearing, speech, ambulation, dexterity, emotion, cognition, and pain), each having five or six levels of difficulty. There are 970,000 possible combinations of levels, of which a subset has been evaluated by members of the Canadian general public (Feeny et al., 2002). The HUI3 focuses on physical and emotional wellbeing and does not cover social aspects of health-related quality of life (like the 'usual activities' question in the EQ5D). However, it includes questions specific to hearing and the ability to be understood whilst speaking. As a result it is sensitive to improvements in quality of life due to better hearing (Barton et al., 2005; Grutters et al., 2007; United Kingdom CI Study Group, 2004). Indeed recent reviews of generic instruments for use with patients with hearing difficulties have shown that the HUI3 is able to detect differences between groups of people with different hearing loss severity whereas the EQ5D is for the most part insensitive to differences (Longworth et al., 2014; Yang, Longworth, & Brazier, 2013).

However, even with its higher sensitivity, Lovett, Kitterick, Hewitt, & Summerfield (2010) found no significant differences between utility values from the HUI3 from parental valuations of children with bilateral and unilateral CIs. Furthermore, Summerfield et al. (2006) found no differences in utility values measured with the HUI3 between bilaterally and unilaterally implanted adults. These findings arose despite there being significant advantages in measures of performance from bilateral cochlear implantation in both children and adults. Thus it could be that the self-reported and behavioural benefits obtained from a second CI do not lead to an increase in health-related quality of life, or it could be that the benefits do improve health-related quality of life but that current instruments are not sufficiently sensitive to detect differences between monaural and binaural hearing. If the latter is the case this could have serious implications for determining the cost-effectiveness of treatments intended to improve binaural hearing. This issue will be addressed in Chapter 8 where the development and validation of a new questionnaire to measure 'hearing-related quality of life' is described.

## 4.3 Using utility in cost-effectiveness analyses

Generic quality of life instruments assign a utility value to a respondent based on valuations made by members of the public. If a respondent who has received a treatment is assigned a value of .7 there are two questions that can be asked: First, is this post-treatment utility value greater than the pre-treatment value (in effect, is the treatment providing any benefit to health-related quality of life)? Second, is the difference in utility values large enough to warrant providing funding (i.e. does the benefit justify the cost of providing the treatment)? In the case where multiple treatments are available, in order to represent an accurate measure of cost-effectiveness it is important that the analyses are conducted by making comparisons with the 'next best alternative'. This is the preferred method outlined by NICE (2013). For instance, whilst the impact of providing one hearing aid should be compared to listening with no aids, an intervention of two hearing aids should be compared to listening with one hearing aid (as this would be the next best alternative).

### 4.3.1 Effectiveness

NICE's preferred form of economic evaluation of an intervention is through a cost-effectiveness analysis in which the effects of an intervention are estimated as a number of quality adjusted life years gained (QALYs, NICE, 2013). A QALY is a measure that takes into account both quality and quantity of life. Utility values can be converted into QALYs by multiplying the utility value by the remaining life years. For example, take a hypothetical 30 year old patient who is expected to live until they are 80 years old. Imagine that prior to an intervention they had a utility value of .50. Had they remained in this state until death at 80 years old they would have continued to live for 25 QALYs (.50 x 50 years). However, if they were to receive an intervention (option A) at 30 years old that did not improve the quality of their life but did extend their life by 10 years they would continue to live for 30 QALYs (60 years x .50). This would be a gain of 5 QALYs from their original state. Alternatively, were the patient to receive a different treatment (option B) at age 30 that did not extend their life but did improve their life quality so that they had a utility value of .7, they would have gained 10 QALYs (.70 x 50 years) – (.50 x 50 years).

### 4.3.2 Costs

In the UK, the costs taken into consideration in cost-effectiveness analyses are the cost to the NHS and personal social services (NICE, 2013). The financial cost of the intervention, the cost of resources (e.g. hospital stays), and the potential savings that would be made from the intervention are all considered. As with effectiveness, costs over a reasonable time horizon long enough in duration to consider all important costs (e.g. repeated prescriptions) are taken into account.

### 4.3.3 Discounting

Typically individuals have a preference for receiving benefits earlier and paying costs later. This has led economists to discount future costs and benefits. By doing so, the savings and costs incurred to the health service now have a greater weight on the decision making process than future savings and costs. In the UK, under current guidelines (NICE, 2013), benefits and costs are discounted at a rate of 3.5% per annum. Costs and benefits are discounted as follows:

$$Discounted\ cost = \frac{c}{(1+d)^y}$$

(Where c is the cost incurred in the future year, d is the discount rate, and y is the number of years in the future).

$$Discounted\ benefit = \frac{q}{(1+d)^y}$$

(Where q is the number of QALYs gained in the future year, d is the discount rate, and y is the number of years in the future).

### 4.3.4 Cost-effectiveness analysis

The incremental cost effectiveness ratio (ICER) is the cost per QALY gained and is determined from evaluating the incremental cost and benefit as shown below.

$$ICER = \frac{Incremental\ cost\ (\Delta C)}{\text{Incremental benefit } (\Delta \text{Q})}$$

The incremental cost is the difference in cost between the treatment and the next best alternative. The incremental benefit between the treatment and the next best alternative is expressed as a number of QALYs. Continuing with the hypothetical patient mentioned above, if the incremental cost of option A over the next best alternative was £50,000, this would result in an ICER of £10,000 per QALY (£50,000/5 QALYs), whereas if the incremental cost of option B was also £50,000 it would have an ICER of £5,000 per QALY (£50,000/10 QALYs). NICE (2013) guidelines suggest that the maximum acceptable ICER lies in the region of £20,000- £30,000. However, a review of NICE's decisions suggested that this is not a strict cut-off, with some treatments having an ICER less than this being rejected, and other treatments with ICERs greater than this being accepted (Devlin & Parkin, 2004). Current guidelines (NICE, 2013) require cost-effectiveness analyses to estimate the incremental net benefit at a willingness to pay threshold of £20,000 per QALY and at £30,000 per QALY.

At a willingness-to-pay threshold of £30,000 a treatment is considered to be cost-effective provided that:

$$\frac{\Delta C}{\Delta \mathrm{Q}} \leq 30{,}000$$

Thus the value of the incremental benefit (30,000 x ΔQ) must exceed the incremental cost (ΔC) for the intervention to be cost-effective. The difference between the two (shown below) is the 'incremental net benefit'.

$$Incremental\ net\ benefit = (\text{Willingness to pay threshold x } \Delta\text{Q}) - \Delta C$$

It is possible to plot the relationship between the gain in utility and the resulting incremental net benefit provided one has two things: (1) an estimate of the costs of an intervention compared to the next best alternative, and (2) an estimate of the relationship between the size of the gain in utility and the resulting gain in QALYs (ΔQ). The resulting plot can then be used to estimate the minimum gain in utility required to result in a positive incremental net benefit and hence a cost-effective intervention. Figures 4.1 and 4.2 show two illustrations of these types of plots.

## 4.4 Cost-effectiveness of binaural devices for CI users

### 4.4.1 Minimum gain in utility required

It is well established that unilateral cochlear implantation compared with non-surgical interventions is cost-effective (Bond et al., 2009; Turchetti, Bellelli, Palla, & Berrettini, 2011; United Kingdom CI Study Group, 2004). In a threshold analysis, Bond et al. (2009) demonstrated that a gain in utility of 0.1 is required for unilateral cochlear implantation to be cost-effective at a willingness-to-pay threshold of £30,000 (see Figure 4.1). Indeed, after evaluating the evidence available at the time, NICE (2009) stated that the ICER was £14,200 per QALY of providing a unilateral CI to post-lingually deafened adults compared with non-surgical intervention. It was therefore deemed to be a cost-effective intervention and NICE recommended unilateral cochlear implantation for adults who meet the candidacy requirements for a CI.

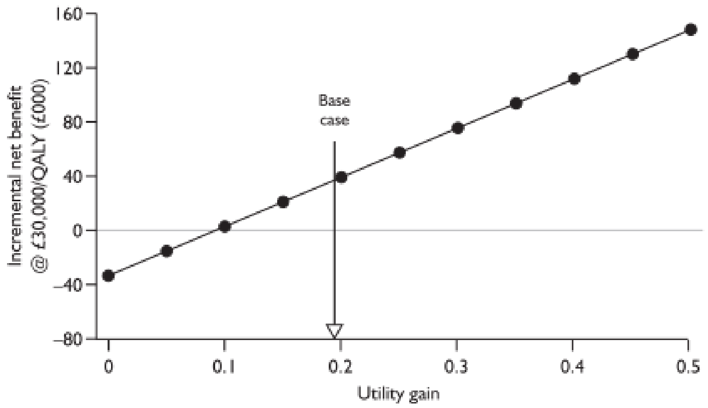


**Figure 4.1. Threshold analysis showing the gain in utility required for unilateral cochlear implantation to be a cost-effective intervention compared to no surgical intervention for adults. At a willingness-to-pay threshold of £30,000 the gain in utility required is about .1. Base case value from decision modelling by Bond et al (2009). Figure from Bond et al.**

However, for the majority of adults who meet the candidacy requirements for one CI, NICE does not recommend the funding of a second CI by the NHS; the exception is for those adults who have other major disabilities such as blindness (see Chapter 1). However, the NHS does provide hearing aids for hearing impaired adults. Compared to a CI, the cost of providing and maintaining a hearing aid is low (see Appendix C). Although no study has directly compared the cost-effectiveness of bilateral cochlear implantation compared to bimodal aiding, the lower cost of the latter option can be inferred from previous research. For instance, Bond et al. (2009) investigated the cost effectiveness of unilateral cochlear implantation compared to no surgical intervention for adults. Using a base case scenario in which 70% of individuals used a contralateral acoustic hearing aid yielded an ICER of approximately £14,500 per QALY. However, in supplementary sensitivity analysis with contralateral acoustic hearing aid use was lowered to 40% or increased to 100% the ICER was not substantially altered. Using Figure 34 in Bond et al., (2009) to estimate the differences in ICER, the incremental net benefit increased by about £112 with 100% of unilateral CI users using a contralateral acoustic hearing aid compared to 70%. Whereas no reduction in cost was observed from 40% of unilateral CI users using a contralateral acoustic hearing aid compared to 70%.

Appendix C reports an analysis on the cost-effectiveness of a contralateral acoustic hearing aid for adult users of a single CI. The incremental cost was estimated to be in the region of £1,262 (using the latest cost estimates from the UK Department of Health, 2013) and £4,171 (using cost data from Summerfield, Marshall, Barton, & Bloor, 2002 inflated to 2013 cost levels). Using actuarial life expectancy data from the Office for National Statistics (2014) the minimum gain in utility required for a contralateral acoustic hearing aid to be cost-effective at a willingness to pay threshold of £30,000 was estimated to be in the region of .002 to .011 (depending upon the cost data used).

In a threshold analysis investigating the cost-effectiveness of bilateral cochlear implantation compared to unilateral cochlear implantation, Bond et al. (2009) demonstrated that a gain in utility of at least 0.05 was required for bilateral cochlear implantation to be cost-effective at a willingness-to-pay threshold of £30,000 (see Figure 4.2).

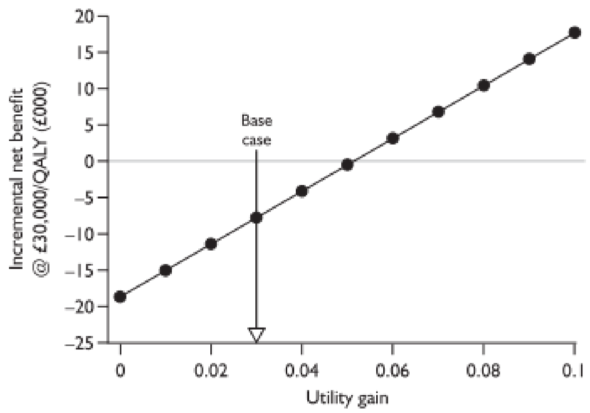


**Figure 4.2. Threshold analysis showing the gain in utility required for bilateral cochlear implantation to be a cost-effective intervention compared to unilateral cochlear implantation for adults. At a willingness-to-pay threshold of £30,000 the gain in utility required is about .05. The base case value was from Summerfield et al. (2006) and was used by Bond et al. (2009) to inform cost-effective estimates. Figure from Bond et al. (2009).**

### 4.4.2 Is bilateral cochlear implantation cost-effective?

A limited literature exists on the cost-effectiveness of a second CI for adults. In one analysis normally-hearing adults with knowledge of cochlear implantation used the time-trade-off technique to value different health states (Summerfield et al., 2002). These valuations were then used to estimate the cost-effectiveness of providing bilateral CIs to profoundly deafened adults. Participants evaluated the quality of life of four scenarios: profound bilateral deafness with no benefit from hearing aids, profound bilateral deafness with some benefit from hearing aids (being able to understand approximately 25% of spoken sentences without the need to lipread), benefitting from a unilateral CI, and benefiting from bilateral CIs. Participants were instructed that they could either live in this state from their current age until they were 75 years old, or they could trade years from the end of their life to live for a shorter period of time but with perfect hearing. The increase in utility from providing a second CI to users of a unilateral CI was estimated to be .031. This was less than the value of .05 estimated by Bond et al (2009) to be the minimum required for bilateral cochlear implantation to be a cost-effective use of resources (see Figure 4.2). Indeed, when comparing either simultaneous bilateral cochlear implantation to unilateral cochlear implantation, or the provision of a second CI to existing unilateral CI users, the ICER was estimated to lie in the region of £43,908 -£116,012 per QALY.

Summerfield et al. (2002) had estimated the cost-effectiveness of bilateral cochlear implantation from valuations made by normally-hearing adults. Although these adults had knowledge of cochlear implantation it was important to assess whether the utility estimates provided by these valuations were similar to the utility gain actually reported by patients. To do this the researchers used responses to the HUI2 (an earlier version of the HUI3[1]) of 202 users of a unilateral CI. Firstly, the utility of patients as measured with the HUI2 were recalculated with the speech and hearing dimensions set to no difficulty. The difference between this new utility value and the original value highlighted the loss of utility due to difficulties with hearing and speech. Secondly, the loss in utility due to difficulties with hearing and speech for valuations made by normally hearing adults was calculated. To do this, new utility values were set to one on the assumption that normally-hearing adults have no difficulty with hearing and speech. Finally, the authors compared the loss in utilities between the two groups. This analysis confirmed that the gain in utility estimated by the normally hearing respondents with the time-trade-off technique for comparing unilateral cochlear implantation to no intervention was similar to the gain estimated by patients. The equivalence in this utility gain gave credibility to the respondents' estimate of the gain from receiving bilateral cochlear implants compared to a unilateral CI.

This study was followed by a randomised control trial in which 28 unilateral CI users were assigned to receive a second CI either immediately or after a delay of twelve months (Summerfield et al., 2006). Twenty-four participants completed the trial. Participants completed the HUI3 and the EQ5D before receiving their second CI and again three and nine months post implantation. No significant difference in utility scores as measured using the HUI3 was found between unilateral and bilateral cochlear implantation. Indeed, the mean gain from bilateral CIs (.030) echoed that found by Summerfield et al. (2002) which used valuations by normally hearing adults. Furthermore, a significant detriment on the EQ5D was found nine months post implantation, which the authors argued could have been driven by worsening tinnitus in a small

[1] The HUI2 covers seven domains (sensation, mobility, emotion, cognition, self-care, pain, and fertility). Like the HUI3 it results in a utility value where 1 indicates perfect health and 0 indicates being dead.

minority of patients. When NICE (2009) were making their recommendations on cochlear implantation, this was the only published study of a randomised control trial that considered the health utility of adults with a second CI both before and after surgery.

However, with such a small sample the Summerfield et al. (2006) study was underpowered. Previous research was used to estimate the variation in utility estimates. The standard deviation of utility estimates is about 0.2 (United Kingdom CI Study Group, 2004). Therefore a trial would be looking for a gain in utility (.05) of one quarter of a standard deviation for a second CI to be deemed cost-effective. Using a two-tailed test with an alpha of .05 would require two groups of 251 participants to achive power of 80%. A randomized control trial could be conducted in which 502 eligible adults are randomly assigned to receive one CI or receive two cochlear implants simultaneously. The use of simultaneous implantation would reduce the cost compared to sequential implantation as there is only one surgical procedure. In a between subjects-design utility values as measured on the HUI3 and EQ5D could be compared between the unilateral and bilateral CI groups to determine if bilateral cochlear implantation is a cost-effective intervention for adults. Although this study would have sufficient power the cost of a trial like this would be very expensive. NICE (2009) guidelines indicate that the price of a second CI should be reduced by 40% or more. However if one considers that the cost of cochlear implantation (including the device costs, surgical costs and maintenance costs) is about £25,000 (Nottingham University Hospitals NHS Trust, n.d.), even with reductions of 40% on the second device and one surgical procedure, the trial is likely to cost over £10 million.

To reduce the financial resources required to run a randomized control trial a within-subjects design could be employed. To achieve 80% power 126 individuals who already have one CI and are willing to obtain a second one would need to participate. The cost-effectiveness of a second CI could then be investigated by administering the HUI3 and EQ5D to participants before they receive a second CI to get a baseline measure of health utility with one CI. After receiving a second CI, the participants could then complete the questionnaires again. It would be beneficial to have participants complete the questionnaires several times both before and after receiving their second CI. This would ensure that any gain in utility is most likely due to the intervention and not due to other factors such as learning and familiarisation. For instance responses have been demonstrated to change between three and nine months after receiving a second CI as individuals became used to life in their new listening configuration (see Summerfield et al., 2006). A comparison could then be made on the utility value before and after implantation to determine if the difference in utility is large enough (0.05) for bilateral cochlear implantation in adults to be cost-effective. However, despite smaller numbers the trial would still cost £3.2 million to run.

Furthermore, the trial would be comparing unilateral cochlear implantation to sequential bilateral cochlear implantation which is not what NICE (2009) guidelines suggest as simultaneous cochlear implantation can reduce costs due to having only one surgical procedure.

In addition, as previous research has demonstrated that the EQ5D is insensitive to differences in hearing ability (e.g. Barton et al., 2005; Grutters et al., 2007), and the HU13 is insensitive to differences between 'some hearing' and 'more than some hearing' (e.g. Lovett et al., 2010), even randomized controlled trials with large numbers may not be capable of detecting differences between one and two CIs. This could be due to one of two reasons. One possibility is that bilateral cochlear implantation does not result in improvements in health-related quality of life. The second alternative is that bilateral cochlear implantation does result in improvements in health-related quality of life but current measures are insensitive to these benefits. This question will be addressed in research reported in Chapter 8.

Since the NICE (2009) guidelines on cochlear implantation were published, there have been four systematic reviews investigating the cost-effectiveness of bilateral cochlear implantation for profoundly deafened adults (Bond et al., 2009; Crathorne et al., 2012; Lammers, Grolman, Smulders, & Rovers, 2011; Turchetti et al., 2011). All have met the same conclusion: that there is uncertainty on the cost-effectiveness of bilateral cochlear implantation due to the limited literature and varied estimated ICERs. Indeed, when reviewing the literature available up until 2010, only four studies with adults met the inclusion criteria for Lammers et al. (2011) and Turchetti et al. (2011). Bond et al. (2009) conducted a sensitivity analysis based on the literature published up to July 2007. It was found that at a willingness-to-pay threshold of £30,000 (typical of NICE) bilateral cochlear implantation was not deemed to be a cost-effective intervention, even if implantation were to occur early in adulthood. The ICER of sequential bilateral cochlear implantation in adults was estimated to be £60,301 per QALY, whereas simultaneous bilateral cochlear implantation came in at a lower ICER of £49,559 per QALY. These ICERs are above the highest willingness-to-pay threshold considered by NICE of £30,000. The most recently published systematic review (Crathorne et al., 2012) considers papers that were published up until January 2012. Whilst able to include several papers investigating the clinical effectiveness of bilateral cochlear implantation, only two included papers considered the cost-effectiveness of bilateral cochlear implantation (Summerfield et al., 2006, 2002) and these had already been included in previous reviews.

### 4.4.3 Literature search

It is important to continually assess the effectiveness of treatments, as technology improves it is possible that greater gains in quality of life may be obtained which may lower the ICER to a more acceptable level. As such a literature search was conducted in PubMed (National Center for Biotechnology Information, n.d.) and Web of Science (Thomson Reuters, n.d.) in July 2014 using the search terms ‘cochlear implant*’ ‘bilateral’ ‘cost utility’ and ‘cost-effective*’ for papers published between January 2010 and July 2014. PubMed produced 6 results whereas Web of Science produced 15 results. After removing duplications there were 14 results remaining. Abstracts were assessed to determine if they met the inclusion criteria. To be included the paper must have reported an investigation of the cost-effectiveness of bilateral CIs in adults and not be a review. Three papers focused on cochlear implantation in children, six did not investigate cost-effectiveness, one investigated the cost-effectiveness of bilateral bone anchored hearing aids, and three were review papers. One paper met the criteria for inclusion (Chen, Amoodi, & Mittmann, 2014). In this study three vignettes were administered to four groups of knowledgeable informants (post-lingually deafened adults eligible to receive a CI, unilateral CI users, bilateral CI users, and expert health professionals). Each vignette described the abilities and challenges of one scenario: profound deafness with no intervention, unilateral CI use, and bilateral CI use. Participants completed the HUI3 three times, each time considering the health state of one of the vignettes. A cost-utility analysis was conducted using the utility values from the HUI3 and costs were considered from the perspective of the Canadian ministry of health. Compared to no intervention, unilateral cochlear implantation resulted in a gain in utility of .270 and bilateral cochlear implantation resulted in a gain of .305. Compared to unilateral cochlear implantation, bilateral cochlear implantation resulted in a gain in utility of .035. Whilst the gain in utility from unilateral cochlear implantation with Canadian respondents is higher than that found by Summerfield et al. (2002), the bilateral gain compared to unilateral cochlear implantation is remarkably similar to that from UK informants (see Table 4.1). Furthermore, consistent with Summerfield et al., the ICER of bilateral cochlear implantation compared to the next best alternative (unilateral cochlear implantation) was not judged to be a cost-effective intervention.

**Table 4.1. Summary of studies investigating the utility gain associated with bilateral cochlear implantation compared to unilateral cochlear implantation.**

| Study | Method | Participants | Mean gain in utility |
|---|---|---|---|
| Summerfield et al. (2002) | Time-trade-off technique | Professional informants | .031 |
| Summerfield et al. (2006) | HUI3 at 3 months post implantation | CI users | .021 |
| | HUI3 at 9 months post implantation | | .030 |
| Chen et al. (2014) | HUI3 completed considering description of clinical scenarios. | Professional informants | .080 |
| | | CI candidates | .030 |
| | | Unilateral CI users | .030 |
| | | Bilateral CI users | .000 |
| | | All | .035 |

## 4.5 Conclusion

Unilateral cochlear implantation is a cost-effective intervention for profoundly deafened adults. Based on the low cost of a contralateral hearing aid it is likely that bimodal aiding is also be a cost-effective intervention (see Appendix C). It is unlikely that bilateral cochlear implantation in adults compared to unilateral cochlear implantation is a cost-effective intervention at current willingness to pay thresholds. Few studies have investigated this issue, and those that have done relied on estimates from normally hearing adults or small numbers of CI users. Furthermore, quality of life has been measured using available generic instruments such as the HUI3 and EQ5D, which are limited in their ability to detect differences between groups that differ in their hearing ability. It may be that bilateral cochlear implantation could be a cost-effective intervention but current instruments are insensitive to differences in health-related quality of life between monaural and binaural hearing. This question will be addressed in Chapter 8.

## 4.6 Summary

- Utility is the standard measure of a health state where a value of 1 corresponds to perfect health and a value of 0 corresponds to being dead.
- The time-trade-off and standard gamble are two techniques used to evaluate the utility of health states.

- Current generic questionnaires such as the EQ5D and HUI3 can be used to assign a utility value to a given health state to measure health-related quality of life without requiring respondents to master the cognitive demands of the standard gamble or the time-trade-off methods.
- The EQ5D is not very sensitive to differences in hearing ability. The HUI3, whilst sensitive to the difference between ‘some hearing’ and ‘no hearing’, is less sensitive to the difference between ‘some hearing’ and ‘more than some hearing’.
- Utility values can be used to determine the number of quality adjusted life years (QALYs) an individual gains from a given treatment.
- Cost-effectiveness analyses compare a treatment to the next best alternative using the incremental cost and the incremental benefit (expressed in QALYs) to generate an incremental cost-effectiveness ratio.
- Although there is no strict threshold, in practice the NHS will typically not fund treatments where the cost of gaining one QALY exceeds £30,000.
- The current literature on the cost-effectiveness of bilateral cochlear implantation in adults is sparse and varied.

# 5 Binaural advantages from a contralateral acoustic hearing aid or a second cochlear implant

Adult users of a single CI who wish to aid their non-implanted ear can either receive a contralateral acoustic hearing aid (bimodal devices) or pay to receive a second CI (bilateral cochlear implantation). This chapter reports an experiment which sought to inform this choice by comparing the benefits of each option for patients in the UK. Twelve bimodal users and twelve bilateral CI users completed a battery of listening tasks. The test battery included tasks for which participants could benefit from the head shadow and tasks for which participants might benefit from access to low-frequency information. Participants completed two sessions. In one session participants used their first (or only) CI, and in the other session participants used both their devices. Comparisons were made between monaural and binaural listening to assess whether provision of a second device resulted in improvements in listening ability. Furthermore, comparisons were made between the benefit obtained from a second CI and the benefit obtained from a contralateral acoustic hearing aid to determine which option provided the greater benefit. Limited benefit from bimodal aiding was found, although participants did benefit from a contralateral acoustic hearing aid when localising sound sources. As expected, bilateral CI users benefitted from a second CI on tasks where the head shadow could be exploited. In comparing the two options, a greater binaural advantage was found from using a second CI. Nevertheless, a contralateral acoustic hearing aid was found to improve localisation accuracy and is an affordable option for individuals with residual hearing in their non-implanted ear.

## 5.1 Introduction

Whilst previous research has highlighted that a contralateral acoustic hearing aid and a second CI each provide benefits over a single CI (see Chapter 2), no clear conclusion has been drawn as to which option is more effective (Ching, Van Wanrooy, & Dillon, 2007; Sammeth, Bundy, & Miller, 2011). However, the majority of research assessing binaural advantages from bimodal aiding has been conducted outside the UK with a large proportion being conducted with patients in the USA. Candidacy requirements for a CI are more relaxed in the USA than in the UK, meaning that individuals may be implanted with greater levels of residual hearing than those in the UK (see Chapter 2). Indeed participants in a USA study reported by Zhang et al. (2010) had a mean unaided three-frequency average (250, 500 and 1000 Hz) pure tone threshold of 53dB HL. Under current guidelines (NICE, 2009) a UK adult with this level of residual hearing would not be a candidate for a CI. Therefore it may be that the bimodal benefits that have been demonstrated may not be realised for UK CI users.

There were a number of aims of the present study that are particularly relevant to UK users of CIs and also to clinicians. Firstly, this study sought to measure the benefit provided by a second CI on a range of listening tasks. Secondly, this study aimed to measure the benefit provided by a contralateral acoustic hearing aid. Thirdly, this study aimed to compare the benefit obtained with each option (a second CI and a contralateral acoustic hearing aid) to determine which option provides the greater benefit. As previous research has highlighted a trade-off in listening abilities between the two options (see Chapter 2), a variety of listening tasks were included that broadly covered three key aspects of listening: spatial listening, speech perception, and sound quality tasks. To assess benefit from a second device, participants in this study completed two sessions. They undertook the tasks in one session using their normal configuration (either bimodal aiding or bilateral CIs) and undertook the tasks in the other session using their first or, in the case of the bimodal users, their only CI. Based on findings from previous research (see Chapter 2), it was hypothesised that a greater benefit would be derived from a second CI on spatial listening tasks where the head shadow could be exploited, whereas a contralateral acoustic hearing aid would provide a greater benefit for tasks involving pitch perception, as the hearing aid would provide access, albeit limited, to low-frequency information. A unilateral CI group were tested as a control group to check for any learning effects or effects of unfamiliarity amongst the bimodal and bilateral groups with one CI.

## 5.2 Method

### 5.2.1 Participants

Three groups of participants completed the listening battery. 12 bilateral CI users (mean age = 64.8 years, SD = 7.7), 12 bimodal users (mean age = 59.4, SD = 16.4), and 11 unilateral CI users (mean age = 64.8 years, SD = 20.1). Participant information is shown in Table 5.1. The unaided pure-tone thresholds for the non-implanted ear of bimodal participants are shown in Figure 5.1. Five unilateral CI users included in the analyses (see section 5.2.6) had some measurable residual hearing remaining in their non-implanted ear. Their hearing thresholds are shown in Figure 5.2. Participants responded to a letter printed in the National CI Users Association magazine asking for participants to take part in this study.

Table 5.1.Summary demographic information of participants. AB indicates Advanced bionics device.

| Participant number | Group | Age (in years) | Gender | 1st CI ear | 1st CI type | Approximate length of use of 1st CI (years) | 2nd CI type | Approximate length of use of 2nd CI (years) |
|---|---|---|---|---|---|---|---|---|
| 205 | Bilateral | 64.2 | Female | Right | Med-El | 16.0 | Med-El | 7.0 |
| 203 | Bilateral | 61 | Male | Left | Med-El | 15.1 | Med-El | 10.1 |
| 201 | Bilateral | 72.3 | Female | Right | Cochlear | 4.9 | Cochlear | 2.2 |
| 206 | Bilateral | 63.5 | Female | Left | Med-El | 10.6 | Med-El | 10.3 |
| 208 | Bilateral | 52.6 | Male | Right | Cochlear | 16.2 | Cochlear | 10.2 |
| 480 | Bilateral | 66.6 | Female | Left | Cochlear | 6.4 | Cochlear | 4.4 |
| 212 | Bilateral | 63.2 | Male | Right | AB | 7.3 | AB | 4.3 |
| 488 | Bilateral | 64.6 | Male | Left | Cochlear | 14.4 | Cochlear | 0.8 |
| 213 | Bilateral | 69.9 | Male | Left | Cochlear | 12.8 | Cochlear | 11.4 |
| 214 | Bilateral | 50.9 | Male | Left | Cochlear | 3.6 | Cochlear | 1.7 |
| 215 | Bilateral | 77.2 | Male | Left | Cochlear | 11.8 | Cochlear | 10.8 |
| 216 | Bilateral | 71.6 | Female | Left | AB | 4.9 | AB | 2.7 |
| 312 | Bimodal | 72.9 | Female | Left | AB | 3.3 | | |
| 111 | Bimodal | 75.4 | Male | Left | AB | 7.6 | | |
| 306 | Bimodal | 65.8 | Male | Left | Med-El | 1.6 | | |
| 303 | Bimodal | 70.5 | Female | Right | Cochlear | 4.1 | | |
| 310 | Bimodal | 66.0 | Male | Right | AB | 3.5 | | |
| 486 | Bimodal | 66.3 | Female | Right | AB | 9.2 | | |
| 481 | Bimodal | 58.5 | Female | Right | Cochlear | 1.4 | | |
| 484 | Bimodal | 35.9 | Male | Right | AB | 11.8 | | |
| 323 | Bimodal | 59.3 | Female | Left | Cochlear | 2.8 | | |
| 324 | Bimodal | 24.2 | Female | Right | AB | 10.1 | | |
| 317 | Bimodal | 44.2 | Female | Left | Cochlear | 12.0 | | |
| 326 | Bimodal | 74.4 | Male | Left | Med-El | 2.1 | | |
| 131 | Unilateral | 68.7 | Male | Left | Cochlear | 4.8 | | |
| 134 | Unilateral | 77.2 | Male | Left | Cochlear | 14.2 | | |

Table 5.1.Summary demographic information of participants. AB indicates Advanced bionics device.

| Participant number | Group | Age (in years) | Gender | $1^{st}$ CI ear | $1^{st}$ CI type | Approximate length of use of $1^{st}$ CI (years) | $2^{nd}$ CI type | Approximate length of use of $2^{nd}$ CI (years) |
|---|---|---|---|---|---|---|---|---|
| 104 | Unilateral | 88.1 | Male | Left | Cochlear | 9.1 | | |
| 126 | Unilateral | 82.0 | Male | Right | Cochlear | 9.5 | | |
| 168 | Unilateral | 67.5 | Male | Right | Cochlear | 10.4 | | |
| 489 | Unilateral | 72.0 | Female | Left | Cochlear | 4.6 | | |
| 135 | Unilateral | 78.8 | Male | Right | AB | 12.7 | | |
| 301 | Unilateral | 30.5 | Male | Left | AB | 7.4 | | |
| 118 | Unilateral | 62.4 | Female | Left | Med-El | 8.4 | | |
| 325 | Unilateral | 52.4 | Male | Left | Cochlear | 0.9 | | |
| 167 | Unilateral | 59.6 | Female | Right | Cochlear | 8.6 | | |

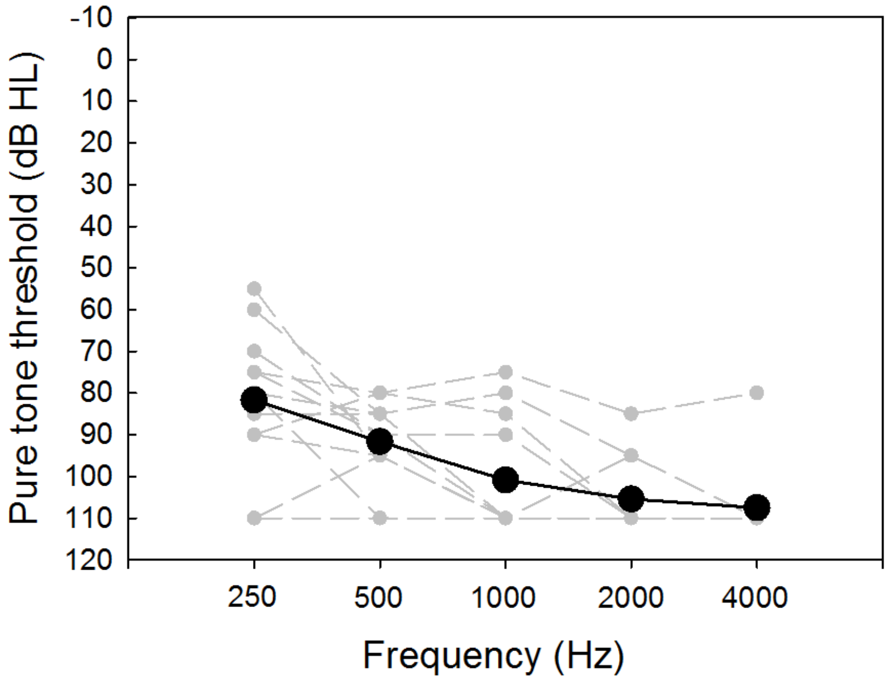


**Figure 5.1. Average unaided pure tone thresholds of the non-implanted ear of the bimodal participants (thick black line). Dashed grey lines show individual thresholds.**

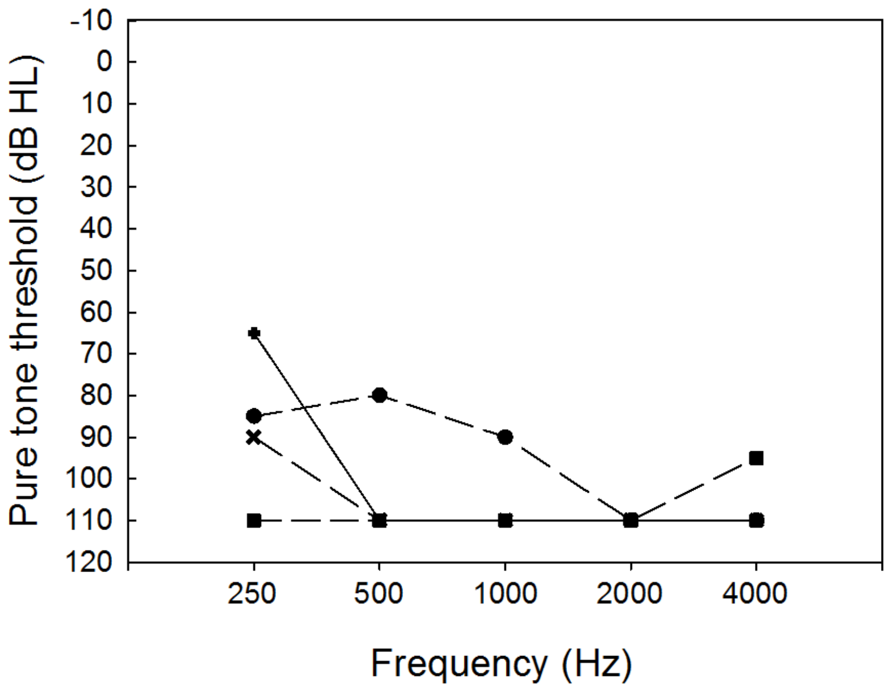


**Figure 5.2. Unaided pure tone thresholds of the non-implanted ear of the five unilateral participants who had some measureable hearing (Patient numbers 134 (•), 104 (▪), 126 (x) , 168 and 489 (both +).**

### 5.2.2 Apparatus

All listening tests were administered using the AB-York Crescent of Sound (Kitterick, Lovett, Goman, & Summerfield, 2011). This apparatus (Figure 5.3) consists of nine loudspeakers positioned in a semi-circular array with a radius of 149cm. Loudspeakers are positioned at a height of 1.1m and located at ±90°, ±60°, ±30°, ±15°, and 0° azimuth. Where 0° azimuth is directly in front of the listener and negative angles correspond to locations to the left of straight ahead and positive angles correspond to locations to the right of straight ahead. Below each of the loudspeakers from -60° through to +60°, is a 15 inch visual display unit. The Crescent of Sound is situated within an Industrial Acoustic Corporation (IAC) single-walled enclosure situated within a larger sound-treated room. A touch-screen is situated in front of the participant.

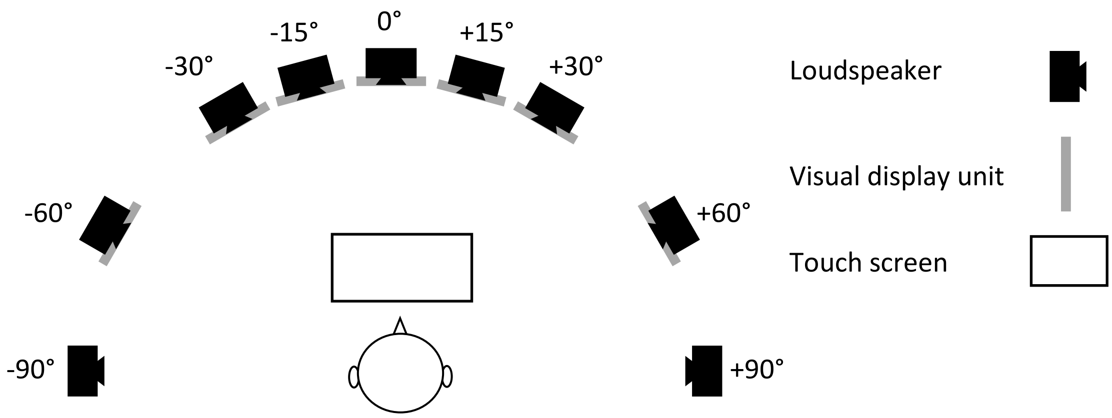


**Figure 5.3. Diagram showing the crescent of sound arrangement in relation to the participant.**

The loudspeaker array was calibrated using a Brüel and Kjaer 0.5 inch microphone (Type 4189) and sound level meter (Type 2260 Investigator). The outputs from each loudspeaker were adjusted so that an octave band of noise centered on 1 kHz was presented at the same intensity (±0.5dB) in the centre of the arc with the participant absent.

### 5.2.3 Listening Test battery

A variety of different listening tests were used. Some of the tests were developed by Lovett, Kitterick, Huang, and Summerfield (2012).

#### *5.2.3.1 Localisation*

This test assessed how well participants can localise sound in the horizontal plane. On each trial the phrase "Hello what's this?" spoken by a female talker was presented from one loudspeaker. The level of the phrase was varied randomly from trial to trial so that participants did not base their decisions entirely upon intensity cues. There were eleven possible presentation levels (ranging from 65dB SPL to 75 dB SPL in 1dB steps). The participant's task was to indicate which loudspeaker the stimulus was presented from. There were three versions of this task, each containing 30 trials, with an equal number of presentations from each possible loudspeaker. The percentage of correct responses was measured for each version of the task. In the 3-alternative (60° separation) version of the task, three loudspeakers were used (-60°, 0°, and +60° azimuth). A training phase was completed before the first run to familiarise participants with the task. The training phase consisted of three trials, presented in a random order, one from each of the three alternative locations. In the 5-alternative (30° separation) version, there were five possible locations separated by 30° (-60°, -30°, 0°, 30°and 60°). In the 5-alternative (15° separation) version, there were five possible locations separated by 15° (-30°, -15°, 0°, 15°and 30°).

#### *5.2.3.2 Movement tracking*

This task assessed whether a participant could track the trajectory of a moving sound. There were two sets of stimuli for this task which simulated a person walking or a horse galloping. There were four possible trajectories. The sound could either move from left to right (starting at -90° and finishing at +90°), from right to left (starting at +90° and finishing -90°), from the left to the centre and back to the left (both starting and finishing at -90°), or from the right to the centre and back to the right (both starting and finishing at +90°). Thus there were 8 movement tracking trials (2 stimuli x 4 trajectories). All nine loudspeakers were used in this task with stimuli being presented at 65dB SPL. The stimuli were presented in a stepped manner between loudspeakers. The stimulus began at either +90° or -90° then moved inwards in 15° intervals. The stimuli at ±75° and ±45° were simulated by presenting stimuli from adjacent loudspeakers at half the intensity. Previous research has indicated that listeners perceive these stimuli as a continuous smooth movement (Lovett et al., 2012). Prior to the first trial, participants were informed that the sound would start either on their left or right and would finish on either their left or right. A trial was scored correctly if the participant correctly identified where the trial began and where the trial ended. The percentage of correct responses was measured.

#### *5.2.3.3 Speech in quiet*

This test measured participants' ability to understand speech in quiet. On each trial a sentence was presented from 0° azimuth at an average level of 70 dB SPL. The participant's task was to repeat back the sentence as best they could. Each sentence contained a number of keywords and the experimenter recorded which keywords were reported correctly by using a loose scoring method. Using this method, a keyword was scored as correct if the root of the word was identified correctly so errors of tense or plurality were not scored as incorrect. Two versions of this task were completed: simple sentences and complex sentences.

### Simple sentences

The sentence corpus consisted of 20 lists of 16 semantically neutral sentences from the Bamford-Kowal-Bench (BKB) corpus (Bench, Kowal, & Bamford, 1979). Each sentence contained three or four keywords and was spoken by a male talker with a British accent with clear articulation. Each list contained a total of 50 key words. The lists used were counterbalanced across participants. Unilateral CI users completed two lists during session one and another two lists during session two. The average percentage of keywords correctly identified across both sessions was calculated. Bimodal and bilateral CI users completed six lists during one session with performance on two lists being measured for each configuration (first (or only) CI, second device, and both devices). The percentage of keywords correctly identified for each configuration was calculated.

### Complex sentences

The sentence corpus consisted of 25 lists of 30 sentences from the Harvard IEEE sentences corpus (Rothauser et al., 1969), spoken by a male and a female talker. Each sentence contained five keywords, thus there were 150 keywords per list. For each session, participants completed two lists, one spoken by a female talker and one spoken by a male talker. This was counterbalanced across sessions so that individuals, who completed the male talker condition first in session one, completed this condition second in session two. The percentage of keywords correctly identified when listening to the male talker, when listening to the female talker, and overall was measured.

#### *5.2.3.4 Speech in concurrent and spatially separated noise*

This test assessed speech perception in the presence of background noise. On each trial the phrase ‘Point to the OBJECT’ spoken by a female talker was presented from the loudspeaker situated in front of the participant (0° azimuth). On each trial ‘OBJECT’ was randomly selected from one of twelve possible objects (cow, cup, duck, fork, horse, house, key, plane, plate, shoe, spoon or tree), with the constraint that the same object could not be presented on two consecutive trials. The participants’ task was to identify which object was mentioned in the phrase. Response options were displayed on a touch screen in front of the participant together with an ‘uncertain’ response option. In addition to the target speech, broadband pink noise was also presented from one loudspeaker. There were three versions of this task. The noise was either presented spatially concurrent with the speech from the loudspeaker situated in front of the participant (0° azimuth), or spatially separated from the speech to the left of the participant (-90°) or to the right of the participant (+90°).

For each version of the task an adaptive procedure was followed. The initial trial presented the speech at 60dB SPL and the noise at 30-38 dB SPL chosen randomly (thus a Signal-to-Noise Ratio (SNR) of +22 to +30 dB). An adaptive procedure was used for each run to measure the speech reception threshold (SRT). The SRT was defined as the SNR at which participants were able to identify the object in the sentence with an accuracy of 70.7% correct. A one-up-one-down adaptive procedure was used with a step size of 6dB for the first two reversals. A reversal was a change in direction of the SNR. Thereafter a two-down-one-up adaptive procedure was used with a step size of 3dB for 6 reversals. The SRT was calculated from the average SNR at these last 6 reversals. On each session participants completed a practice run to familiarise themselves with the task. This consisted of one run of the noise front version of this task. Two runs of each version of the task were competed in each session and an average SRT for each version was calculated.

#### *5.2.3.5 Speech in speech*

This test assessed speech perception in the presence of competing speech. Three versions of this task were completed. One version assessed speech perception in the presence of one other talker, whilst the other two versions assessed speech perception in the presence of multiple talkers. Each sentence took the form "Ready CALL-SIGN go to COLOUR NUMBER now." There were eight possible call signs (Arrow, Baron, Laker, Charlie, Hopper, Tiger, Eagle, and Ringo), four possible colours (blue, red, green and white), and four possible numbers (1, 2, 3, 4). Thus an example sentence is "Ready Charlie go to blue two now". Sentences were spoken by four female talkers and four male talkers.  Seven were native British-English talkers, whilst one male was a native Irish talker. Thus the corpus consisted of 1024 sentences (8 call signs x 4 colours x 4 numbers x 8 talkers). On each trial the participants' task was to identify the colour and number in the target sentence. A response was scored correctly if both the colour and number were identified correctly. For each trial, the target sentence was randomly selected from one of the sentences containing the call sign 'Baron'. The competing sentence(s) were selected from the remaining sentences which did not contain the call-sign Baron, did not contain the same colour-number co-ordinate as the target sentence, and were not spoken by the talker saying the target sentence. The SRT was calculated for each version of the task. The SRT was defined as the target to masker ratio (TMR) at which participants were able to correctly identify the colour and number in the target sentence with an accuracy of 50% correct.

##### One other talker

On each trial two sentences were presented simultaneously, one target sentence and one competing sentence, both from the loudspeaker situated at 0° azimuth. A masker of the opposite gender to the target talker was randomly selected on each trial. Each run began with the target voice presented at 60dB SPL and the masker sentence presented at 30dB SPL (thus a TMR of +30dB). TMR changes were achieved by varying the intensity of either the target or the masker sentence. Positive TMRs were achieved by keeping the level of the target fixed at 60dB SPL but varying the level of the masker. For a negative TMR the level of the masker talker was fixed at 60dB SPL and the level of the target talker was varied. A one-up-one-down adaptive procedure was used. The step-size was 10dB for one reversal, then 5dB for one reversal, then 2.5dB for fifteen trials. Using the method outlined by Plomp and Mimpen (1979), thresholds from the final 14 trials and the threshold at which the 15$^{th}$ trial would have been presented at were averaged to estimate the SRT. Two runs of this task were completed in each session and the average SRT was calculated.

#### Multiple talkers

On alternating trials a target sentence was presented in the presence of either six or twelve competing talkers. In the six-masker version of the task, sentences were presented in an overlapping sequential manner wherein one sentence started every 800ms. Each sentence was spoken by a different talker and the target sentence was either the 3$^{rd}$, 4$^{th}$ or 5$^{th}$ sentence. In the 12-masker version of the task, sentences also started every 800ms. Two masker sentences were presented concurrently and the target sentence was either the 7$^{th}$, 9$^{th}$ or 11$^{th}$ sentence which ensured competing sentences fully overlapped with the target sentence. The SRT was calculated using the same method as the one other talker version of the task discussed above. Two runs of this task were completed in each session and the average SRT was calculated.

### *5.2.3.6 Vocal emotion recognition*

The corpus contained 32 semantically neutral BKB sentences spoken by a male and female talker in five emotions (angry, anxious, happy, sad and neutral). These five emotions were chosen as they cover a range of emotional states and there are acoustical differences in their expression (Pittam & Scherer, 1993). For instance, compared to neural utterances, angry and happy utterances have a higher mean f0, higher intensity and often a higher rate of articulation. Anxious utterances also have a higher mean f0, whereas sadness on the other hand, is characterised by a lower mean f0, lower intensity and slower rate of articulation. Vocal emotion recognition was measured by using a five-alternative forced-choice task. Participants were shown the five possible options ‘angry’, ‘anxious’, ‘happy’, ‘sad’, and ‘neutral’. For both talkers, the five sentences from each emotion category that were most recognisable as belonging to that category by normal hearing listeners were selected. Thus, the sub-set used in this study contained 50 utterances (2 talkers x 5 emotions x 5 sentences). Three normally-hearing listeners were able to identify the vocal emotion of these sentences with 96% accuracy. On each trial a single sentence was randomly selected from the sub-set and was presented at 70 dB SPL from 0° azimuth. Participants were instructed to indicate, from the five options, the emotional tone of the voice for each trial. Two versions of this task were completed in each session. In one version, the original recordings were presented. In the other version (‘normalised version’) the average root-mean-square (RMS) power across the sentences was normalised so that listeners could not rely on differences in amplitude. The order of the two versions was counterbalanced so that individuals, who completed the original version first in session one, completed the original version second in session two. The percentage of correct responses was calculated for the original condition, the normalised condition, and overall.

#### *5.2.3.7 Melody recognition*

This task assessed how well participants were able to use changes in pitch to recognise a simple tune. Ten simple and familiar tunes (see Appendix D) comprised of single notes were synthesised. Rhythmic information was removed by keeping the duration of each note the same. Thus the only cue remaining for listeners to identify the tune was changes in pitch. A similar procedure has been used elsewhere (Moore & Rosen, 1979; Kong et al., 2005). Before completing the task, participants were shown the names of the tunes and asked if there were any that they did not recognise. Throughout the task the names of the tunes were displayed in front of the participant. A practice run was conducted to familiarise participants with the task and the stimuli being used. The practice run contained 10 trials, with each trial containing a single tune. The tune was presented at 0° azimuth at 70dB SPL. Participants were asked to indicate which tune they thought was presented. Feedback was provided and regardless of whether the participant was correct or not, the tune was repeated. Following the practice, a 20-trial run was completed. The run contained two instances of each tune presented in a random order. Participants indicated which tune they thought they had heard. If the participant was unsure they were encouraged to make a guess; if they were unwilling to guess a null response was recorded by the experimenter. The percentage of correct responses was scored.

### 5.2.4 Design

A mixed design was used. Participants completed two sessions held on separate days, each lasting about three hours. In one session the bimodal and bilateral groups completed the listening tasks using both their devices. In the other session the bilateral and bimodal groups completed the listening tasks using their first (or only) CI. The ordering of the sessions was counterbalanced across participants within each group. This enabled within-group analyses to be conducted to assess the benefit (if any) from a second device. The unilateral group also completed two sessions. They served as a comparison group in order to check for the effects of learning and to check that the bimodal and bilateral groups were not unfairly disadvantaged due to unfamiliarity when performing with their first (or only) CI. The between-subjects aspect of the design allowed comparisons between the benefit provided by a second CI and the benefit provided by a contralateral acoustic hearing aid.

### 5.2.5 Procedure

Pure-tone audiometry was conducted within a double-walled sound attenuated IAC booth to measure the hearing thresholds in the non-implanted ear of participants in the bimodal and unilateral groups. The procedure set out by the British Society of Audiology (BSA, 2004) was followed, with thresholds measured for each ear at 250Hz, 500Hz, 1000Hz, 2000Hz and 4000Hz. All participants completed the listening tasks in the same order with the exception that some participants found certain tasks extremely challenging. As a result, rather than completing all runs of a task in one go and risking the frustration and disengagement of the participant, completion of some tasks was postponed to a later stage of the session. All participants attempted the listening tasks in the following order with regular breaks:

- Speech in quiet: simple sentences
- Localisation
    - 60 degree separation
    - 30 degree separation
    - 15 degree separation
- Speech in noise
    - Version A[2]
    - Version B
    - Version C
    - Version C
    - Version B
    - Version A
- Speech in quiet: complex sentences
    - Gender A[3]
    - Gender B
- Speech perception in the presence of one other talker x 2
- Speech perception in the presence of multiple talkers (Run 1)
- Vocal emotion Identification
    - Version 1[4]
    - Version 2
- Melody Recognition

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[2] *Where Versions A, B and C correspond to the three versions of this task. The ordering was counterbalanced between sessions and across participants.*

[3] *Where Genders A and B correspond to male or female. The ordering was counterbalanced between sessions and across participants.*

[4] *Where Versions 1 and 2 correspond to original or normalised. The ordering was counterbalanced between sessions and across participants.*

- Speech in the presence of multiple talkers (Run 2)

The eight movement tracking trials were interspersed throughout the session.

### 5.2.6 Analyses

Three unilateral CI users (118,167 and 325) are not included in the analyses. One participant (167) only completed one session. Participants 118 and 325 were unable to complete all the tasks. These two participants had modified Z-scores (Iglewicz & Hoaglin, 1993) on the speech in quiet task using simple sentences greater than 3.5. One bimodal participant (326) had particular difficulty with the speech in speech tasks which resulting in elevated thresholds so high that it effectively became a speech in quiet task. Therefore data from participant 326 are not included in the analyses on the speech in speech tasks. As there were multiple comparisons a Bonferroni correction was applied (.05/15) for the listening tasks. As there were multiple comparisons a Bonferroni correction was applied (.05/15) for the listening tasks thus the alpha level was adjusted to be .003. Normality was tested using the Sharipo-Wilk test (also Bonferroni corrected). Statistical tests were conducted with SigmaPlot Version 12.0.

In comparing performance with one or two devices, paired samples t-tests were conducted for each task. If the assumption of normality was not met, a Wilcoxon signed ranks test was used. In comparing performance with one CI across the three groups, analyses of variance were conducted. In order to present a summary of the overall pattern of the data, raw scores from all the tasks were converted to Z-scores enabling comparisons to be made between the tasks in terms of the degree of benefit received from a second device.

## 5.3 Results

### 5.3.1 Familiarity with configurations and learning

No significant differences were found between the three groups when using one CI on any of the listening tasks. Thus there was no disadvantage for the bilateral and bimodal patients in the condition where they were using their first (or only) CI. No learning effects were observed with no significant differences in performance by unilateral CI users found between session one and session two.

### 5.3.2 Monaural Vs binaural hearing

#### *5.3.2.1 Summaries*

Scores on the listening tasks were standardized and converted to Z-scores to illustrate the general pattern of performance on the battery of listening tasks. Performance results on each of the tasks will be discussed in greater detail in the following sections. Figure 5.4 shows the overall pattern of performance on the battery of listening tasks by the bilateral group. It can be seen that users received a significant benefit from using a second CI on spatial listening tasks. Speech perception in quiet shows a trend to be better with two CIs although this is not significant. When listening to speech in noise, performance was significantly improved from the addition of a second CI when noise was presented on the side ipsilateral to the users' first CI. However, no advantage from a second CI is found when noise was presented from the side contralateral to the users' first CI or when the noise was spatially concurrent with speech. Performance on the quality of sounds tasks showed no advantage from a second CI.

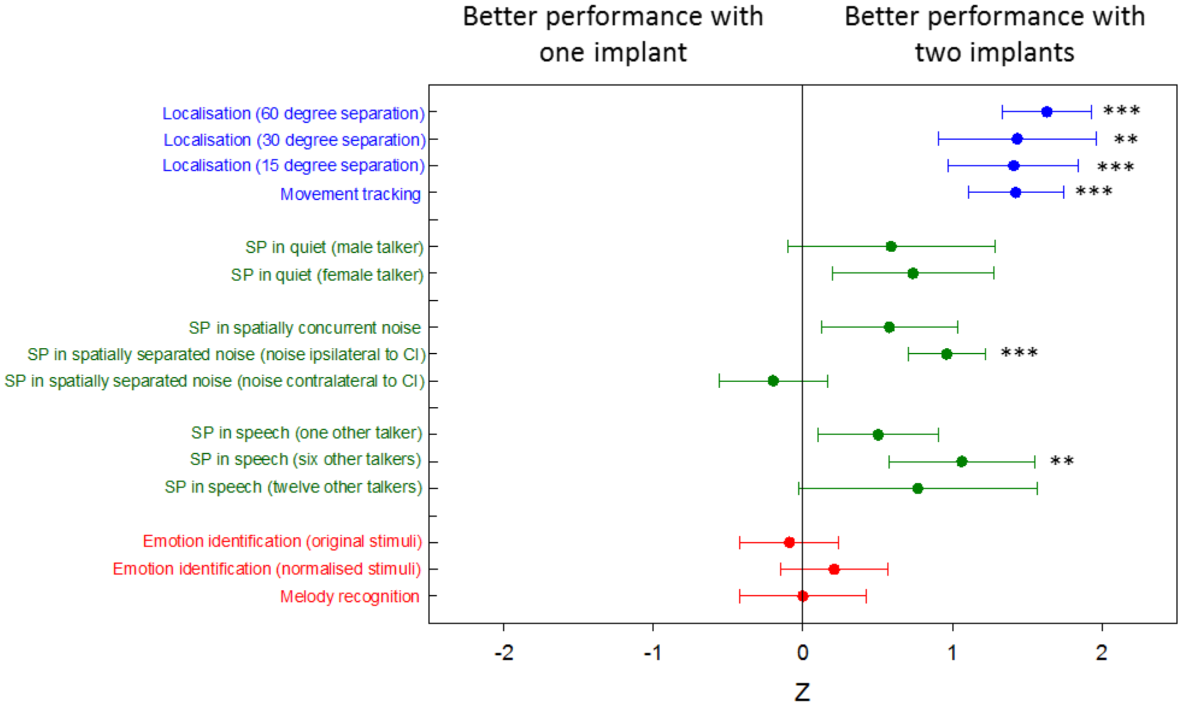


**Figure 5.4. Standardized mean performance on the listening battery for the bilateral group. Spatial, speech and qualities of listening tasks are shown in blue, green and red respectively. Scores to the right of the central line indicate performance was numerically better with two CIs. Error bars show 95% confidence intervals. SP = speech perception. A significant difference between monaural and binaural listening after a Bonferroni correction had been applied is indicated by asterisks (*** indicates p<.001 and ** indicates p<.01).**

Figure 5.5 shows the overall pattern of performance on the battery of listening tasks for bimodal users. It can be seen that performance on spatial listening tasks shows a trend to be better with two devices although a significant benefit was found only for localising sound sources separated by 15°. There is no significant advantage from a second device on any of the speech tasks. Performance on the vocal emotion tasks shows a trend for a two device advantage although no significant benefit was found. Furthermore no advantage from a contralateral acoustic hearing aid was found for the melody recognition task.

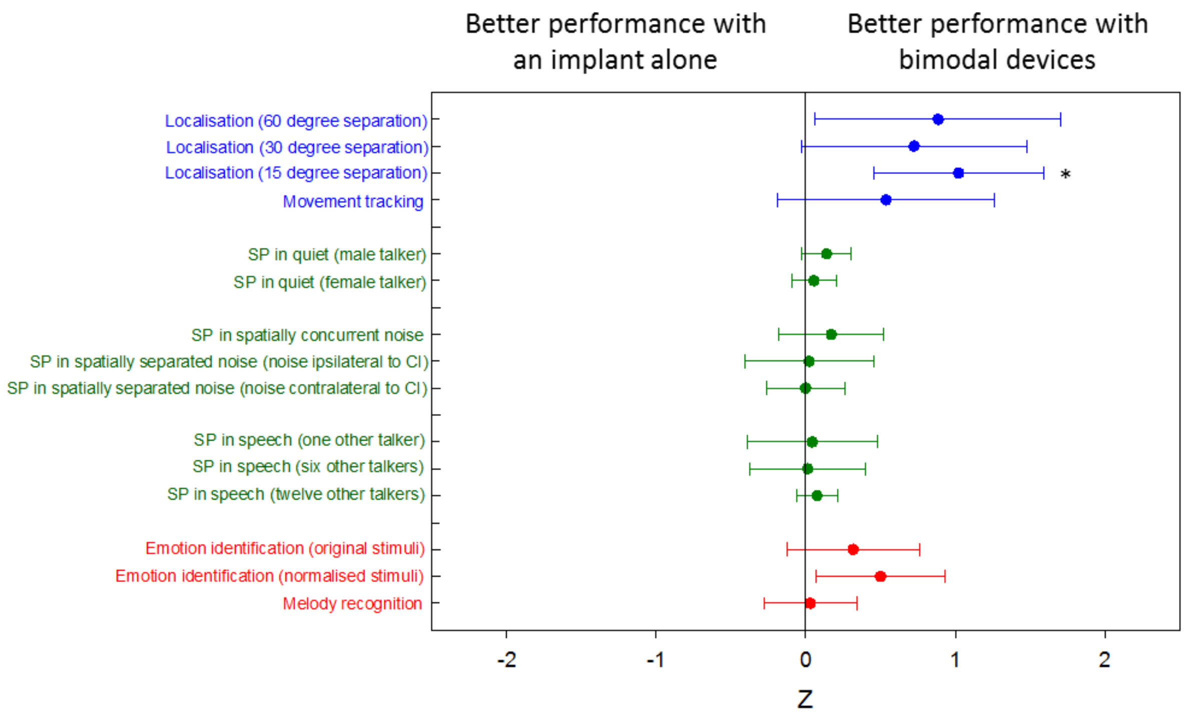


**Figure 5.5. Standardized mean performance on the listening battery by the bimodal group. Spatial, speech and qualities of listening tasks are shown in blue, green and red respectively. Scores to the right of the central line indicate performance was numerically better with two devices. Error bars show 95% confidence intervals. SP = speech perception, A significant difference between monaural and binaural listening after a Bonferroni correction had been applied is indicated by an asterisk (* indicates p<.05).**

### *5.3.2.2 Spatial listening*

Sound localisation

Mean performance on the three versions of the localisation task for both the bilateral and bimodal groups is shown in Figure 5.6. For the bilateral group performance was significantly higher than chance when localising sources separated by 60° and 30° in both listening configurations. However, when localising sounds separated by 15°, performance was only significantly greater than chance when listening with two CIs. Paired samples t-tests showed that localisation accuracy was significantly higher with two CIs than one when localising sounds at each level of separation (60°: t(11) = -12.08, *p*<.001, 30°: t(11)=-5.98, *p*<.001, and 15°: t(11) = -7.13, *p*<.001).

For the bimodal group, performance on all three versions of the localisation task was not significantly different from chance when using one CI. However, performance with bimodal devices was significantly higher than what would have been expected by chance for all three versions of the task. Although performance was numerically higher with two devices for all three versions of the task, no significant differences were found between the two listening configurations for the 60° separation (t(11)= -2.37, *p*= .037) or 30° separation (t(11)=-2.11, *p*=.059) versions of the task. However, localisation accuracy on the 15° separation version of the task was significantly greater with two devices than one (t(11) = -3.94, *p*=.002).

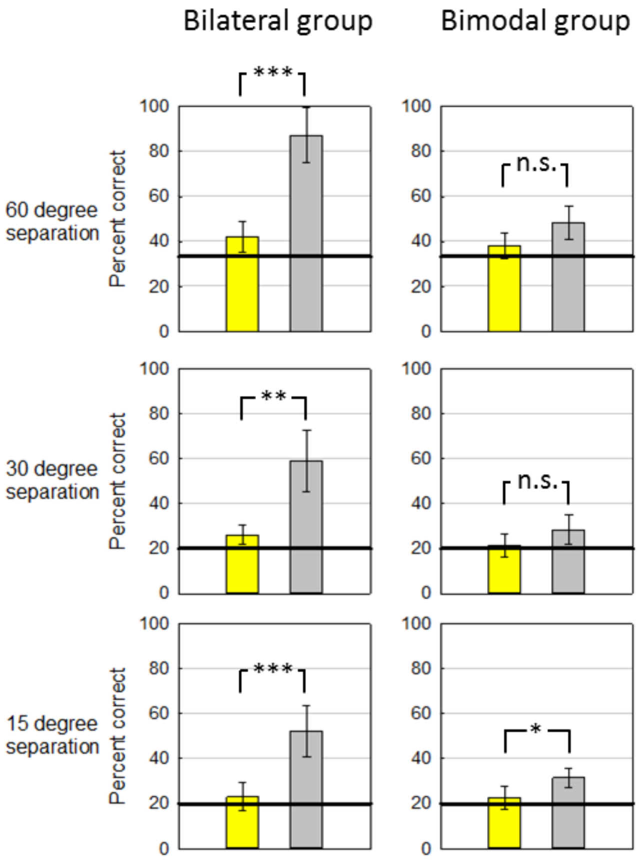


**Figure 5.6. Mean localisation performance with one (yellow bars) and two (grey bars) devices when sounds were separated by (a) 60°, (b) 30°, and (c) 15°. Left column shows data from the bilateral group and the right column shows data from the bimodal group. Error bars show 95% confidence intervals. The thick black line shows chance performance for the task.**

### Movement tracking

The bilateral group displayed more accurate performance tracking moving sounds when using two CIs (mean = 80.21%, SD = 26.36) than when using one CI (mean = 31.25%, SD =21.65). A paired samples t-test showed this difference to be significant (t(11) = -9.84, *p*<.001). For the bimodal group, although performance when tracking moving sounds was numerically higher with two devices (mean = 41.67%, SD = 31.68) than one device (mean = 27.08%, SD = 20.53), this difference was not significant (t(11) = -1.63, *p*=.131). For both groups, performance with one device did not differ significantly from chance (25%), however performance with two devices was significantly greater than chance.

#### *5.3.2.3 Speech perception*

Speech perception in quiet

*Simple sentences*

Mean performance by the bilateral and bimodal groups for each listening configuration is shown in Table 5.2. High accuracy was achieved by the bilateral group for all three listening configurations. The data were not normally distributed so a Friedman repeated measures ANOVA on ranks was conducted which showed no significant differences in mean scores across listening configurations ($\chi^2(2)= 5.86$, *p*=.053). The bimodal group achieved accurate speech perception in quiet scores when listening with both their devices or their CI alone. However performance was very poor when listening with just their acoustic hearing aid. The data were not normally distributed so a Friedman repeated measures ANOVA on ranks was conducted which showed that there was a significant main effect of listening configuration ($\chi^2(2)= 19.60$, *p*<.001). Post-hoc comparisons using the Tukey HSD test revealed that there were no significant differences in the percentage of keywords correctly identified when using both devices and when using the CI alone (*p*=.839). However significantly fewer keywords were correctly identified with the hearing aid alone than when listening with both devices or the CI alone (both *p*<.001).

**Table 5.2. Mean percentage of keywords correctly identified in quiet by the bilateral and bimodal groups when using both devices, the first (or only) CI alone and the second device alone. SD in parentheses.**

| | Bilateral group Mean (SD | Bimodal group Mean (SD) |
|---|---|---|
| Both devices | 94.92 (10.14) | 88.08 (22.92) |
| First (or only) CI | 86.92 (16.07) | 83.25 (27.71) |
| Second device only | 89.00 (17.35) | 15.92 (25.43) |

*Complex sentences*

Mean performance is shown in Table 5.3. Performance was numerically higher with two devices than one for both groups however paired samples t-tests revealed no significant difference between monaural and binaural listening for either group (all p>.003). Both the bilateral and bimodal groups had significantly higher mean speech perception scores when listening to the male talker than the female talker when using one device (bilateral: (t(11) = 5.76, *p*<.001; bimodal: t(11) = 4.40, *p*=.001) and when using two devices(bilateral: t(11) = 3.24, *p*=.008; bimodal: t(11) = 4.01, *p*=.002).

**Table 5.3. Mean percentage of keywords correctly identified in quiet by the bilateral and bimodal groups when using one or two devices. SD in parentheses.**

| | Bilateral group | | Bimodal group | |
|---|---|---|---|---|
| | First CI | Both implants | Implant only | Bimodal aiding |
| Male talker | 77.56 (23.39) | 89.77 (16.36) | 76.17 (28.59) | 79.94 (26.88) |
| Female talker | 65.83 (24.83) | 83.44 (20.27) | 63.61 (29.74) | 65.20 (30.85) |
| Average | 71.70 (23.86) | 86.61 (18.10) | 69.89 (28.75) | 72.58 (28.23) |

### Speech perception in noise

Table 5.4 shows the mean SRTs for the three noise conditions when using one or two devices. In comparing monaural and binaural performance for the bilateral group, no significant difference in SRTs was found when noise was spatially concurrent with the speech ($t(11) = 2.82$, $p$=..017) or when noise was presented on the side contralateral to the first CI ($t(11) = -1.21$, $p=.250$). When the noise was presented on the side ipsilateral to the first CI, performance was significantly better with two CIs compared to one CI ($t(11) = 8.27$, $p<.001$). For the bimodal group no significant difference in performance between monaural and binaural listening was found for any of the three versions of the task (all $p>.003$).

The spatial release from masking was calculated for both sides for both groups. For the bilateral group, when using one CI the mean SRT worsened by 1.43dB (SD = 4.08) when the noise was moved from the front to the side ipsilateral to the first CI. When the noise was moved from the front to the side contralateral to the first CI mean performance improved by 6.62dB (SD = 3.29). When using two CIs the mean performance improved by 2.55dB (SD = 3.44) when the noise was moved to the side ipsilateral to the first CI, and improved by 2.26dB (SD = 3.44) when the noise was moved to the side contralateral to the first CI. For the bimodal group when the noise was moved from the front to the side ipsilateral to the CI, mean performance worsened by 2.43dB (SD = 2.02) when listening with one device and worsened by 3.10 dB (SD = 3.73) when listening with two devices. When the noise was moved from the front to the side contralateral to the CI mean performance improved by 5.33 dB (SD = 2.08) when listening with one device and improved by 4.53dB (SD = 3.14) when listening with two devices.

**Table 5.4. Mean SRTs (dB) for the speech perception in noise task by the bilateral and bimodal groups with one CI and with two devices. Also shown is the mean spatial release from masking (in dB). SD in parentheses.**

| | Bilateral CI users | | Bimodal users | |
|---|---|---|---|---|
| | First CI | Both implants | Implant only | Bimodal aiding |
| Noise spatially concurrent with speech: | | | | |
| Noise in front of listener | 4.84 (6.29) | 1.69 (4.11) | 3.78 (4.91) | 2.98 (4.71) |
| Noise spatially separated from speech: | | | | |
| Noise ipsilateral to first device | 6.27 (6.21) | -0.86 (6.97) | 6.22 (6.23) | 6.07 (7.30) |
| Noise contralateral to first device | -1.78 (4.85) | -0.57 (7.29) | -1.55 (4.63) | -1.55 (3.81) |
| Spatial release from masking (1st device) | -1.43 (1.08) | 2.55 (3.44) | -2.43 (2.02) | -3.10 (3.73) |
| Spatial release from masking (2st device) | 6.62 (3.29) | 2.26 (3.92) | 5.33 (2.08) | 4.53 (3.14) |

## Speech perception in speech

Participants completed three speech in speech tasks; one with one spatially concurrent competing talker, another with six spatially separated competing talkers and a third with twelve spatially separated competing talkers. As can be seen from Table 5.5, for bilateral CI users, performance was numerically better when using two CIs compared to one CI for all three versions of the task. The improvement from the addition of a second CI on the six spatially separated competing talker version of the task was significant ($t(11) = 4.83$, $p<.001$) but the improvement was not significant in the one competing talker ($t(11) = 2.74$, $p=.019$) or the twelve competing talkers ($t(11)=2.11$, $p=.058$) versions of the task. When using one CI the bilateral group performed best when there was one competing talker, but SRTs for the six and twelve competing talkers were similar. When using two CIs performance worsened numerically as the number of competing talkers was increased. For the bimodal group in both listening conditions performance worsened numerically as the number of competing talkers increased although the differences between monaural and binaural listening on the three versions of the task were not significant.

**Table 5.5. Mean SRTs by the bilateral and bimodal groups for the three speech in speech tasks when using one or two devices. SD in parentheses.**

| | Bilateral group | | Bimodal group | |
|---|---|---|---|---|
| | One CI | Two CIs | Implant only | Bimodal aiding |
| One spatially concurrent competing talker | 6.63 (7.87) | 3.35 (5.58) | 3.74 (5.32) | 3.26 (4.62) |
| Six spatially separated competing talkers | 10.07 (5.22) | 4.73 (3.13) | 7.76 (3.87) | 7.65 (3.88) |
| Twelve spatially separated competing talkers | 10.03 (4.12) | 6.54 (4.41) | 8.91 (2.21) | 8.06 (2.60) |

#### *5.3.2.4 Qualities of sound*

##### Vocal emotion identification

Mean performance on both versions of the task is shown in Table 5.6. Mean identification performance was significantly higher than chance (20%) for both groups and both sentence types in all listening configurations. Performance by the bilateral group was very similar across monaural and binaural listening conditions. There was no significant benefit from the addition of a second CI for either the original (t(11) = 0.59, *p*=.564) or amplitude normalised (t(11) = -1.28, *p*=.228) sentences. For the bimodal group there was no significant benefit from the addition of a contralateral acoustic hearing aid for either sentence type (original: t(11) = --1.58, *p*=.142; normalised: t(11) = -2.54, *p*=.027).

For both groups, having access to amplitude information did improve performance in the monaural condition (Bilateral: t(11) = 2.35, *p*=.038; bimodal: t(11) = 2.86, *p*=.016) but did not improve performance in the binaural condition (bilateral: t(11) = 0.41, *p*=.688; bimodal t(11) =.094, *p*=.367).

**Table 5.6. Mean percent correct scores on the vocal emotion identification and melody recognition tasks when using one and two CIs. SD in parentheses.**

| | Bilateral group | | Bimodal group | |
|---|---|---|---|---|
| | One CI | Two CIs | Implant only | Bimodal aiding |
| Vocal emotion identification: | | | | |
| Original sentences | 57.00 (13.09) | 55.83 (13.50) | 55.50 (12.33) | 58.83 (8.51) |
| Normalised sentences | 51.83 (17.11) | 55.00 (13.31) | 51.08 (12.22) | 57.17 (11.77) |
| Average | 54.42 (14.75) | 55.42 (12.94) | 53.29 (11.98) | 58.00 (9.80) |
| Melody recognition | 32.50 (25.27) | 32.50 (26.07) | 36.25 (28.61) | 37.08 (28.88) |

#### Melody recognition

Mean performance on the melody recognition task is shown in Table 5.6. Performance was significantly above the chance level of 10% correct for both groups in both listening conditions. However, there was no significant benefit in performance from a second CI ($t(11) = 0.00$, $p=1.000$) or contralateral acoustic hearing aid ($t(11) = -0.21$, $p=.838$).

### 5.3.3 Bimodal or Bilateral

The benefit that a second device provided for each listening task for both groups were converted to Z-scores and the standardized benefit scores are shown in Figure 5.7. A significantly greater advantage from a second CI compared to a contralateral acoustic hearing aid was observed for spatial listening tasks ($t(22) = 6.08$, $p<.001$, $t(22) = 4.058$, $p<.001$, and $t(22) = 4.39$, $p<.001$ for localisation separated by 60°, 30° and 15° respectively and $t(22) = 3.36$, $p=.003$ for movement tracking). In addition, a greater benefit was achieved with a second CI than a contralateral acoustic hearing aid when listening to speech in noise when the noise was presented on the side ipsilateral to the first CI ($t(22) = 4.48$, $p<.001$). No other significant differences in the amount of benefit received were found between the bimodal and bilateral groups. However, numerically, a greater benefit was obtained from using a second CI than using a contralateral acoustic hearing aid for all of the listening tasks except vocal emotion identification and melody recognition which showed a numerical bimodal advantage. The addition of a second CI resulted in numerically poorer speech perception performance in noise with noise presented on the side contralateral to the first CI but performance did not change for the bimodal group when a contralateral acoustic hearing aid was added.

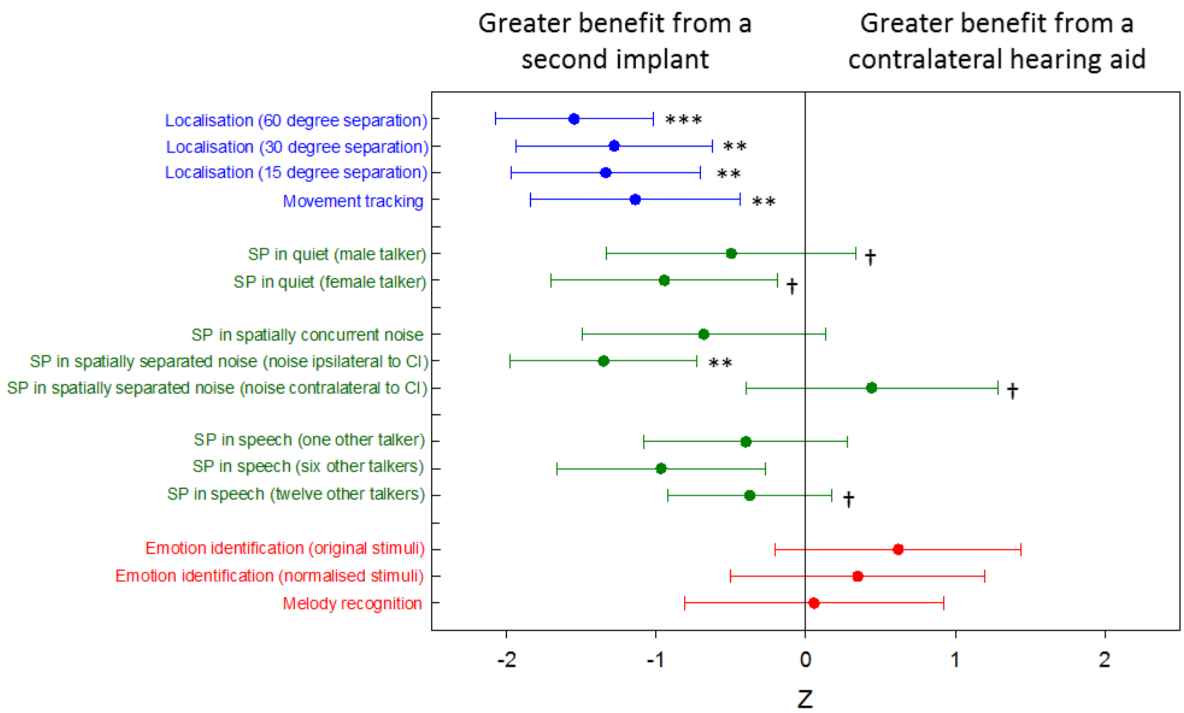


**Figure 5.7.Standardized mean benefit scores from the listening test battery for the bimodal and bilateral groups. Spatial, speech and qualities of listening tasks are shown in blue, green and red respectively. Scores to the left of the central line indicate benefit was numerically higher with a second CI. Scores to the right of the central line indicate benefit was numerically higher with a contralateral acoustic hearing aid. Error bars show 95% confidence intervals. SP = speech perception. A significant difference between the benefit obtained from each option after a Bonferroni correction had been applied is indicated by asterisks (*** indicates p<.001 and ** indicates p<.01).† indicates that the assumption of normality was not met).**

## 5.4 Discussion

### 5.4.1 Familiarity with devices and learning

The bimodal and bilateral groups completed the listening tasks in an unfamiliar configuration using just their first (or only) CI. This could have inflated the amount of benefit observed from a second device, if the bilateral and bimodal groups had performed poorly with one CI due to being unfamiliar with listening in that configuration. Therefore, in order to check whether this issue arose, performance on all listening tasks when using one device was compared with performance by a group of unilateral CI users. No significant differences between the three groups were found for any of the listening tasks. Therefore any difference in performance when using two devices compared to one device can be attributed to the addition of the second device. No learning effects were found as unilateral CI users performed similarly in both sessions on all of the listening tasks.

### 5.4.2 Spatial listening

As hypothesised, a second CI provided significant benefit over a single CI for localising sound sources and tracking moving sounds. This result is consistent with previous research that has also demonstrated bilateral CI advantages in spatial listening over using a unilateral CI (Ching et al., 2007; Crathorne et al., 2012; Dunn et al., 2008; Kerber & Seeber, 2012; Litovsky et al., 2009; Sammeth et al., 2011; van Hoesel & Tyler, 2003). Comparing the acoustic input at the two ears in terms of intensity and time differences enables normally hearing listeners to locate sound sources (Akeroyd, 2006). However, CI users rely more heavily upon interaural level differences (ILD) than interaural time differences (ITD) (Seeber & Fastl, 2008). The stimuli were roved in level from trial to trial so that listeners could not base their response entirely on the intensity of the stimulus at either ear alone. However, on any individual trial, the use of two CIs compared to one CI enabled participants to utilise ILDs to determine the location of sounds.

This study found mixed results for bimodal participants. No significant benefit from a contralateral acoustic hearing aid was found when localising sounds separated by 60° or 30° or when tracking moving sounds. These results may suggest that the different processing delays of the two devices restricted the ability of users to use interaural timing difference cues. It may also be the case that some participants did not have sufficient residual hearing in their non-implanted ear to use these cues. However, a significant benefit was found from the addition of a contralateral acoustic hearing aid when localising sound sources separated by 15°. This was the most challenging version of the task and the reason for only benefitting on this version of the task is not clear from the present study. It may be that there were too few trials in the less challenging versions of the task to enable a difference to be measured. These mixed findings for spatial listening are in accordance with the literature which has shown varied results for sound localisation by groups of bimodal users (Dunn et al., 2005; Olson & Shinn, 2008; Seeber et al., 2004; Tyler et al., 2002)

In comparing the two options, as hypothesised a greater spatial listening benefit arose from using a second CI.

### 5.4.3 Speech perception

#### *5.4.3.1 Speech in quiet*

Simple sentences

Participants listened to simple sentences in quiet when using both their devices, their first device alone, and their second device alone. The sentences used were short and were articulated clearly and neither group benefitted significantly from their second device. When listening with their first

CI alone, the bimodal group had good speech perception scores and the bilateral group had very good speech perception scores leaving little room for any improvement due to binaural summation to arise.

### Complex sentences

The present study found no significant benefit from a second CI when listening to complex sentences in quiet. In a recent review on the effectiveness of bilateral cochlear implantation, van Schoonhoven et al. (2013) highlighted that, consistent with the present study, the vast majority of studies published between 2006 and 2011 showed no significant benefit from a second CI for speech perception in quiet. In a between-subjects design with bilateral CI users matched to unilateral CI users on duration of profound deafness and age at implantation, Dunn et al. (2008) assessed speech perception ability for sentences spoken by a male talker. Contrary to the present study, it was found that bilateral CI performance was significantly greater than unilateral CI performance. In the study by Dunn, the hearing in noise test sentences were used (HINT, Nilsson, Soli, & Sullivan, 1994) whereas the present study used IEEE sentences. The IEEE sentences have been argued to be more challenging for hearing impaired listeners than the HINT sentences due to the IEEE sentences having limited semantic cues (Wilson, Mcardle, & Smith, 2007). Users of bilateral CIs in the present study reached very good levels of speech perception in quiet and showed a numerical, albeit non-significant, benefit from a second CI. Benefits may have been observed with stimuli with more semantic cues (such as the HINT sentences). It may be that this task lacked power and was not sufficiently long for a difference in monaural and binaural speech perception ability to be detected.

No significant benefit from a contralateral acoustic hearing aid was found for perception of complex sentences. This result is contrary to Zhang et al. (2010) who found patients demonstrated a significant improvement from the addition of low-frequency acoustic information. Although, acoustic information below 125Hz alone was not sufficient for speech perception of monosyllabic words, Zhang et al. demonstrated that when combined with electric information from a CI speech perception significantly improved. However, Zhang et al. used an insert ear phone to present stimuli with real-ear insertion gain whereas the current study tested participants using their hearing aids. In a study which did test speech perception of monosyllabic words by participants with their hearing aids, only four out of twelve individuals benefitted significantly from using a hearing aid in conjunction with a CI (Dunn et al., 2005). One might have expected a benefit from a hearing aid in the present study as the low frequency region contains cues to consonant voicing and manner of articulation which are important for speech perception (Rosen, 1992). Ching et al. (2007) highlighted that voice and manner information were transmitted better with bimodal aiding than with a CI alone. However, Sheffield and Zeng (2012) found that bimodal users received limited voicing information from the low-frequency information when listening to consonants in quiet. Furthermore, Most et al. (2012) found no significant benefit from bimodal devices over a single CI for consonant voicing perception. Therefore participants in the current study may not have received sufficient information on low-frequency cues from their bimodal devices compared to their CI alone.

A comparison of the benefit derived from a second device between bilateral and bimodal patients showed no significant differences in the amount of benefit obtained from either option for speech perception in quiet when listening to either a male or female talker. Given the non-significant within-subjects benefits observed, this result was not surprising.

#### *5.4.3.2 Speech in noise*

When the speech and noise were spatially concurrent, the bilateral CI users did not benefit significantly from the use of a second CI suggesting that participants in the present experiment were not able to benefit from binaural redundancy. No benefit was observed from using a second CI when noise was on the side contralateral to the first CI. In this version of the task performance was already good when listening with one CI, with a negative mean SRT (see Table 5.4). However, as expected, when the noise was presented ipsilateral to the first CI a significant benefit from a second CI was observed. When listening with two CIs the participants' head acted as an acoustic baffle that improved the signal-to-noise ratio at the ear further from the noise. When noise was presented ipsilateral to the first CI, the ear further from the noise was the ear with the second CI. When listening with just the first CI, there was no contralateral device from which participants could benefit from. Consistent with Kokkinakis and Pak (2014) the use of a second CI enabled listeners to take advantage of the head shadow. Although binaural summation and, binaural squelch can also improve speech perception in the presence of noise, the largest benefit has been shown to arise as a result of the head shadow effect (Kokkinakis & Pak, 2014; Müller et al., 2002; Schleich et al., 2004). The present findings are somewhat discrepant to that found by Müller et al. (2002). In a similar design to the present study, Müller et al. tested bilateral CI users both monaurally and binaurally on a speech in noise task where the noise was presented from either straight ahead, +90° or -90°. Contrary to the present findings, performance was better with both CIs for all three versions of the task. One possible explanation for this difference is that Müller et al., used sentences whereas the present study used words. It is possible that the context provided by the sentences could have benefitted the participants in Müller et al.'s study with the task in the present study being more challenging. Furthermore Müller et al. measured the percentage of speech correctly identified at a fixed SNR of +10dB, whereas the present study used an adaptive procedure to measure SRTs at which 50% of keywords could be correctly identified. The adaptive procedure used in the current study is likely to have been more challenging than the fixed procedure (Schafer et al., 2011) which could account for these discrepant findings.

No significant benefit was obtained from the addition of a contralateral acoustic hearing aid for any version of the speech in noise task. This result is contrary to Tyler et al. (2002) who found that two out of three users performed better with bimodal devices than with a CI alone when the speech and noise were presented from 0° azimuth. However, Tyler et al. also found no significant benefit when noise was presented on the side of the hearing aid, consistent with the present study. The current findings suggest that the addition of a hearing aid is neither an advantage nor a hindrance to the accuracy of speech perception in noise.

In comparing the two options, no significant difference in the amount of benefit from a second device was found when the noise was on the side contralateral to the first CI. However, a significantly greater benefit was found from using a second CI when the noise was on the side ipsilateral to the first CI. These findings suggest that users are better able to benefit from the head shadow with a second CI. This is unsurprising considering the poor speech perception in quiet scores achieved with a hearing aid alone (see Table 5.2).

#### *5.4.3.3 Speech in speech*

Three speech in speech tasks were conducted. One task had one competing talker, one task had six competing talkers and one task had twelve competing talkers. The SRTs from the bilateral group improved numerically from the addition of a second CI for all three versions of the task (see Table 5.5). However, only the improvement for the version with six competing talkers was significant. The finding for the two talker version of this task is consistent with Loizou et al. (2009) who also found no differences between bilateral and unilateral CI performance when a male and female talker were presented from 0° azimuth. Furthermore, when listening bilaterally the mean SRT on the one competing talker version of the task found in the current study (3.35dB, see Table 5.5) was similar to that found by Loizou (about 4dB inferred from their Figure 1a).

In the one competing talker version of the task, the target sentence and the competing sentence were presented from the same location. An important cue for segregating the two talkers is a difference in voice pitch. Based on previous research (Kong et al., 2005), it had been anticipated that the bimodal group would benefit from the addition of a contralateral acoustic hearing aid as they would be able to use information conveyed in the low frequencies (such as the fundamental frequency) to segregate the two talkers. This was not the case as the addition of a contralateral acoustic hearing aid did not significantly improve the SRT. The bimodal users who participated in

Kong et al's study were American and had moderate to profound pure-tone thresholds, which were more favourable than those of the participants in the present study. Therefore these results suggest that the advantages found for bimodal users in the USA are not always realised for UK users. In addition, the present study found no significant benefit from a contralateral acoustic hearing aid on speech perception performance in the presence of spatially separated talkers. This result suggests that the bimodal users were unable to receive sufficient benefit from the head shadow, consistent with the present findings for speech in noise.

Using an adaptive procedure for a speech perception task in the presence of spatially separated noise presented from five locations, Ricketts, Grantham, Ashmead, Haynes, & Labadie (2006) found an average benefit of 3.3 dB from the use of a second CI over performance with the better monaural ear. The present study found a similar amount of benefit from a second CI (3.49dB, 95% CI ±3.63) for the twelve competing talker version of the task (see Table 5.5). However a greater benefit (5.34dB, 95% CI ±2.43) was found from a second CI when there were just six competing talkers. This benefit was not significantly greater than the benefits found in the twelve talker version of the task or the average benefit found by Ricketts et al. as illustrated by these mean benefits being embraced by the 95% confidence interval of the mean for the six talker version. Few studies have compared bilateral to unilateral speech perception performance in the presence of multiple spatially separated speech maskers. One study which has, used three female talker maskers and one male target (Loizou et al., 2009). The target sentence was always presented from 0° azimuth, and the three spatially separated masker sentences were presented in two configurations: presented from both sides (-30°, 60°, and 90°, one masker at each location), or from the right side only (30°, 60° and 90° , one masker at each location). They found that when the masker sentences were on the right hand side bilateral CI performance was better than the monaural right ear performance but not monaural left ear performance, suggesting that the users were able to use the ear with the better SNR to hear out the target speech. However, the current study utilised a more difficult stimulus set: there were more talkers, the target location was not fixed and could come from any location on each trial, and the masker sentences were spoken by talkers of both genders. The fact that a significant benefit was obtained from a second CI for the six competing talker version of the task suggests that the participants were able to utilise the head shadow and listen with the ear with the better SNR. The twelve competing talker version of this task is very challenging and although monaural performance on this version was similar to monaural performance on the six competing talker version of the task, the addition of a second CI did not provide as much benefit. This result could be due to a reduction in the head shadow effect as a result of a large number of masker talkers (Firszt, Reeder, & Skinner, 2008).

The current study found no significant difference in the amount of benefit obtained from a second device between bimodal and bilateral groups for any of the speech in speech tasks. This result is consistent with Cullington and Zeng (2011) who found that bimodal and bilateral CI users performed similarly when listening to speech in the presence of one other competing talker. When the competing talker was of a different gender, Cullington and Zeng measured similar mean SRTs for both groups with 2.17 dB for bilateral CI users and 2.52 dB for bimodal users. This level of performance is similar to that reached by the participants in the present study with mean SRTs of 3.51 dB for the bilateral CI users and 3.26dB for the bimodal users. The current findings suggest that neither a second CI nor a contralateral acoustic hearing aid is better than the other for separating out concurrent talkers.

### 5.4.4 Quality of sound tasks

The bilateral group did not obtain a significant benefit from a second CI for vocal emotion identification or melody recognition. This was expected as CIs do not convey low frequency information and they also do not convey the temporal fine structure of sounds very well, an important feature of pitch perception (Moore, 2008). Although changes in pitch are an important cue in distinguishing different vocal emotions, other cues include duration and intensity (Pittam & Scherer, 1993). In order to assess the role of pitch more specifically there were two versions of the vocal emotion task – one with the original recordings and one where the average RMS power of the sentences were normalised, so that average intensity could not be used as a cue to identify the vocal emotion. Based on previous research by Luo, Fu, and Galvin (2007) it was expected that, although a challenging task, the bilateral CI users would perform better with the original recordings as they would have been able to detect intensity differences and utilise this information to infer the vocal emotion to some extent. However this was not found, rather the participants in the present study found vocal emotion identification difficult, irrespective of the range of cues available.

No benefit from using bimodal devices over a CI alone was found for the quality of sounds tasks. This did not support the hypothesis that the bimodal users would benefit from using a contralateral acoustic hearing aid on pitch-related tasks because the hearing aid would provide access to pitch information conveyed in the low frequencies that the CI does not convey. Contrary to the present findings, previous research has demonstrated that having access to low-frequency information provided by an acoustic hearing aid can improve music perception (Flynn & Schmidtke, 2004; Kong et al., 2005) and vocal emotion recognition (Most et al., 2012). The present study's results suggest that UK users of bimodal devices have difficulty in identifying the vocal emotion of a talker and recognising musical melodies and are less able to utilise the information contained in the lower frequencies for these tasks.

Although the benefit obtained from a contralateral acoustic hearing aid was numerically greater than that obtained from a second CI, the differences between the two options were not significant. This finding is consistent with that of Cullington & Zeng (2011) who presented bilateral and bimodal users a semantically neutral sentence spoken in six emotional states (neutral, happy, angry, sad, disinterested, and surprised), four of which are the same as that used in the current study. Consistent with the present study, no significant difference in performance between the groups was found.

### 5.4.5 Strengths and weaknesses

A wide range of tasks was completed over two sessions. An advantage of this approach was that different aspects of listening could be assessed. Furthermore, the mixed design enabled both the difference in performance between monaural and binaural listening to be evaluated and the difference in benefit between the two types of binaural hearing to be investigated. Although the bimodal and bilateral participants did not have much time to acclimatize to using one device, no significant differences in performance were found between these users using one device and performance by a group of unilateral CI users. The use of this comparison group provided a check that the bimodal and bilateral groups did not perform worse when using one CI simply due to unfamiliarity with this listening configuration. This in turn provided confirmation that any difference in performance when using two devices instead of one was due to the addition of the second device. Another advantage from including a group of unilateral CI users was that any learning effects could be measured. Similar performance across two days demonstrated that there were not any learning effects. Had there been learning effects, the use of a counterbalanced design would have overcome this with users of two devices completing the two sessions in both orders.

It is important to acknowledge that the foregoing results were obtained with a small, self-selecting sample. The participants who took part in this study had responded to a letter published in the National CI Users Association magazine which invited users to take part in the study. It is therefore possible that those who responded were individuals who were satisfied with their devices and therefore the findings may not be representative of UK CI users in general. It was also possible that they would show advantages from binaural listening precisely because they were satisfied with their devices. Thus it is justifiable to conclude that this study demonstrates the potential for UK adults to receive advantages from a second device. Users who are not satisfied with their devices may not receive as large a benefit and therefore it would be informative to test a larger sample of UK CI users on tasks such as those used in the current study to investigate what a unilateral CI user considering obtaining a second device is likely to achieve. The ordering of the tasks in the present study was not fully counterbalanced. Although regular breaks were included over the course of testing, the length of the session and the cognitive demands of some of the tasks may have fatigued some of the listeners, potentially worsening their performance on some of the later tasks.

Due to the size of the test battery, only a limited number of trials for each task could be included in the test session, therefore it is possible that the tests did not include a sufficient number of trials to have the statistical power to demonstrate an advantage from a second device. In a future study if a trade-off were to be made in increasing the number of trials in some listening tests and omitting others the most useful sub-set of tests in the present study to include would be localisation (15° separation), speech in noise, and emotion perception. The reason for selecting the 15° version of the localisation task is that this was the most challenging version of the task and both groups benefitted from a second device. It would be enlightening for future research to assess why bimodal users benefit in this condition.  A key advantage from binaural listening over monaural listening is the ability to benefit from the head shadow if the noise is on either side of the head. By using the speech in noise tests from the battery, one can assess if a second device provides advantages when the noise is ipsilateral to the first CI but also assess if a second device is a hindrance to performance when noise is contralateral to the first CI. Emotion perception showed a trend to be better with bimodal devices although this was not significant. Including more trials in a future study would enable a comparison in performance on the different types of emotions. For instance, the sad vocal emotion is characterised by a longer duration in addition to pitch differences (Pittam & Scherer, 1993), it may be that bimodal users benefit less on this emotion from a second device than they do for other emotions.

No new hearing-aid fittings were provided to patients as part of this study. Some previous studies that have shown significant benefits from a contralateral acoustic hearing aid have fitted the hearing aids of participants as part of the study (Ching et al., 2003, 2004; Flynn & Schmidtke, 2004; Incerti et al., 2011; Seeber et al., 2004). It may be that greater benefits could be observed with a properly and recently fitted hearing aid. It would also be informative for future research to test bimodal users who have had their hearing aid and CI fitted together prior to testing to optimize performance as suggested by Ching, Hill, Dillon, and Van Wanrooy (2004). Nevertheless, this study outlines the potential benefits that can be achieved from a second device in everyday listening.

### 5.4.6 Conclusion: Which option is better?

In comparing monaural to binaural hearing, using a second CI provided significant advantages for spatial listening tasks. A contralateral acoustic hearing aid provided some advantage in spatial listening ability. As an acoustic hearing aid can be obtained free of charge from the NHS, this study supports the recommendations by Ching et al. (2004) that bimodal aiding should be the standard provision for users of a unilateral CI. A key aim of the present study was to assess which option, a second CI or a contralateral acoustic hearing aid, provides the greater benefit for UK CI users. The results have shown that for the patients in this study, a second CI provided greater benefit than a contralateral acoustic hearing aid for spatial listening and speech perception in the presence of noise. No tasks revealed a significantly greater benefit from a contralateral acoustic hearing aid compared to a second CI. In conclusion, this study has demonstrated that listening with two devices is better than listening with one CI alone for some listening tasks. Furthermore, bilateral cochlear implantation provides greater benefits than bimodal aiding for UK CI users.

## 5.5 Summary

- Bilateral Vs. Unilateral
    - Significant advantages were found from a second CI on spatial listening tasks.
    - When listening to speech in spatially separated noise, performance was significantly improved from a second CI when the noise was presented on the side ipsilateral to the first CI.
    - Mixed findings were observed for speech in speech tasks with a significant advantage from a second CI on a version with six competing talkers but not on versions with one or twelve competing talkers.
    - No significant advantage from a second CI was observed for perception of speech in quiet, emotion recognition, or melody identification.
- Bimodal Vs. Unilateral
    - A significant advantage from a contralateral acoustic hearing aid was found for localising sources of sound separated by 15°.
    - No other significant advantages from a contralateral acoustic hearing aid were found.

- Bilateral Vs. Bimodal
    - Significantly greater benefit was obtained from a second CI for spatial listening tasks and speech perception in spatially separated noise when the noise was on the side of the first (or only) CI.
    - No other significant differences in the amount of benefit obtained from each device was found.

# 6 Self-reported advantages from a contralateral acoustic hearing aid or a second cochlear implant

This chapter outlines research comparing the self-reported benefits of each option (either a second CI or a contralateral acoustic hearing aid) for users of a unilateral CI in the UK. Comparisons were made between monaural and binaural listening to assess if provision of a second device results in self-reported benefit for everyday listening and quality of life. Furthermore, comparisons were made between the benefit obtained from a second CI and the benefit obtained from a contralateral acoustic hearing aid to ascertain which option provides greater self-reported benefit.

## 6.1 Introduction

There is a keen interest in establishing whether aiding the non-implanted ear of unilateral CI users provides clinical benefits for listeners. The study reported in Chapter 5 investigated the clinical benefits obtained from using either a contralateral acoustic hearing aid or a second CI. It was found that, compared to unilateral CI listening, both options resulted in improvements in spatial listening, and also, in the case of bilateral implantation, improvements to speech perception in the presence of spatially separated noise. In comparing the benefit provided from both options, the results in Chapter 5 demonstrated that a greater advantage was obtained from a second CI. The study reported in this chapter sought to establish whether these benefits in listening performance are also reflected in self-reports. The study also investigated whether self-reported listening ability highlights additional benefits which are not found in listening performance tasks. For instance, the findings reported in Chapter 5 did not show an improvement on some listening tasks in the test battery; notably vocal emotion identification and melody recognition. In the laboratory, the tests used captured only a small part of everyday listening. It is possible that the tests were not sufficiently long for an advantage to be measured or the tests used were not sensitive to the type of advantages obtained from binaural listening. In addition, it is possible that there are further advantages from using a second device that cannot be measured using listening tests (such as effects on quality of life). As the current study used self-report measures, the following sections describe how self-reports have been used previously to measure binaural advantages to everyday listening and quality of life amongst CI users.

### 6.1.1 Self-reported listening ability

***The Speech, Spatial and Qualities of hearing scale (SSQ)***

The SSQ (Gatehouse & Noble, 2004) is a measure of self-reported listening ability in everyday environments. The scale is divided into three sections each addressing a different aspect of listening: listening to speech, spatial listening, and other qualities of hearing and listening. The speech section contains 14 questions on listening to speech in quiet, listening to speech in noise, and listening to speech in the presence of other talkers. The spatial section includes 17 questions on determining where a sound is coming from, where a sound is moving from and to, and how far or close a sound is. The qualities section contains 18 questions that address aspects of listening that are not covered by the previous two sections such as identifying sounds, clarity of sounds, and listening effort. For each question participants rate their ability on an 11-point visual analogue scale which extends from no ability to perfect ability. There are multiple ways of scoring ratings on the SSQ. One option is to calculate an overall score by taking the mean rating across all the questions (e.g. as used by Tyler, Perreau, & Ji, 2009) A second approach is to calculate a mean score for each section, resulting in three scores, one each for the speech, spatial, and qualities of hearing sections (e.g. as used by Summerfield et al., 2006). The questionnaire can further be broken down into ten sub-sections (speech in quiet, speech in noise, speech in speech, multiple speech stream processing and switching, localisation, distance and movement, sound quality and naturalness, identification of sounds and objects, segregation of sounds, and listening effort), resulting in ten scores (Gatehouse & Akeroyd, 2006). Although a factor-analysis was not conducted to form these sub-scales, Gatehouse and Akeroyd assigned questions from the SSQ to each sub-scale based on the content of each question. This enables a summary score of ability in each listening area to be obtained.

Higher self-rated listening ability has been found with bilateral CIs compared to using a unilateral CI (Noble, Tyler, Dunn, & Bhullar, 2008; Summerfield et al., 2006; Tyler et al., 2009). In a within-subjects comparison with 24 participants Summerfield et al. found ratings with bilateral CIs compared to a unilateral CI were significantly higher on all three sections of the SSQ. Using a larger sample than Summerfield et al, Tyler et al. compared the overall SSQ score between a group of 99 unilateral CI users and a group of 40 bilateral CI users. Although the relative benefit on each of the three sections was not investigated individually, the mean self-rated listening ability score of bilateral CI users was significantly higher than the mean score of the unilateral CI users.

Noble et al. (2008) compared self-rated listening ability on the ten sub-sections of the SSQ between 70 unilateral and 36 bilateral CI users. Although no correction for multiple comparisons was made, no difference was found between ratings by bilateral and unilateral CI users on any of the speech sub-sections, but significantly higher ratings by bilateral CI users on the spatial and quality sub-sections were found (with the exception of the 'segregation of sounds' sub-section). Noble et al. also compared self-rated listening ability between 70 unilateral CI users and 39 bimodal users. However, no significant difference in scores was found from the addition of a contralateral acoustic hearing aid. Comparisons were also made between bilateral CI users and bimodal users and a bilateral advantage was found on three of the ten sub-sections (speech in speech, distance and movement, and listening effort). Thus self-reported listening advantages have been observed from a second device for some aspects of listening.

### 6.1.2 Quality of life measures

The EuroQol questionnaire (EQ5D; Brooks, 1996; The Euroqol Group, 1990) and Health Utilities Index Mark III (HUI3; Boyle, Furlong, Feeny, Torrance, & Hatcher, 1995; Feeny et al., 2002; Torrance, Furlong, Feeny, & Boyle, 1995) are generic quality of life instruments resulting in a utility score where '1' indicates perfect health and '0' indicates being dead. They are described in detail in Chapter 4. Table 6.1 contains a summary of the gains obtained from a contralateral acoustic hearing aid or second CI as measured in previous studies. The EQ5D contains no questions related to hearing or listening and is insensitive to hearing difficulties (Grutters et al., 2007; Longworth et al., 2014; Yang, Longworth, & Brazier, 2013). Grutters et al. administered the EQ5D to 315 respondents with hearing difficulties and found that 44% indicated that they had perfect health. Summerfield et al. (2006) administered the EQ5D to 24 unilateral CI users. The questionnaire was re-administered to the same participants after they had received a second CI. A significant detriment in utility was observed nine months after receiving the second CI. The authors argued that this detriment could have arisen as a result of worsening tinnitus in a few participants.

The HUI3 is sensitive to benefits from providing 'some hearing' compared to 'no hearing' such as one CI compared to no surgical intervention (United Kingdom CI Study Group, 2004). However, despite the HUI3 containing questions related to hearing and speech understanding, it is less able to detect differences between 'some hearing' and 'some more hearing' (Lovett, Kitterick, Hewitt, & Summerfield, 2010; Summerfield et al., 2006). Indeed, Summerfield et al. found no difference in HUI3 scores between unilateral CI use and bilateral CI use. One possibility is that providing a second device to users of a single CI does not result in improvements in quality of life. An alternative possibility is that improvements in quality of life do arise as a result of receiving a second device but current measures (such as the EQ5D and HUI3) are not sensitive to them. To address this issue the current study administered a further measure, the York Quality of Life Questionnaire (YorQol), which asked CI users to rate their overall quality of life.

**Table 6.1. Gain in utility obtained from a second device as reported in previous research. Gains reported are means unless otherwise specified. Gains from Summerfield et al. (2006) are inferred from figure.**

| Study | Participants | Comparison | Measure used | Gain in utility | Significance |
|---|---|---|---|---|---|
| Grutters et al. (2007) | 315 individuals with hearing complaints | Before and after hearing aid fitting | EQ5D (UK Tariff) | .001 (SD = .13) | n.s. |
| | | | EQ5D (Dutch Tariff) | .000 (SD = .12) | n.s. |
| | | | HUI2 | .07 (SD =.13) | p<.001 |
| | | | HUI3 | .12 (SD =.18) | p<.001 |
| UKCISG (2004) | 316 unilateral CI users | Before unilateral cochlear implantation and 9 months after | HUI3 (All) | .197 (95% CI = .176-.218) | Significant benefit |
| | | | HUI3 (Traditional candidates) | .214 (95% CI =.189-.239) | Significant benefit |
| | | | HUI3 (Marginal hearing aid users) | .151 (95% CI =.113-.190) | Significant benefit |
| Summerfield et al. (2006) | 24 CI users | Within subjects: Unilateral Vs. 3 months post bilateral implantation | EQ5D | -0.06 (95% CI = 0.04 - -0.16) | n.s. |
| | | | HUI3 | -0.02 (95% CI = 0.70 - -0.11) | n.s. |
| | | Within subjects: Unilateral Vs. 9 months post bilateral implantation | EQ5D | -0.06 (95% CI = -0.01 - -0.14) | p<.05 |
| | | | HUI3 | -0.01 (95% CI = 0.80 - -0.10) | n.s. |
| Lovett et al. (2010) | Children (14 bilateral and 20 unilateral) | Unilateral Vs. Bilateral implantation | HUI3 | .05 (median gain) | n.s. |
| Damen et al. (2007) | 59 unilateral CI users | Before and after unilateral cochlear implantation | HUI3: Group implanted between 1989-1997 (n=37), gain measured in 1998 | 0.32 | n.s. |
| | | | HUI3: Group implanted between 1989-1997 (n=37), gain measured in 2004 | 0.05 | n.s. |
| | | | HUI3: Group implanted between 1999-2004 (n=22), gain measured in 2004 | 0.15 | p<.05 |

### 6.1.3 Current study

The first aim of this study was to assess whether self-reported listening ability is greater with binaural hearing compared to monaural hearing among adult users of CIs, and whether a second CI provides a greater advantage than a contralateral acoustic hearing aid. To test this, the SSQ was administered to three groups of CI users (bilateral, bimodal, and unilateral). It was hypothesised that, consistent with previous research (Noble et al., 2008b; Summerfield et al., 2006; Tyler et al., 2009), higher self-ratings on the SSQ would be reported when using bilateral CIs compared to unilateral CI use. Limited research has compared bimodal to unilateral self-reported listening ability. This coupled with the mixed advantages of actual listening performance discussed in Chapters 2 and 5 made it unclear whether the bimodal users would demonstrate a self-reported listening ability advantage over using a single CI. The only previous study that has compared bimodal to unilateral responses on the SSQ found no bimodal advantage (Noble et al., 2008b). The bimodal users in Noble et al.'s study were from the USA where candidacy for a CI is more relaxed than the UK (see Chapter 1.4.1). Although the pure tone audiograms for bimodal participants were not reported by Noble et al. it is possible that the participants in that study had higher levels of residual hearing than the participants in the current study. This difference could mean that the participants in the current study are less likely to show self-reported benefits on listening ability. This possibility coupled with the expected bilateral advantages led to the hypothesis that a greater benefit would be found from a second CI rather than from a contralateral acoustic hearing aid.

The second aim was to assess whether there is a relationship between self-reported listening ability and actual listening performance reported in Chapter 5. Noble et al. (2008) investigated the relationship between scores on the ten sub-sections of the SSQ and performance on tasks of monosyllabic word recognition in quiet and localisation. Moderate positive relationships were found between speech-recognition performance and scores on the ten sub-sections of the SSQ. Interestingly, the weakest correlation with speech-recognition performance (with a correlation of .31) was with the scores on the speech in quiet sub-section, suggesting that the other sub-sections sample abilities which are relevant to understanding speech in quiet. Only the two spatial sub-section scores of the SSQ correlated significantly with localisation performance. The alpha level used by Noble et al. was not Bonferroni corrected which increases the risk of some of these significant correlations arising as a result of a Type 1 error. Therefore the current study identified those listening tasks with which a relationship with self-rated listening ability would be expected and Bonferroni corrected the alpha level accordingly. Performance tasks were divided into three types (speech, spatial, and qualities of listening) and were correlated with scores on the associated SSQ section (e.g. performance on spatial tasks was correlated with scores on the spatial section of the SSQ). It is possible that correlations would also be observed between tasks and other dimensions of the SSQ (for instance the qualities section of the SSQ contains questions related to the segregation of sounds which could potentially be related to performance on the speech in speech tasks). However, were correlations conducted between all 15 listening tasks and scores on the three sections of the SSQ, a Bonferroni correction would likely be too conservative to allow useful conclusions to be drawn.

The third aim was to assess whether the addition of a second device results in improvements in quality of life compared to unilateral cochlear implantation. To assess this, three questionnaires (the EQ5D, the HUI3, and the YorQol) were administered to the three groups of CI users. Based on previous research which has demonstrated that the EQ5D is insensitive to hearing difficulties (Grutters et al., 2007; Longworth et al., 2014; Yang et al., 2013) it was hypothesised that the EQ5D would not show any significant differences between monaural and binaural listening, and bimodal and bilateral benefit. As previous research has demonstrated that the HUI3, whilst able to discriminate between ‘no hearing’ and ‘some hearing’, is less sensitive to differences between ‘some hearing’ and ‘more than some hearing’, it was hypothesised that the addition of a second device would not show significant advantages on the HUI3 compared to unilateral CI use. It was also hypothesised that there would be no difference in the amount of benefit gained from a contralateral acoustic hearing aid compared to a second CI. The YorQol (described in section 6.2.2) assesses overall wellbeing and asks participants to indicate their quality of life directly. It may be that this approach to measuring quality of life would be sensitive to differences between listening configurations that current generic measures do not detect. Measures of annoyance from tinnitus were also administered to assess if any negative changes in quality of life (as found by Summerfield et al., 2006) could be explained by worsening tinnitus. The Tinnitus Handicap Inventory (Newman, Jacobson, & Spitzer, 1996) was administered as it is a widely used tinnitus inventory. The Annoyance from Tinnitus questionnaire was administered as this was the questionnaire administered by (Summerfield et al., 2006).

Finally, amongst the bimodal users the relationship between self-reported benefit and residual hearing was assessed to determine if those with better residual hearing showed greater benefit from using a contralateral acoustic hearing aid. The three frequency pure tone threshold average from 250Hz, 500Hz and 1000Hz was used as this is the range over which participants had measureable residual hearing (see Chapter 5, Figure 5.1).

## 6.2 Methods

### 6.2.1 Participants

The 32 participants who took part in the study described in Chapter 5 also took part in the study described in this chapter. Demographic information can be found in Chapter 5, Table 5.1.

### 6.2.2 Questionnaires

Participants completed one questionnaire about their listening ability, three quality of life questionnaires, and two questionnaires which asked about their experience of tinnitus.

#### *Self-reported listening ability: SSQ*

The SSQ is a 49-item questionnaire assessing listening to speech ability, spatial listening ability, and ability on other aspects of hearing and listening. Responses to each question were made on an 11-point scale from 0 (unable to perform task) to 10 (can perform task perfectly). Figure 6.1 shows an example question from the spatial section of the SSQ. A mean score out of 10 for each section of the SSQ was calculated for each participant resulting in three scores.

You are outside. A dog barks loudly. Can you tell immediately where it is without having to look?

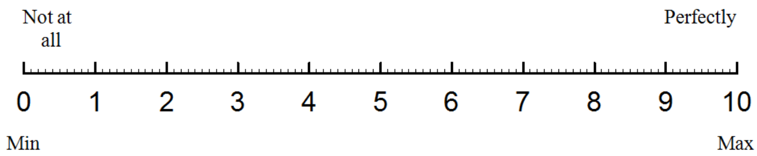


**Figure 6.1. Example question from the spatial section of the SSQ. Participants responded by making a mark on the scale to indicate how well they can perform the task described in the scenario.**

#### *Measures of quality of life*

EQ5D

The EQ5D is a five-item generic quality of life questionnaire assessing mobility, self-care, usual activities, pain/discomfort, and anxiety/depression. Participants indicated whether they had 'no difficulty', 'some difficulty', or 'great difficulty' on each dimension. An algorithm (Dolan, Gudex, Kind, & Williams, 1995) converts their responses into a utility value (see Chapter 4).

HUI3

The HUI3 is a 17-item generic health related quality of life questionnaire containing questions related to eight domains of health (vision, hearing, speech, ambulation, dexterity, emotion, cognition, and pain). Each question is followed by five or six levels of difficulty. The participant responded by selecting the level of difficulty that best described them An algorithm (Feeny et al., 2002) converts their responses into a utility value (see Chapter 4).

#### York Quality of Life scale (YorQol)

The YorQol is a one-item questionnaire assessing overall quality of life. The questionnaire asks participants to *"think about your overall quality of life taking account of your health, your ability to communicate, your ability to get around and travel, and your ability to take part in social activities and work*". Participants respond by making a mark on a visual analogue scale which extends from 0 to 100, where 0 is labelled the "worst imaginable quality of life" and 100 is labelled the "best imaginable quality of life". Similar to Summerfield, Lovett, Bellenger, and Batten (2010) the score is then transformed and compressed to a value between 0 and 1 (1-(1-raw score/100)^1.6) to bring it into alignment with measures of utility. As responding using a visual analogue scale does not incur risk aversion (which is reflected in utility measured with the Standard Gamble technique, see Chapter 4), compressing the scores compensates for this effect (Drummond et al., 2000; Summerfield et al., 2010).

### *Experience with tinnitus*

#### Tinnitus Handicap Inventory (THI)

The THI (Newman et al., 1996) is a 25-item questionnaire assessing the impact of tinnitus on everyday life. Participants are instructed to indicate 'Yes', 'Sometimes' or 'No' to each question depending on whether tinnitus affects the aspect of their life described. In accordance with the the instructions for scoring the questionnaire, a total score is then calculated as follows ( (Number of 'Yes' responses x 4) + (Number of 'Sometimes' responses x 2)), resulting in a score out of 100.

#### Annoyance because of tinnitus (TIN)

The TIN is a 13-item questionnaire which assesses the impact of tinnitus on everyday life. For each question, participants responded by marking a scale from 0 (tinnitus does not adversely impact everyday life) to 10 (tinnitus substantially adversely impacts everyday life). Figure 6.2 shows an example question.

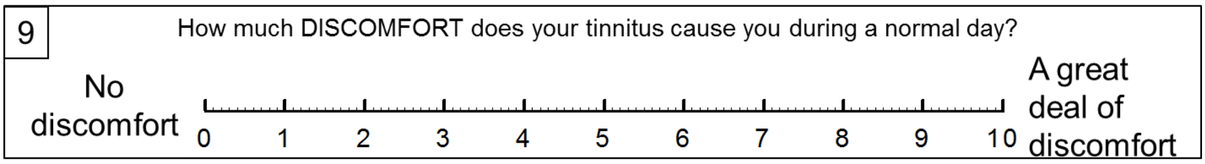


**Figure 6.2. Example question from the Annoyance because of Tinnitus Questionnaire. Participants responded by making a mark on the scale to indicate (in this example) how much discomfort they experienced.**

### 6.2.3 Design

A mixed design was used. Participants completed two sessions held on separate days. In one session the bimodal and bilateral CI users completed the questionnaires considering their lives when they use both their devices together. In this session the participants undertook performance tests using both their devices. In the other session the bilateral and bimodal groups were instructed to complete the questionnaires considering how their lives would be if they did not have their second device. In this session the users undertook performance tests using just one device. The ordering of these sessions was counterbalanced across participants within each group. This enabled within-group analyses to assess the self-reported benefit (if any) from a second device. The unilateral group also completed two sessions. They served as a comparison group in order to check that there was not an overestimation of any benefits from a second device due to unfamiliarity with using just one device. The between-subjects aspect of the design allowed comparisons between the three groups when using one device, and comparisons of the benefit from a contralateral acoustic hearing aid and a second CI.

### 6.2.4 Procedure

Participants completed the questionnaires during breaks between performing listening tasks described in Chapter 5. In both sessions the questionnaires were completed in the following order: (1) EQ5D, (2) HUI3, (3) THI, (4) TIN, (5) SSQ, and (6) YorQol.

### 6.2.5 Analyses

Statistical tests were conducted with SigmaPlot 12.0. Normality was tested using the Sharipo-Wilk test.

#### Within-subjects analyses

In comparing performance with one or two devices, paired samples t-tests were conducted for each questionnaire. If the data was not normally distributed then a Wilcoxon signed ranks test was conducted.

#### Between-subject analyses

In comparing questionnaire scores with one CI across the three groups, individual analyses of variance were conducted. If the data was not normally distributed then a Kruskal-Wallis test was conducted. When comparing the benefit provided from either a contralateral acoustic hearing aid or a second CI independent sample t-tests were conducted. If the data were not normally distributed then a Mann-Whitney U test was conducted.

#### Relationship with listening performance

Pearson correlation coefficients were calculated to assess the relationship between performance on listening tasks reported in Chapter 5 and self-ratings on the SSQ. The listening tasks were separated into three domains (speech tasks, spatial listening tasks, and qualities of listening tasks). The listening tasks were correlated with the scores on the corresponding scale of the SSQ (e.g. performance on spatial listening tasks was correlated with scores on the spatial section of the SSQ). A Bonferroni correction was applied within each domain to correct for multiple comparisons. As outlined in Chapter 5, one bimodal participant (326) found the speech in speech tasks very challenging resulting in thresholds so high that they effectively became a speech in quiet task. Therefore data from participant 326 on these tasks were are not included in the correlations.

Relationship to residual hearing

For the bimodal group, a Pearson correlation coefficient was calculated to assess the relationship between self-reported listening ability and the three frequency (250Hz, 500Hz, 100Hz) pure tone threshold average (see Chapter 5, Figure 5.1) of the non-implanted ear.

## 6.3 Results

### 6.3.1 Familiarity with configurations

No significant differences were found between the three groups when using one CI on any of the questionnaires.

### 6.3.2 Monaural Vs. Binaural hearing

***Self-reported listening ability: SSQ***

Figure 6.3 shows mean ratings on the SSQ when using one device and two devices for the bilateral and bimodal groups. Paired samples t-tests demonstrated that self-rated listening ability of the bilateral group was significantly higher when listening with two devices compared to one for the speech (t(11) = -3.69, *p*= .004), spatial (t(11) = -6.26, *p*<.001), and qualities of hearing sections (t(11) = -4.78, *p*=.001). For the bimodal group, ratings were also significantly higher with both devices compared to one for the speech (t(11) = -3.15, *p*=.009), spatial (t(11) = 3.55, *p*=.005) and qualities sections (t(11) = -2.57, *p*=.026).

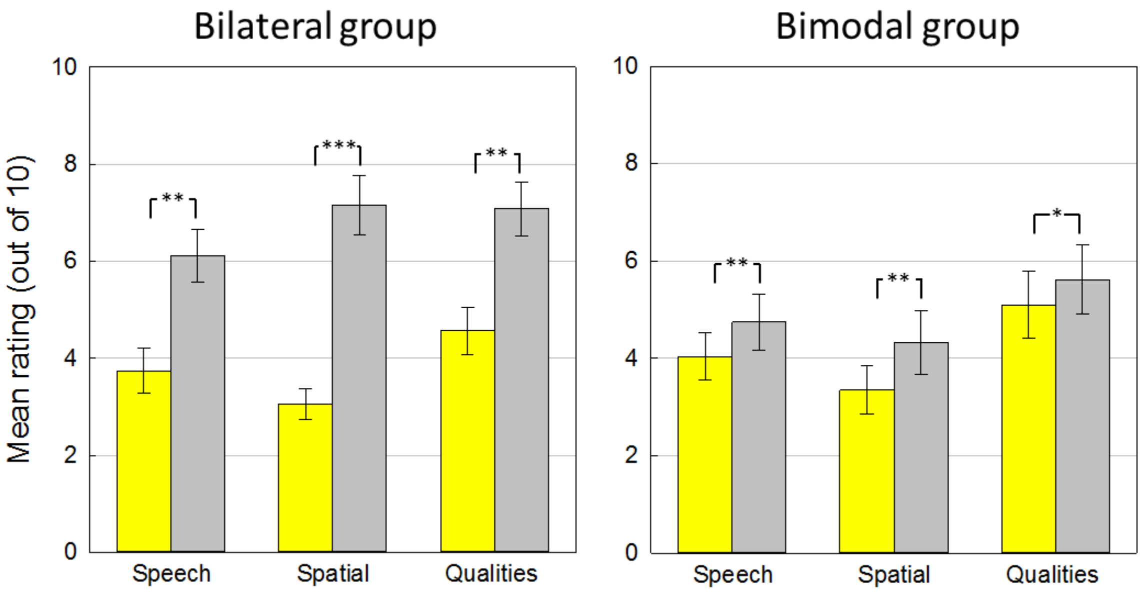


**Figure 6.3. Mean self-rated listening ability on the speech, spatial, and qualities sections of the SSQ. Grey bars indicate ratings when using one CI and yellow bars represent ratings when using two devices. The left figure shows ratings by the bilateral group and the right figure shows ratings by the bimodal group. Error bars represent ± 1SE. A significant difference between monaural and binaural conditions is indicated by asterisks (*** indicates p<.001, ** indicates p<.01, * indicates p<.05).**

### *Measures of quality of life*

Shapiro-Wilk tests demonstrated that the data from measures of quality of life did not distribute normally (with the exception of the bimodal data from the HUI3) so Figure 6.4 shows box plots to illustrate the median utility values with one device and two devices for both the bilateral and bimodal groups. A Wilcoxon signed ranks test found no difference in utility value with between two CIs and one CI as measured with the HUI3 ( $W = 17.00$, $Z = 1.78$, $p = .094$). A paired-samples t-test found no significant difference between utility values between bimodal devices and a single implant as measured on the HUI3 ($t(11) = -1.02$, $p=.331$).

Median utility ratings were at ceiling using the EQ5D and Wilcoxon signed ranks tests found no difference in utility ratings between one and two devices for either the bilateral group ($W = 1.00$, $Z = 0.45$, $p=1.00$) or the bimodal group ($W = 4.00$, $Z = 1.07$, $p=.500$). However, Wilcoxon signed ranks tests did demonstrate that ratings were significantly higher with two devices than one device using the YorQol for both the bilateral ($W = 66.00$, $Z = 2.93$, $p<.001$) and bimodal ($W = 54.00$, $Z = 2.40$, $p=.014$) groups.

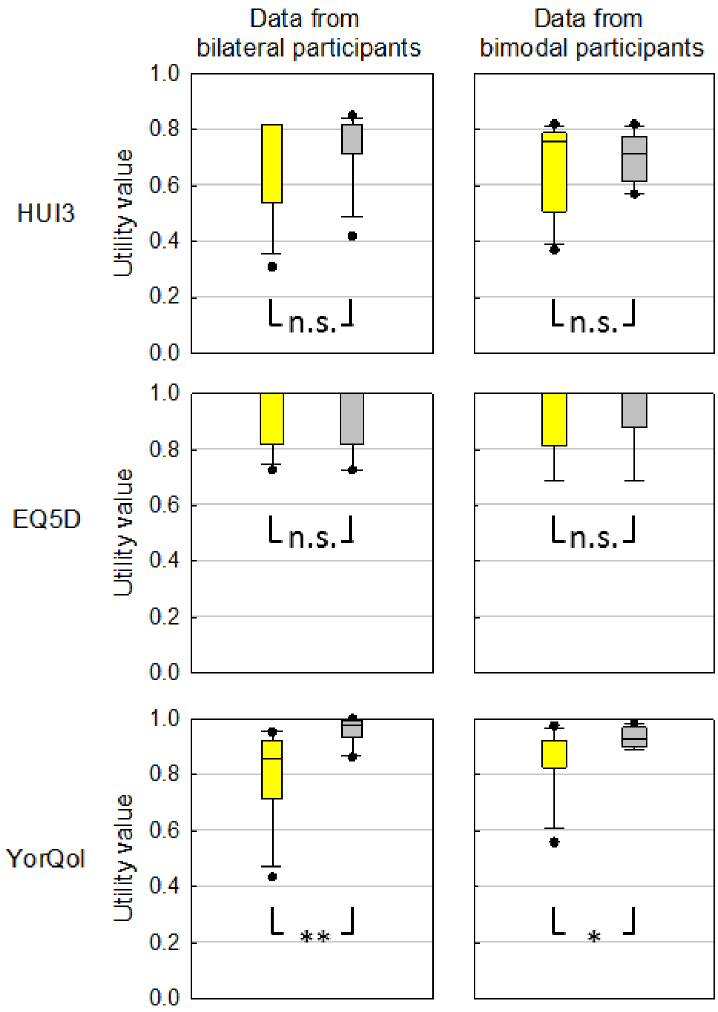


**Figure 6.4. Median utility ratings on the three quality of life measures by bilateral (left column) and bimodal (right column) participants using one (grey bars) or two (yellow bars) devices. A significant difference between monaural and binaural listening is indicated by asterisks (** indicates p<.01, * indicates p<.05). n.s. indicates there was no significant difference between monaural and binaural conditions.**

### *Measures of tinnitus*

Median scores on the tinnitus questionnaires were at, or close to, floor and are displayed in Table 6.2. Shapiro-Wilk tests demonstrated that the assumption of normality was not met for either the bilateral or bimodal groups so Wilcoxon signed ranks tests were conducted. No significant differences between one device and two devices were found.

**Table 6.2. Median, 25th percentile (25%) and 75th percentile (75%) scores from the Tinnitus Handicap Inventory (THI) and the Annoyance because of Tinnitus Questionnaire (TIN) with one device and two devices for the bilateral and bimodal groups.**

| | One device | | Two devices | | | | |
|---|---|---|---|---|---|---|---|
| | Median | 25%, 75% | Median | 25%, 75% | W | Z | *p* |
| Bilateral | | | | | | | |
| THI | 1.00 | 0.00, 15.50 | 1.00 | 0.00, 5.50 | -15.00 | -2.03 | .063 |
| TIN | 0.26 | 0.00, 1.40 | 0.12 | 0.00, 0.94 | -17.00 | -1.78 | .094 |
| Bimodal | | | | | | | |
| THI | 0.00 | 0.00, 12.00 | 0.00 | 0.00, 10.00 | -9.00 | -0.95 | .438 |
| TIN | 0.00 | 0.00, 1.07 | 0.19 | 0.00, 1.77 | 1.00 | -0.11 | 1.00 |

No significant relationships were found between difficulties with tinnitus and health-related quality of life (see Table 6.3).

**Table 6.3. Pearson correlation coefficients (r) between tinnitus difficulties (as measured on the THI and TIN) with two devices and health utility on the HUI3 and EQ5D and YorQol with two devices (n=24).**

| | THI | | TIN | |
|---|---|---|---|---|
| | r | *p* | r | *p* |
| HUI3 | .002 | .991 | -.113 | .600 |
| EQ5D | .077 | .722 | -.043 | .840 |
| YorQol | .080 | .710 | -.079 | .715 |

### 6.3.3 Relationship with listening performance

Correlations between listening performance and scores on the speech, spatial, and qualities of hearing sections of the SSQ are shown in Tables 6.4, 6.5, and 6.6 respectively. Moderate to strong relationships were found.

**Table 6.4. Pearson correlation coefficients (r) between scores on the speech section of the SSQ and performance on speech listening tasks. Significant relationships after Bonferroni correction (alpha level = .007) are emboldened.**

| Listening task | r | *p* |
|---|---|---|
| Speech in quiet: | | |
| Average performance on complex sentences | .362 | .042 |
| Speech in speech: | | |
| One competing talker | .180 | .333 |
| Six competing talkers | .426 | .017 |
| Twelve competing talkers | .363 | .045 |
| Speech in noise: | | |
| Speech reception threshold (noise spatially concurrent with speech at 0° azimuth) | **.498** | **.004** |
| Speech reception threshold (noise spatially separated from speech, noise ipsilateral to (first) cochlear implant) | **.538** | **.001** |
| Speech reception threshold (noise spatially separated from speech, noise contralateral to (first) cochlear implant) | .438 | .012 |

**Table 6.5. Pearson correlation coefficients (r) between scores on the spatial section of the SSQ and performance on spatial listening tasks. Significant relationships after Bonferroni correction (alpha level = .013) are emboldened.**

| Listening task | r | *p* |
|---|---|---|
| Localisation (60°) | **.705** | **<.001** |
| Localisation (30°) | **.568** | **<.001** |
| Localisation (15°) | **.608** | **<.001** |
| Movement tracking | **.652** | **<.001** |

**Table 6.6. Pearson correlation coefficients (r) between scores on the qualities section of the SSQ and performance on listening tasks. Significant relationships after Bonferroni correction (alpha level = .025) are emboldened.**

| Listening task | r | *p* |
|---|---|---|
| Emotion average | .402 | .023 |
| Melody recognition | **.478** | **.006** |

### 6.3.4 Relationship to residual hearing

A significant positive relationship between the three frequency average hearing threshold and benefit on the spatial section of the SSQ was found (r = .751, *p*=.029). No other significant relationships were found (Table 6.7).

**Table 6.7. Pearson correlation coefficients (r) between the three frequency average hearing threshold (250Hz, 500Hz, and 1000Hz) and benefit in scores on the three sections of the SSQ, the HUI3, the EQ5D, and the YorQol.**

| Questionnaire | r | *p* |
|---|---|---|
| SSQ: Speech section | .143 | .658 |
| SSQ: Spatial section | .751 | .005 |
| SSQ: Qualities section | .125 | .698 |
| HUI3 | .013 | .967 |
| EQ5D | .336 | .286 |
| YorQol | -.297 | .348 |

### 6.3.5 Bilateral Vs bimodal hearing

Table 6.8 shows that both the bimodal and bilateral CI users rated their listening abilities to be numerically better with two devices on all three aspects of the SSQ. However, the benefit from a second CI was only significantly higher than the benefit from a contralateral acoustic hearing aid for the spatial and qualities sections. No significant difference in ratings on the speech section was found. Furthermore, no significant difference in benefit was found on any of the quality of life measures or measures of tinnitus.

**Table 6.8. Median, 25th percentile (25%), and 75th percentile (75%) self-reported benefits from a second device for bilateral and bimodal listeners. Significant differences are emboldened.**

| Questionnaire | Median benefit from a second CI | 25%, 75% | Median benefit from a contralateral acoustic hearing aid | 25%, 75% | U | *p* |
|---|---|---|---|---|---|---|
| SSQ: Speech | 2.35 | 0.60, 4.16 | 0.97 | -0.10, 1.25 | 43.00 | .100 |
| SSQ: Spatial | **4.59** | **1.79, 5.22** | **0.63** | **0.41, 1.60** | **16.00** | **.001** |
| SSQ: Qualities | **1.89** | **0.84, 4.18** | **0.65** | **-0.12,1.07** | **24.50** | **.007** |
| HUI3 | 0.00 | 0.00, 0.16 | 0.00 | -0.06,0.14 | 58.00 | .418 |
| EQ5D | 0.00 | 0.00, 0.00 | 0.00 | 0.00,0.00 | 66.50 | .684 |
| YorQol | 0.10 | 0.03, 0.26 | 0.04 | 0.00,0.11 | 42.500 | .094 |
| THI | 0.00 | 0.00, 6.50 | 0.00 | 0.00, 4.00 | 151.50 | .950 |
| TIN | 0.00 | 0.00, 0.54 | 0.00 | -0.38, 0.54 | 165.00 | .371 |

## 6.4 Discussion

### 6.4.1 Familiarity with devices

The bimodal and bilateral CI users completed the questionnaires considering their life in an unfamiliar configuration using just their first (or only) CI. This could have inflated the amount of benefit observed from a second device with participants reporting much poorer listening ability and quality of life with one device than is actually the case, either due to unfamiliarity with using one CI alone, or to simply disliking that configuration. Therefore, in order to check that this was not the case scores on the questionnaires using one device were compared to scores by a group of unilateral CI users. No significant differences between the three groups were found for any of the measures. Therefore any difference in self-reported ability and quality of life when using two devices instead of one can be attributed to the addition of the second device.

### 6.4.2 Self-reported ability

Table 6.9 shows the mean gain obtained from a second device found in this study and in previous studies. The self-reported abilities of participants in this study suggest that both bilateral and bimodal users perceive there to be benefits in everyday listening from a second device, but a greater self-rated benefit is obtained from a second CI than a contralateral acoustic hearing aid. The bilateral CI users reported significantly higher ratings on all three sections of the SSQ when using two CIs compared to one CI (Figure 6.3). This finding is consistent with that of Summerfield et al. (2006) who, in a within-subjects comparison, found significant improvements on all three sections of the SSQ three and nine months after receiving a second CI. However, the findings differ somewhat from those reported by Noble et al. (2008) who compared ratings on the ten sub-sections of the SSQ by bilateral CI users to ratings by unilateral CI users. They found that whilst the bilateral CI users showed higher ratings on the spatial sub-sections and three out of four of the qualities sub-sections, no significant differences in ratings were found on any of the speech sub-sections. However, it is worth noting, that whilst Summerfield et al. found within-subjects advantages on all three sections from a second CI, no advantage from a second CI was found on the speech section of the SSQ when comparing *between* unilateral and bilateral groups. In addition, although Summerfield et al. found a benefit in the qualities section nine months after the users received their second CI, this was not evident three months after receiving a second CI. Thus these differences in findings could be explained due to the different designs and the time the ratings took place. For instance, in the present study the participants had been using their normal configuration for a mean of 7 years (standard deviation (SD) = 4) before the ratings were obtained. The ratings in the study by Summerfield et al. were gathered just three and nine months later and the ratings by Noble et al occurred within 12 months of receiving a second device. Thus it may be that it takes time for self-rated benefits from a second device to be realised.

**Table 6.9. Mean increase in scores on the three sections of the SSQ from a second CI or contralateral acoustic hearing aid compared to a unilateral CI, and the mean gain from a second CI compared to a contralateral acoustic hearing aid. 95% confidence intervals (CI) are shown in parentheses. Means from Noble et al. (2006) were averaged across the 10 sub-sections of the SSQ. Means from Summerfield et al. (2006) were inferred from a figure showing within-subjects comparisons.**

| | Mean bilateral gain (95% CI) | | | Mean bimodal gain (95% CI) | | | Bilateral Vs. Bimodal: Mean bilateral gain (95% CI) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Speech | Spatial | Qualities | Speech | Spatial | Qualities | Speech | Spatial | Qualities |
| Current study | 2.38 (0.96-3.80) | 4.10 (2.66–5.53) | 2.52 (1.36 – 3.67) | 0.71 (0.21 – 1.20) | 0.98 (0.37 – 1.58) | 0.53 (0.08 – 0.97) | 1.68 (0.26 – 3.10) | 3.12 (1.65 – 4.59) | 1.99 (0.82 - 3.16) |
| Noble et al (2006) | 0.08 | 1.70 | 1.10 | -0.10 | 0.40 | -0.07 | 0.90 | 1.30 | 1.17 |
| Summerfield et al (2006) | 0.05 | 0.03 | 0.01 | n/a | n/a | n/a | n/a | n/a | n/a |

In the current study the bimodal users gave significantly higher ratings when listening with two devices compared to one on all three sections of the SSQ (Figure 6.3). Previous research investigating self-reported benefit from bimodal aiding has found mixed results. For instance, contrary to the present findings, Noble et al. (2008) did not find any significant differences in ratings between unilateral CI users and bimodal users on any of the ten sub-sections of the SSQ. The different findings between the present study and that of Noble et al. could be due to differences in the sample used. Noble compared ratings from a larger, possibly more representative sample (70 unilateral CI users and 39 bimodal users). Participants in the study by Noble et al. had all received their device(s) at the CI program at the University of Iowa within 100 months of the analyses being conducted whereas the current sample was small and self-selecting (as discussed in Chapter 5). However, the results from the present study are in line with other reports. For instance, Flynn and Schmidtke (2004) found self-reported advantages of bimodal listening over unilateral CI listening for listening to music using the Bimodal Benefits Questionnaire. Also, Ching, Incerti, and Hill (2003) administered a custom made questionnaire assessing speech communication in quiet and noise as well as alertness to environmental sounds to six CI users and found self-reported advantages from bimodal aiding compared to unilateral CI listening.

In comparing the two options, no difference in the amount of benefit on the speech section was found (Table 6.8). However, a greater benefit was obtained from a second CI on the spatial and qualities sections of the SSQ. The spatial benefit was to be expected as behavioural and self-reported spatial listening benefits among bilateral CI users have been reported consistently (Dunn, Tyler, Oakley, Gantz, & Noble, 2008; Kerber & Seeber, 2012; Litovsky, Parkinson, & Arcaroli, 2009; van Hoesel & Tyler, 2003) whereas spatial advantages for bimodal users are inconsistent (Dunn et al., 2005; Seeber et al., 2004; Tyler et al., 2002). The fact that a greater self-reported benefit on the qualities section was obtained from a second CI and not an acoustic hearing aid is somewhat unexpected. The qualities section of the SSQ incorporates questions related to music, voice naturalness, vocal emotion recognition and the segregation of sounds. Previous research has demonstrated that self-reported sound quality and sound naturalness are improved when acoustic and electric information are combined (Ching et al., 2007; Flynn & Schmidtke, 2004; Potts, Skinner, Litovsky, & Strube, 2009). The current finding suggests that these benefits are not being realised for users of bimodal devices in the UK.

### *Relationship with listening performance*

Strong positive relationships between spatial listening performance and ratings on the spatial section of the SSQ were found (Table 6.5). This is consistent with Noble et al. (2008) who found moderate positive relationships between performance on a localisation task and ratings on the two spatial sub-sections of the SSQ (localisation, and distance and movement). A significant positive relationship was found between scores on the speech section of the SSQ and speech-reception thresholds obtained in a speech perception task in the presence of spatially concurrent noise (Table 6.4). A positive relationship was also found between scores on the speech section of the SSQ and speech-reception thresholds with noise ipsilateral to the first (or only) CI. No other significant relationships between scores on the speech section of the SSQ and speech perception tasks were found. This is contrary to Noble et al. (2006) who found significant relationships between all speech sub-scales and speech perception in quiet performance. This difference in findings could be due to the different tasks used. Noble et al. (2008) correlated ratings on the SSQ with performance on a monosyllabic word recognition in quiet task. However, the present study investigated the relationship between speech perception of *sentences*. However, it is worth noting that in the current study Bonferroni corrections were applied to correct for multiple comparisons which Noble et al. did not do. Indeed, if a Bonferroni correction had not been applied a significant relationship would have been observed. However, as previously discussed, a Bonferroni correction was applied as using an uncorrected alpha level increases the chance of a Type 1 error.

### *Relationship with residual hearing*

Access to low frequency information provides cues for voicing (Rosen, 1992) which can help listeners to improve speech perception in quiet (Incerti et al., 2011; Zhang et al., 2010). Furthermore, pitch information conveyed by low frequencies can help listeners to separate two speech streams (Kong et al., 2005), recognise vocal emotion (Most et al., 2012) and improve music perception (Flynn & Schmidtke, 2004). Therefore one might have expected better low frequency hearing to be associated with greater self-reported improvements on tasks such as emotion recognition, melody recognition, segregating talkers, and improvements in speech perception. However, no relationship was found between audiometric thresholds and the speech or qualities sections of the SSQ (Table 6.7), where these listening abilities are addressed. This is consistent with the findings reported in Chapter 5 which also showed no relationship between audiometric thresholds and listening performance. Whilst this could be due to the small number of participants and limited range of thresholds, the present study did find a relationship between audiometric thresholds and scores on the spatial section of the SSQ. The reason for this is unclear, however the only listening task reported in Chapter 5, for which the bimodal group received significant benefit from their contralateral acoustic hearing aid was a spatial task. However the lack of relationship between audiometric thresholds and spatial listening performance (discussed in Chapter 5) demonstrates that whilst individuals with better levels of residual hearing perceived themselves to be better spatial listeners, this did not manifest in better spatial listening performance compared to individuals with lower thresholds.

### 6.4.3 Quality of life

This experiment examined two possibilities. One possibility was that despite improvements in actual listening ability reported in Chapter 5, using a second device does not improve quality of life compared to listening with a single CI alone. The second option was that a second device does result in improvements to quality of life compared to listening with a single CI alone but that current instruments are not sensitive to these differences. The results found support for the second alternative.

Results varied depending upon the measure of quality of life used (Figure 6.4). With the HUI3 and the EQ5D, no significant benefit from adding a second device was found for either group. Indeed ratings on the EQ5D were at ceiling for both groups when using one device alone, allowing no room to measure any potential improvement from adding a second device. This finding is not surprising as the EQ5D contains no questions on hearing or listening. Furthermore this finding is consistent with Grutters et al. (2007) who found that 44% of hearing impaired individuals had a utility score of one ('perfect health') when measured with the EQ5D. One issue is that the EQ5D emphasises 'health', whereas hearing impairment can affect other aspects of life and hearing impaired individuals may not consider their impairment a health issue. This is reflected in two recent reviews in which the EQ5D has been shown to be insensitive to differences in hearing ability (Longworth et al., 2014; Yang et al., 2013).

However, in previous research the HUI3 has shown some sensitivity to differences in hearing ability. For instance, Grutters et al. (2007) found that although many individuals were at ceiling on the EQ5D only 1% of the hearing-impaired sample indicated perfect health with the HUI3. In the present study median utility values of .82 (IQR = .54-.82) and .76 (IQR = .51-.79) were reported by the bilateral and bimodal groups with their first (or only) CI, respectively, and no respondent indicated they had perfect health. Thus there was room for improvements in quality of life due to a second device to be measured. However, no significant advantage from a second device was found when using the HUI3 as a measure. Whilst both the EQ5D and HUI3 have shown some benefit in quality of life from unilateral implantation compared to no surgical intervention (see Damen, Beynon, Krabbe, Mulder, & Mylanus, 2007; Summerfield et al., 2006) the results from this study support the notion that these instruments are less sensitive to detecting differences between 'some hearing' and 'more than some hearing' (Barton, Bankart, & Davis, 2005; Grutters et al., 2007; Lovett et al., 2010).

The YorQol was included as a measure of quality of life with the potential to be sensitive to overall wellbeing. The YorQol is a straightforward questionnaire where participants simply have to indicate their overall quality of life by marking a visual analogue scale. This is a more direct measure of quality of life than the HUI3 and EQ5D as participants are explicitly asked to think about their overall quality of life rather than answering questions relating to aspects of health related quality of life. When using this measure, a significant benefit in quality of life was observed for both groups when using a second device (Figure 6.4). This finding coupled with the finding that standardized health related quality of life questionnaires do not detect any benefit from a second device provides support for the suggestion that using a second device does indeed provide benefits to quality of life but that the widely used instruments are insensitive to these benefits.

However, in comparing bimodal aiding to bilateral cochlear implantation, there was no difference in the amount of benefit obtained on any of the quality of life measures (Table 6.8). Given the finding that using the EQ5D and HUI3 neither group benefitted significantly from a second device, it was not surprising that a difference between the benefits obtained by each option was not observed. This issue will be investigated in Chapter 8 which discusses the development and validation of a new questionnaire to measure 'hearing-related quality of life'. The focus of the research presented in this chapter is on the self-reported clinical-effectiveness of a second device. However, standardized quality of life measures such as the HUI3 and EQ5D can be used to inform the effectiveness component in cost-effectiveness analyses. These types of analyses are important in helping policy makers determine the allocation of funding. Chapter 8 considers the cost-effectiveness of a second device and uses utility values obtained from the HUI3 and EQ5D in this study to calculate incremental-cost-effectiveness ratios.

### 6.4.4 Tinnitus

No difference in the severity or impact of tinnitus between monaural and binaural listening or between bimodal and bilateral CI listening was found (Table 6.2). Summerfield et al. (2006) had observed a significant detriment in health related quality of life as measured on the EQ5D between unilateral and bilateral CI listening. The authors suggested that this was due to worsening tinnitus in a few of the participants as revealed by scores obtained with the TIN questionnaire. However, the current study found no relationship between tinnitus difficulties and health-related quality of life (Table 6.3). Median scores on the tinnitus measures were close to floor due to the majority of participants reporting no difficulty or annoyance from tinnitus.

### 6.4.5 Strengths and weaknesses

This study is limited by the sample used and full details of the impact of this limitation are discussed in Chapter 5. It would therefore be informative to test a larger more representative sample of CI users. Although the bimodal and bilateral participants completed questionnaires considering life in an unfamiliar configuration, the use of a unilateral comparison group enabled checks to be made to ensure that any benefit observed arose from the use of a second device.

### 6.4.6 Conclusion: Which option is better?

A key aim of the present study was to assess which option, a second CI or a contralateral acoustic hearing aid, provides the greater benefit for UK CI users. It has been demonstrated that compared to unilateral cochlear implantation, bilateral cochlear implantation and bimodal aiding both result in improved self-reported listening ability. Furthermore, there is some evidence to suggest that quality of life may be improved from using a second device. However, in comparing the benefit provided from the two options, there were few differences. Indeed the only differences were between self-rated spatial listening and qualities of listening as measured with the SSQ which revealed an advantage from a second CI over a contralateral acoustic hearing aid. Furthermore, the study has demonstrated that existing questionnaires assessing health related quality of life are insensitive for assessing the benefits of binaural over monaural listening. This could have important implications for policy makers determining the allocation of funding. This implication will be discussed in more detail in Chapter 8.

In conclusion, this study has demonstrated that self-reported listening ability is greater when using two devices. As an acoustic hearing aid can be obtained free of charge from the National Health Service, the results support the recommendations by Ching et al. (2004) that bimodal aiding should be the standard provision for users of a unilateral CI. However, a greater self-reported benefit in everyday listening for spatial tasks and other qualities of listening tasks suggests that bilateral cochlear implantation is more clinically effective than bimodal aiding.

## 6.5 Summary

- Both bimodal and bilateral CI users indicated greater self-reported listening ability with two devices compared to one.
- No significant difference in health-related quality of life was found between one device and two devices using the HUI3 and EQ5D.
- Quality of life as measured with the YorQol showed significant benefits from both a second CI and a contralateral acoustic hearing aid.

- Measures of tinnitus annoyance did not show any difference between one device and two devices.
- In comparing the benefit from a second CI to the benefit from a contralateral acoustic hearing aid, self-reported listening ability for spatial tasks and listening quality were better with a second CI.
- No significant difference in the gain in quality of life from a second device was observed between bilateral and bimodal listening.

# 7 The role of head movements: sound orientation, sound localisation, listening effort, and speech perception in noise.

This chapter reports three experiments investigating the association between head movements and listening performance. Section 7.1 describes and assesses the equipment used in the experiments reported in this chapter. Section 7.2 reports an experiment investigating the patterns of head movements made by CI users when orienting to either a short or long sound in the horizontal plane. Section 7.3 reports an experiment investigating the potential for head movements to reduce front-back localisation confusions in normally-hearing adults and CI users. Section 7.4 reports an experiment that investigated whether listeners make use of optimal head orientation strategies for maximising speech perception performance in the presence of noise.

## 7.1 Assessing the accuracy of a head tracking system for movements in the horizontal plane

### 7.1.1 Introduction

Methods for monitoring head movement have progressed substantially over time. Early research by Thurlow, Mangels, & Runge (1967) utilised a camera in a procedure in which recordings were taken from the left hand side of participants while a stimulus was presented. A head mounted frame, worn by the participant, aided researchers in measuring angular movement. The accuracy of this device for measuring changes in yaw (horizontal movement), pitch (vertical movement), or roll (rolling the head left or right so that one ear moves closer to the shoulder) was not reported by the authors. However, the technology available at that time is likely to have had a limited sampling rate compared to standards today and therefore likely incapable of detecting small movements which would alter interaural level and timing differences which can help listeners locate the source of a sound (see Section 2.1.1).

Nevertheless, cameras still play a pivotal role in some modern motion tracking software, from closed circuit television cameras (Buhagiar et al., 2004) to multiple motion cameras positioned around the testing room (Brimijoin, Boyd, & Akeroyd, 2013; Brimijoin et al., 2010, 2012). Brimijoin et al. (2012) used six motion tracking cameras to track the position of multiple markers mounted on top of a participant's head. Tracking occurred at a sample rate of 100Hz and enabled the researchers to locate the horizontal and vertical position of the participant to within 0.2°. However, cameras are not the only method for monitoring head movements with some researchers making use of magnetic tracking (Perrett & Noble, 1997b; Toyoda, Morikawa, &

Hirahara, 2011). For instance, Perrett and Noble (1997) used a 3Space Isotrak II which can allow accurate measurements (within 0.75°) of yaw, pitch and roll with a resolution of 1° (Polhemus Incorporated, 2000). Toyoda et al. (2011) used pulsed magnetic tracking in which participants wore a cap containing multiple sensors which also had high precision (0.5° RMS error, Ascension Technology Corporation, n.d.). Other researchers are making use of inertial based tracking, such as Cooper, Carlile, and Alais (2008) who used an Intersense InertiaCube3 which involves placing a small cube shaped sensor on top of a participants head. This technology has an accuracy of detecting yaw to within 1°, and to just 0.25° for pitch and roll (Intersense Inc., n.d.). Non-camera based technology has the advantage that measurements are not limited by the field of view of the camera.

However, these options can be expensive[5] and recently researchers have begun developing affordable systems which make use of equipment from games consoles. Brimijoin et al. (2013) developed a head tracking system utilising a Nintendo Wii remote. For this, three infrared light emitting diodes (LEDs) were positioned on top of a participant's head and a Nintendo Wii remote was positioned approximately 1.5 metres above the participant. The infrared camera in the Wii remote detected the XY coordinates of each of the LEDs and relayed the co-ordinates to a computer via a wireless Bluetooth connection. The XY co-ordinates of the three LEDs were recorded at a rate of 100Hz to determine the direction in which the participant was facing. Brimijoin et al. (2013) provided instructions for setting up a similar system and it is from these guidelines that the current system was created.

The aim of this section is to (1) describe the equipment, which is used in experiments in the following sections, and (2) test the accuracy of the equipment in measuring yaw.

### 7.1.2 Methods

#### *7.1.2.1 The head tracking equipment*

The cap

A custom made cap incorporating three LEDs is worn by the participant (Figure 7.1). The back two LEDs are positioned 4.5cm apart, whereas the front LED is positioned 3.0cm in front of the middle LED. A battery pack provides power for the LED array.

[5] For instance, Intersense InertiaCube3 is marketed between £1350 and £3000 (Cybermind, 2010; Ilixco, n.d.)

**Figure 7.1. Custom made cap with three LEDs positioned on top. The two front LEDs are positioned closer together than the back two LEDs to determine the direction the participant is facing.**

## The tracking system

A Nintendo Wii remote was suspended from the ceiling approximately 0.5m above where the participant sat. The infrared sensor of the Wii remote detected the position of the 3 LEDs at a rate of 100Hz. The XY co-ordinates of the three LEDs within the camera's field of view were recorded and relayed to the computer via Bluetooth. The Euclidian distances between the three LEDs were then calculated using Matlab to infer the direction the participant was facing (described below). A further Nintendo Wii remote was used as a handheld response instrument in the experiments reported in this chapter.

## Calculating yaw

Yaw was calculated from the 3 XY co-ordinates to an angle of azimuth using Matlab. The *atan2* function was used to extract the four-quadrant inverse tangent of the XY co-ordinates to determine the position in space. This was restricted to a 360° array using the *mod* function. When the three LEDs were detected by the Wii remote, the direction in which the participant was facing could be determined as the position of the front LED was unambiguous. If the positions from only two LEDs were recorded (for instance if the third LED went outside the field of view of the infrared sensor) the direction in which the participant was facing was ambiguous as the identity of the front most LED was unknown. With only two points of reference, the participant could be facing in one of two directions whose azimuths differ by 180°. However, due to the reasonably high sampling rate, the direction of the participant could be inferred based on temporarily-adjacent samples in which all three LEDs were tracked. With a maximum reasonable horizontal head rotation speed of around 171°/second (Cooper et al., 2008), a delay of at least 1.05 seconds would be required to rotate the head by 180°. If the timing between the current 2-point measurement and the previous 3-point measurement was less than 1.05 seconds, it was therefore considered reasonable to assume that the direction in which the participant was facing had not been rotated by 180°. If the position of only one LED was recorded the yaw could not be calculated and the yaw for that time-point was left blank.

#### *7.1.2.2 Procedure*

The cap was mounted on top of a Head and Torso Simulator (HATS, Brüel & Kjaer Type 4128C). The HATS was positioned on a rotating chair in the centre of a 360° array of 24 loudspeakers separated by 15°. During recording, the experimenter rotated the chair 360° pausing at each 15° interval when the HATS was directly facing each loudspeaker. At each 15° interval the experimenter pressed the response button on the handheld Wii remote to mark the time point at which the HATS was facing each location so that the XY co-ordinates of this position could be extracted and used in later analyses. This procedure was repeated three times and the recorded yaw angle for each location was averaged from the three measurements.

##### Calibration

The angle measured when the HATs was facing 0° azimuth was extracted using timing information from the response press. The difference between the measured location and 0° azimuth was calculated. This deviation was corrected for, for instance if there was an undershot at 0° azimuth by 2°, the recorded data was calibrated to this point with 2° being added to each data point.

### 7.1.3 Results

#### *7.1.3.1 Precision/Resolution*

The left portion of Figure 7.2 shows a five second section of the recording with raw yaw angles calculated from the XY co-ordinates of the LEDs. Close inspection of the measurements revealed the limited resolution of the Wii remote tracking system. The right portion of Figure 7.2 shows the trajectory of a one second section of the recording. As the yaw calculations are computed with high numerical precision using Matlab, the limited resolution of the Wii remote tracking system leads to rapid changes in motion being indicated in the yaw angles. The rapid changes in yaw angle suggest that the absolute position of each LED is known to within about 1°.

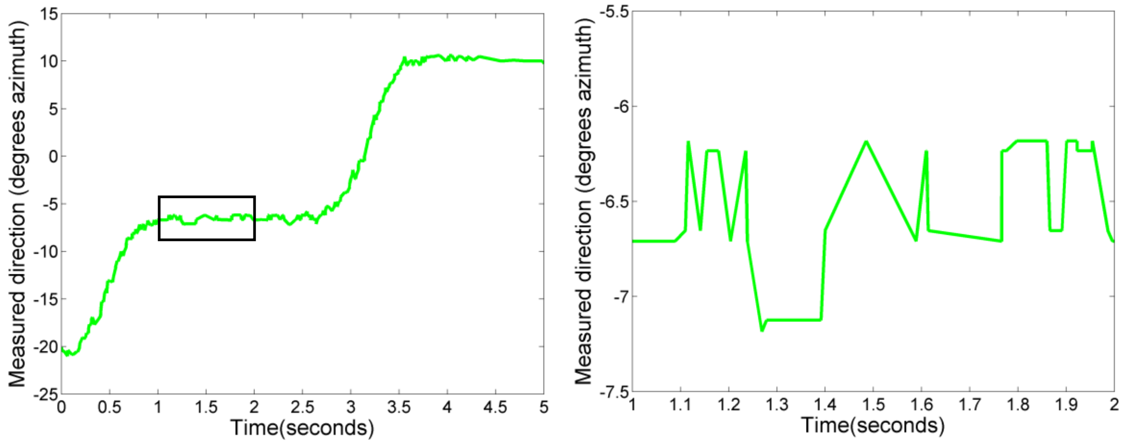


**Figure 7.2. Left: Five section sample of calculated yaw angles from the recording. The black box highlights the one second section of the recording that is shown in detail in the right-hand diagram.**

To overcome this limitation a 50ms sliding Hanning window was applied to smooth the data (this technique has also been used by Brimijoin et al., 2010). Figure 7.3 shows the smoothed yaw data overlaying the original unsmoothed data. The Hanning window preserves the overall movement whilst removing much of the noise which arose from sampling error.

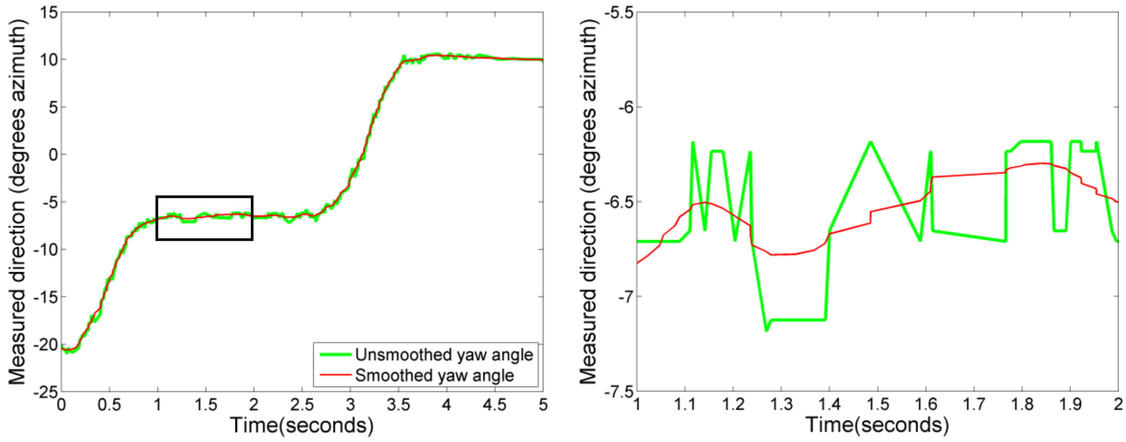


**Figure 7.3. Unsmoothed yaw angle (green line) of a five second section of the recording. The red line shows the yaw calculation after a 50ms sliding Hanning window has been applied to the data. The black box highlights the one second section of the recording that is shown in detail in the right-hand diagram.**

### *7.1.3.2 Accuracy*

Figure 7.4 displays the mean yaw angle for each of the target directions. The results demonstrate that the head tracking equipment has a high degree of accuracy in measuring yaw angle. The average RMS error for all measurements was 2.33°.

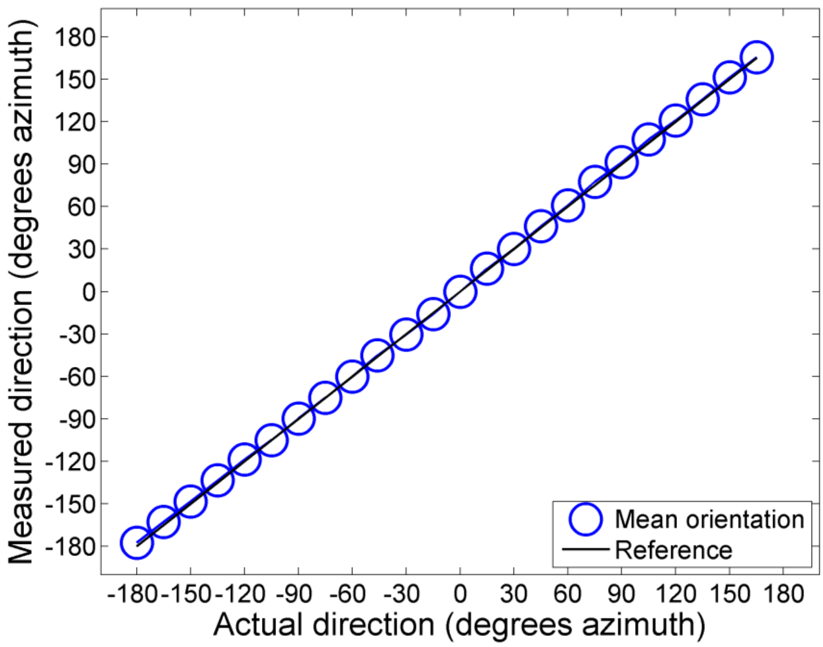


**Figure 7.4. Mean recorded yaw (blue circle) in degrees azimuth for target directions in the horizontal plane across 360° as measured by the head tracking equipment. Black line indicates perfect yaw measurement for reference.**

#### *7.1.3.3 Reliability*

The recording lasted for 3 minutes and 54 seconds. The co-ordinates of the three LEDs were recorded for the duration of this time with no missing values.

### 7.1.4 Discussion

The motion tracking system accurately measured changes in yaw across a full 360° of azimuth. This result is compatible with data reported by Brimijoin (2013) who also used a similar head tracking system. The limited resolution of the Nintendo Wii remote has previously been noted by Lee (2008). The RMS error measured in the current test was larger than that found for more expensive commercially available equipment using cameras (0.2°, Brimijoin, 2010), magnetic tracking (0.75°, Polhemus Incorporated, 2000), or inertia tracking (1°, Intersense Inc., n.d.). However, the RMS error was still within 2.5°, therefore suggesting that the Wii Remote head tracking system is able to accurately detect most head movements in the horizontal plane.

The head tracking system was also reliable, recording the position of the three LEDs for the duration of the recording session. However, it is important to note that the recording was for a short period of time with a mannequin. It may be that missing data will arise with human participants who may move their heads outside of the field of view of the infrared sensor. By its very nature, the system is capable only of tracking changes in yaw, and therefore it is unable to measure and record changes in pitch or roll. Listeners may use these types of head movements in strategic ways to determine the horizontal location of a sound source. For instance, when locating sounds in the horizontal plane, although changes in pitch will not alter the interaural timing or level differences, the spectra may change from reflections off the pinna (Moore, 2012). Brimijoin (2012) measured the pitch, roll, and yaw movements of listeners with asymmetric hearing loss during a speech in noise task. Stimuli were presented in the horizontal plane across 360°. Median pitch was -7.5° (for better right-ear listeners, 6.2° for better left-ear listeners) and average roll was +2.5° (for better right-ear listeners, 2.7° for better left-ear listeners). However, changes in yaw played a much larger role with median changes in yaw being -40.8 (for better right-ear listeners; +51.8° for better left ear listeners). Having asymmetrical hearing difficulties may result in a greater reliance on changes in yaw to compensate for reduced hearing on one side. Nevertheless, the relatively small changes in pitch and roll demonstrate the reduced role these types of movements have in locating sounds in the horizontal plane. In conclusion, this head tracking system is a financially viable piece of equipment capable of accurately and reliably recording changes in yaw.

## 7.2 Sound orientation in the horizontal plane by normally hearing listeners and cochlear implant users

### 7.2.1 Introduction

As outlined in Chapter 3, Brimijoin, McShefferty, and Akeroyd (2010) demonstrated that both normally hearing (NH) and moderately hearing impaired listeners undershot when orienting to auditory and visual targets in the frontal-horizontal plane. Brimijoin et al. instructed listeners to turn their head so that they were facing the source of either a visual stimulus or a short (1.3 seconds) auditory stimulus. The present experiment sought to replicate this experiment with a group of NH listeners but also extend the study to test profoundly hearing impaired listeners who use CIs. The study sought to answer the following questions:

1. How accurately can CI users orient to sound sources in the frontal horizontal plane?
2. How do CI users make use of head movements during this task?
3. Are unilateral and bilateral CI users more accurately able to orient to an auditory target when they have longer than 1.3 seconds?

In a sound localisation task with 12 loudspeakers in the horizontal plane (separated by 30°), Mueller, Meisenbacher, Lai, and Dillier (2014) demonstrated that the mean RMS error of bilateral CI users was 30.6°, 26.9° and 27.6° for stimuli lasting 0.5 seconds, 2.2 seconds and 4.5 seconds respectively. This pattern suggests that increasing the duration of an acoustical stimulus does not improve localisation accuracy. With a short stimulus there is limited time available to make a movement whilst the stimulus is presented and it is possible that the sound will have ceased before a natural head movement has begun. Indeed, Brimijoin et al. (2010) measured the time listeners took from the onset of an acoustical stimulus to move their heads ±3°. The average time taken by NH listeners was 0.3 seconds whereas moderately hearing impaired listeners took 0.6 seconds. Listeners may benefit from a brief pause before moving to ascertain the loudness of a stimulus whilst they keep their head still, before making a movement to monitor changes in loudness across space. It may be that bilateral CI users will take longer than unaided moderately hearing impaired listeners to make a movement because they must base their judgement largely on ILDs rather than both ILDs and ITDs. They also have to integrate information from two different processors. A 1.3 second stimulus should allow time for some movement to be made however, this may not be sufficiently long for CI users to benefit. For instance both Brimijoin et al. (2010) and Mueller et al. (2014) demonstrated that moderately hearing impaired individuals and bilateral CI users respectively made longer and more complex, search-like head movements than NH listeners. With just 1.3 seconds there may not be sufficient time for informative head movements to be made and completed. When more time is available participants will have the opportunity to make and complete search-like head movements which could improve performance.

Consistent with previous research by Brimijoin et al. (2010), it was hypothesised that both NH listeners and CI users would increasingly undershoot in their orientation to auditory and visual targets in the periphery due to restrictions in the ability to turn the neck (Tousignant & Breton, 2006). It is well documented that NH listeners are able to locate sounds accurately in the frontal horizontal plane (e.g. Brimijoin et al., 2010; Mueller et al., 2014; Oldfield & Parker, 1984). In the experiment reported in Chapter 5, localisation accuracy for five sources of sounds separated by 15° in the frontal horizontal plane by bilateral CI users was 52% correct (mean RMS error: 13.30°, SD = 6.02°). The duration of the stimulus in that experiment was 1.68 seconds (SD = 0.12) therefore, it was hypothesized that bilateral CI users in the present study would be less accurate than NH listeners at orienting to the source of a short stimulus. It was anticipated that a continuous stimulus would enable bilateral CI users to benefit from the changes in ILD afforded by a longer stimulus. This may help them to discriminate between the locations to determine where the target was presented from more accurately than with a shorter stimulus. Previous research has shown localisation accuracy by unilateral CI users to be poor (see Chapter 2). Furthermore, the experiment reported in Chapter 5 showed that unilateral CI users had an accuracy of 26% with target locations separated by 15° (mean RMS error: 26.36°, SD = 4.71°). Therefore, it was expected that unilateral CI users in the present study would be unable to locate and orient to an auditory target with just 1.3 seconds. Localisation performance by unilateral CI users has been shown to be poor even when head movements are permitted (see Chapter 3), thus it was anticipated that performance would remain poor even when a longer stimulus was used as even though there would be sufficient time to make head movements, the unilateral CI users will not benefit from them. Based on results by Brimijoin et al. (2010) and Mueller et al. (2014) it was hypothesised that CI users would make longer, more complex head movement trajectories than NH listeners. Consistent with Brimijoin et al., a visual control condition was included to check that any differences between the groups tested were due to hearing differences and not any other factors, such as limited neck movement ability or age differences.

### 7.2.2 Method

#### *7.2.2.1 Participants*

Twenty-four NH listeners (5 male, mean age = 21.56 years, SD=2.61) and eight CI users (4 bilateral) participated. All NH participants had pure-tone thresholds more favourable than, or equal to 20 dB HL at 0.25, 0.5, 1, 2, and 4 kHz and were recruited from within the University of

York. Users of CIs that had participated in the research study described in Chapters 5 and 6 were contacted with details of the present research. Additional participants (participants 169 and 216) responded to an advertisement in the National CI Users Association calling for participants. Demographic information of CI users is displayed in Table 7.1. The Research Ethics Committee of the Department of Psychology at the University of York approved the study.

**Table 7.1. Summary demographic data of CI users**

| Participant | Age | Gender | Contralateral hearing aid? | 1st CI make | Duration of 1st CI use (years) | 2nd CI make | Duration of 2nd CI use (years) |
|---|---|---|---|---|---|---|---|
| 111 | 78.8 | Male | No | Advanced Bionics | 11.0 | - | - |
| 169 | 55.1 | Female | No | Advanced Bionics | 6.3 | - | - |
| 303 | 74.1 | Female | Yes | Cochlear | 7.7 | - | - |
| 323 | 62.6 | Female | Yes | Advanced Bionics | 6.1 | - | - |
| 201 | 55.0 | Female | - | Cochlear | 8.6 | Cochlear | 5.9 |
| 480 | 69.9 | Female | - | Cochlear | 9.7 | Cochlear | 7.7 |
| 214 | 52.9 | Male | - | Cochlear | 5.6 | Cochlear | 3.7 |
| 216 | 71.6 | Female | - | Advanced Bionics | 4.9 | Advanced Bionics | 2.7 |

#### *7.2.2.2 Apparatus*

All stimuli were presented through 11 loudspeakers (Bose Acoustimass 3 Series IV) positioned in a semi-circular array with a radius of 1.5m extending from -75° to +75° in 15° steps (Figure 7.5). Loudspeakers were positioned at a height of 1m. The array of loudspeakers was situated within an Industrial Acoustic Corporation (IAC) single-walled enclosure situated within a larger sound-treated room. The loudspeaker array was calibrated using a Brüel and Kjaer 0.5 inch microphone (Type 4189) and sound level meter (Type 2260 Investigator). The outputs from each loudspeaker were adjusted so that an octave band of noise centred on 1kHz was presented at the same intensity (±0.5dB) in the centre of the arc with the participant absent. Positioned just directly underneath each loudspeaker was a red light-emitting diode (LED), which could be turned on or off. The head tracking equipment described in Section 7.1 was used to record the head movements of participants.

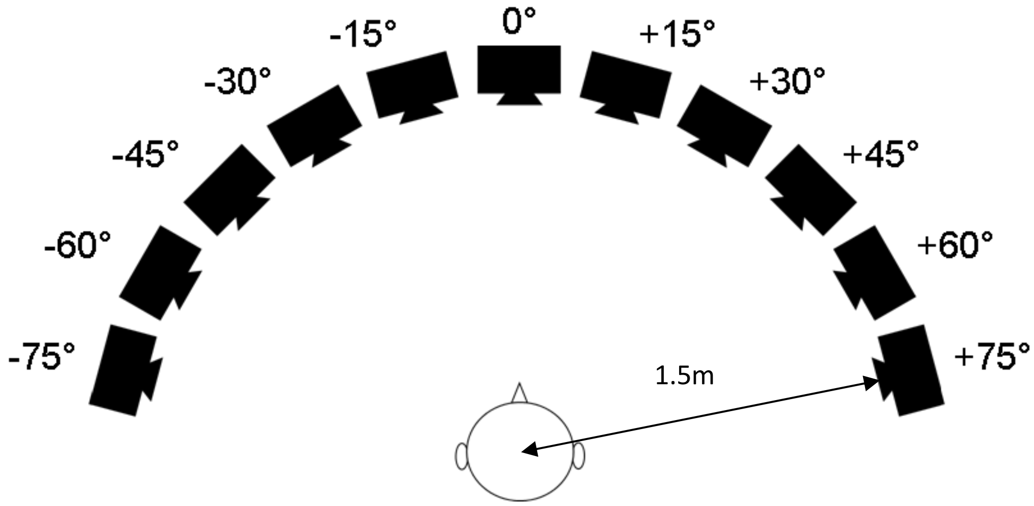


**Figure 7.5. Diagram showing loudspeaker position in relation to the participant.**

#### *7.2.2.3 Design*

A mixed design with three experimental conditions (visual, auditory short and auditory long) and three groups (NH, bilateral CI users, and unilateral CI users) was used. The experimental conditions were blocked and the order in which the conditions were completed was counterbalanced across participants.

#### *7.2.2.4 Stimuli*

Auditory stimuli

Forty Bamford-Kowal-Bench (BKB, Bench, Kowal, & Bamford, 1979) sentences spoken by a British male talker were used. Sentences were selected to be as close in duration to 1.3 seconds as possible (to match those used by Brimijoin et al., 2010). The mean duration of the sentences was 1.32 seconds (SD= .06). In the auditory short condition the stimulus was presented once. In the auditory long condition the sentence was repeated continuously until the participant responded (up to a maximum of 27 presentations or about 36 seconds).

Visual stimulus

A red light-emitting diode positioned directly beneath each loudspeaker was illiminated until the participant made a response.

#### *7.2.2.5 Procedure*

Prior to the experiment 25 modified de Bruijn sequences were generated (Brimijoin & O'Neill, 2010). This produced 25 unique orderings that ensured stimuli were presented from each location an equal number of times (11) and that each location was followed by each other location once.

Thus there were 110 trials (11 locations x 10 transitions). Participants completed each condition in a different de Bruijn order.

For the auditory conditions, on each trial one of the sentences was randomly selected and presented from the loudspeaker determined by the de Bruijn order at 65dB SPL. Stimuli were randomly roved (by 0, -5, or -10dB) on each trial. In the visual condition, on each trial a red LED was presented from the location determined by the de Bruijn order. On each trial the participant's task was to turn to face the light (visual condition) or the loudspeaker from which the sentence was presented (auditory conditions). Participants were instructed that when they were satisfied that they were facing the light/loudspeaker, they should press a handheld response button and continue facing that light/loudspeaker until the next stimulus was presented. Prior to each block, 11 practice trials, in which the stimulus was presented from each possible location, were included to familiarise participants with the task.

#### *7.2.2.6 Analyses*

Head-movement trajectories were smoothed with a 50ms Hanning window as described in Section 7.1.2.2. Individual trials were excluded from the analysis if the there was a gap in the head tracking recordings for 300ms or more. To ensure that measurements by the head tracking equipment matched where the participant was actually facing, the head tracking equipment was calibrated immediately before and immediately after each condition. For this, a light was presented below each loudspeaker used in the experiment in turn from left to right and then back to left. The participant was instructed to turn to face the light and then when satisfied that their nose was pointing at it, press a handheld response button. After a response was made the next light was presented. The mean yaw head orientations when the participant responded to a light at 0° azimuth (4 instances per condition) were extracted and averaged to produce a calibration yaw. This value was used to correct each recorded head position for that condition as described in section 7.1.2.2. Descriptions of the outcome measures are shown in Table 7.2. Two CI users (303 and 323) used a hearing aid in their non-implanted ear. Due to the small sample size, these two participants and participants 111 and 169 were treated as one group as users of a single cochlear implant.

**Table 7.2. List of outcome measures with descriptions.**

| Outcome measure | Definition |
|---|---|
| Final Orientation | Position (°) at which the participant was orienting when they pressed the response button. |
| Accuracy | Mean root-mean square error (°) of the final orientation relative to the target orientation. |
| Latency to Respond | The time (seconds) taken from the target onset until the participant pressed the response button. |
| Initial Latency | The time (seconds) taken from target onset until the participant moved more than ±3°. |
| Duration at Fixation | Length of time (seconds) for which participants remained within ±3° of their final orientation. |
| Duration of Movement | The time (seconds) between initiating a movement and fixating the target (i.e. the period of time after Initial Latency and before the start of Duration at Fixation). |
| Length of Movement | Absolute length of the head trajectory (°) |
| Maximum Velocity | Maximum speed (°/s) at which the participant moved during a trial. The average maximum velocity from each participant for each condition was calculated. |
| Reversals | A change in the direction of head movement (e.g. a change from leftward movement to rightward movement) was counted as a 'reversal'. The number of reversals per trial was counted and an average per participant for each condition was calculated. |

Individual 3 (group) by 3 (conditions) ANOVAs were conducted for each measure however Levene's test indicated that the assumption of homogeneity had not been met for the majority of analyses. Therefore the data were transformed (log10) and Levene's test was conducted again. However, the assumption of homogeneity was still not met. Therefore, 3 (group) by 3 (condition) linear mixed models were calculated with maximum likelihood estimation. All pairwise comparisons reported are Bonferroni corrected. Individual data from the CI users is displayed in Appendix E.

### 7.2.3 Results

#### *7.2.3.1 Accuracy*

Figure 7.6 shows the mean Final Orientation for each target location by the NH listeners. Participants accurately oriented to the loudspeaker at 0° azimuth however, there was a slight undershoot as the target location moved further into the periphery, reaching about 25° of undershoot at the furthest target locations. Furthermore, this pattern was consistent across all three conditions. Also shown, as an inset to Figure 7.6, are the equivalent findings for NH listeners from Brimijoin et al. (2010) which show a similar amount of undershoot in the periphery as the present study.

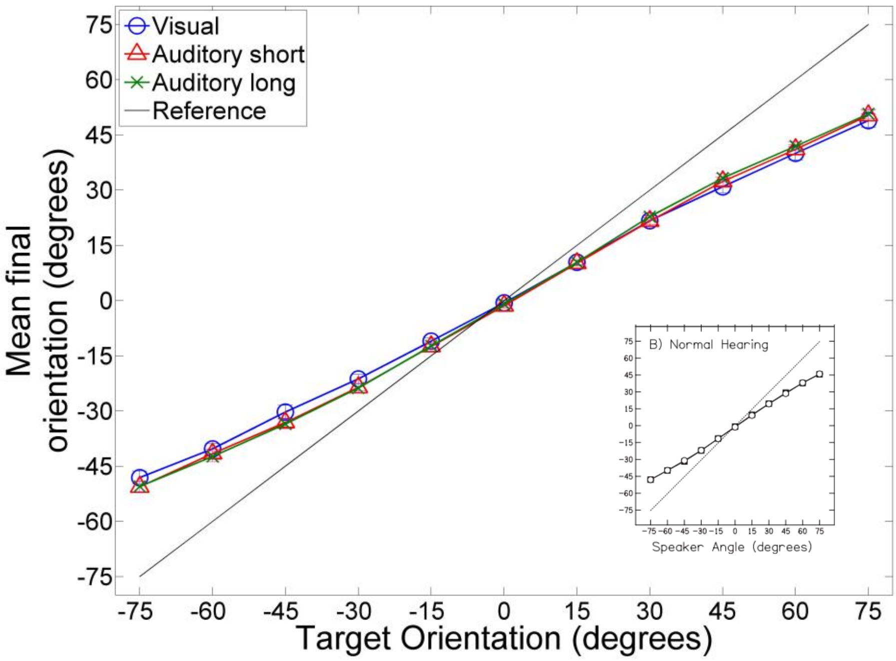


**Figure 7.6. Mean Final Orientation in the visual, auditory short, and auditory long conditions for each target location by NH listeners. Error bars show standard errors. Inset figure from Brimijoin et al (2010).**

Figure 7.7 shows the mean Final Orientation for each target location for the CI users individually. All listeners were able to orient accurately to the visual target (blue lines). The bilateral CI users (top four graphs) were able to orient to the target locations in the auditory conditions with a reasonable level of accuracy. The unilateral CI users were more varied, for example participant 323 was reasonably accurate whereas participant 303 consistently perceived the sound to be coming from the right hand side (the side ipsilateral to their CI).

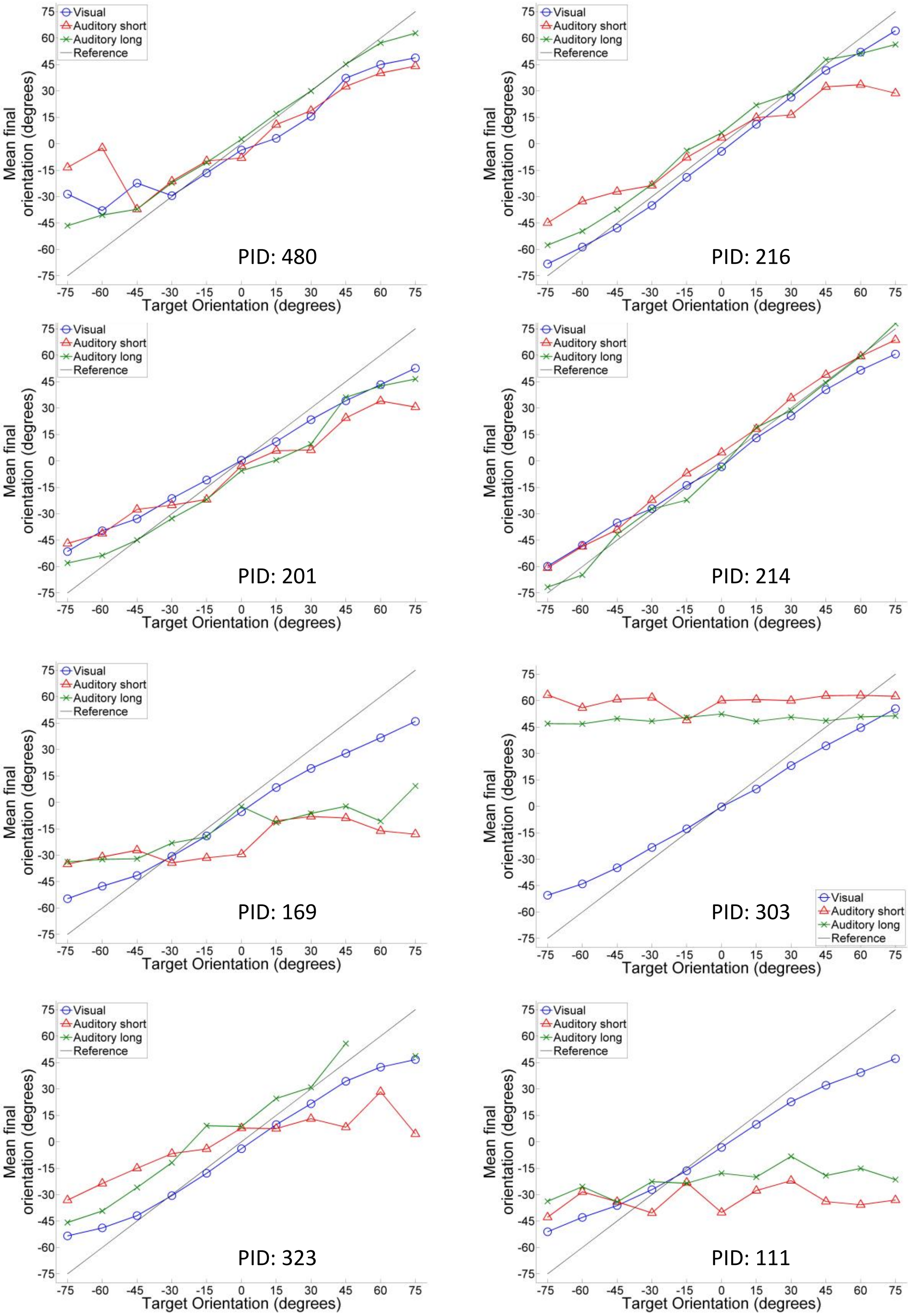


**Figure 7.7. Mean Final Orientation in visual, auditory short, and auditory long conditions for each target location by the eight CI users. The top 4 graphs show orientation by bilateral CI users and the lower four graphs show orientation by unilateral CI users.**

Table 7.3 displays the mean RMS error for each condition by each listener group. Average RMS error was calculated for each participant in each condition and used as the dependent variable in a linear mixed model. Significant main fixed effects of group ($F(2,94.618) = 59.028$, $p<.001$), condition ($F(2,60.758) = 30.481$, $p<.001$), and a significant group by condition interaction ($F(4,60.758) = 22.295$, $p<.001$) were found. The interaction was investigated by examining the simple effects of group and condition at each level of the other factor. The simple effect of group was found in the auditory short ($F(2,32) = 62.910$, $p<.001$) and auditory long conditions ($F(2,32) = 33.438$, $p<.001$) but was not found in the visual condition ($F(2,32) = .837$, $p=.442$). Pairwise comparisons revealed that RMS error was significantly greater for unilateral CI users than bilateral CI users and NH listeners in both auditory conditions (all $p<.001$). Bilateral CI users had higher RMS errors than NH listeners in the auditory short condition ($p=.050$) but there was no significant difference between the two groups in the auditory long condition ($p=.622$). The simple effect of condition was evident only for the unilateral CI group ($F(2,67.105) = 46.687$, $p<.001$). Pairwise comparisons revealed that RMS error was significantly lower in the visual condition than the auditory short or auditory long conditions (both $p<.001$).

**Table 7.3. Mean RMS error for the three listener groups in the three conditions. SD in parentheses.**

| | Visual | Auditory short | Auditory long |
|---|---|---|---|
| NH listeners | 17.75 (6.75) | 16.08 (4.10) | 15.54 (4.31) |
| Bilateral CI users | 14.57 (8.95) | 25.17 (11.37) | 20.63 (11.25) |
| Unilateral CI users | 14.23 (1.06) | 56.24 (14.62) | 47.88 (17.41) |

#### *7.2.3.2 Latency to respond*

Table 7.4 shows the mean latency to respond for each condition by the bilateral and unilateral CI users. A linear mixed model demonstrated significant fixed effects of group ($F(2,42.476) = 89.006$, $p<.001$) and condition ($F(2,41.078) = 140.759$, $p<.001$) and a significant group by condition interaction ($F(4,41.078) = 31.639$, $p<.001$). The interaction was investigated by examining the simple effects of group and condition at each level of the other factor. The simple effect of group was found for each condition (all $p<.001$). Pairwise comparisons revealed that in the visual condition the bilateral CI users were significantly slower to respond than the NH listeners ($p=.001$). In both auditory conditions the NH listeners were significantly faster to respond than both the unilateral and bilateral CI users (all $p<.001$). In the auditory long condition, the bilateral CI users were significantly faster to respond than the unilateral CI users ($p=.017$). No other significant differences were found.

**Table 7.4. Mean latency to respond (in seconds) for each condition by the unilateral and bilateral CI users. SD is shown in parentheses.**

| Group | Visual | Auditory short | Auditory long |
|---|---|---|---|
| NH listeners | .63 (.23) | 1.26 (.34) | 1.27 (.38) |
| Bilateral CI users | 1.13 (.28) | 2.67 (.80) | 4.70 (1.36) |
| Unilateral CI users | .91 (.13) | 3.23 (.61) | 7.18 (3.45) |

### 7.2.4 Maximum velocity

A 3 (group) by 3 (condition) mixed ANOVA was conducted on the average maximum velocities. No main effect of group was found ($F(2,29) = .586$, $p=.563$). A significant main effect of condition ($F(2,58) = 6.097$, $p=.004$) and a significant group by condition interaction was found ($F(4,58) = 3.031$, $p=.024$). The interaction was investigated by examining the simple effects of group and condition at each level of the other factor. No simple effect of group was found for any condition (all $p>.05$). The simple effect of condition was found only for the unilateral CI users ($F(2,28) = 7.744$, $p=.002$). Pairwise comparisons revealed that the mean maximum velocity was significantly smaller in the auditory short condition than the visual ($p=.009$) and auditory long conditions ($p=.003$).

**Table 7.5. Mean maximum velocity of head turn (degrees per second) for the three groups in the three conditions. SD is shown in parentheses.**

| Group | Visual | Auditory short | Auditory long |
|---|---|---|---|
| NH listeners | 127.63 (31.51) | 121.52 (29.67) | 120.36 (32.66) |
| Bilateral CI users | 126.10 (39.58) | 113.17 (50.52) | 112.13 (24.77) |
| Unilateral CI users | 125.60 (11.52) | 75.45 (62.95) | 117.30 (38.42) |

### 7.2.5 Trajectory complexity

Figure 7.8 shows the head movements made by one representative NH listener on each trial. In the visual condition the participant initiated an orienting head movement in the direction of the target almost immediately whereas there was a delay before movement in the two auditory conditions. Figure 7.9 (top panel) displays those same head movements but on a 20-second timescale to enable comparisons with the head movements made by the CI users shown in the bottom two panels. A visual inspection shows that the head movements made in the visual condition were similar across these three participants, whereas in the auditory short condition, the unilateral participant did not orient his head in the hemispace contralateral to his CI. In the auditory long condition the unilateral CI user did move his head from left to right but finished most of the trials in the left hand hemispace. The bilateral CI user also made use of head movements but to a lesser extent than the unilateral CI user. The following sections seek to quantify the differences in the trajectories made by the three groups as a measure of trajectory complexity.

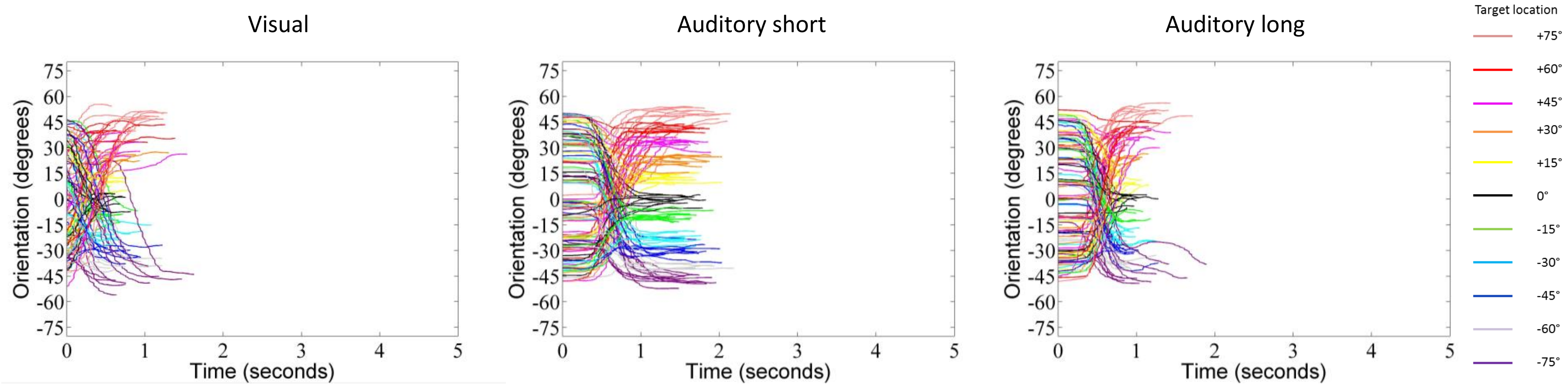


**Figure 7.8. Head movement trajectories made by a representative NH listener in the visual (left), auditory short (centre) and auditory long (right) conditions. Each line corresponds to the head movement trajectory made in a single trial from target onset to participant response. The colour of the line corresponds to the location of the target stimulus.**

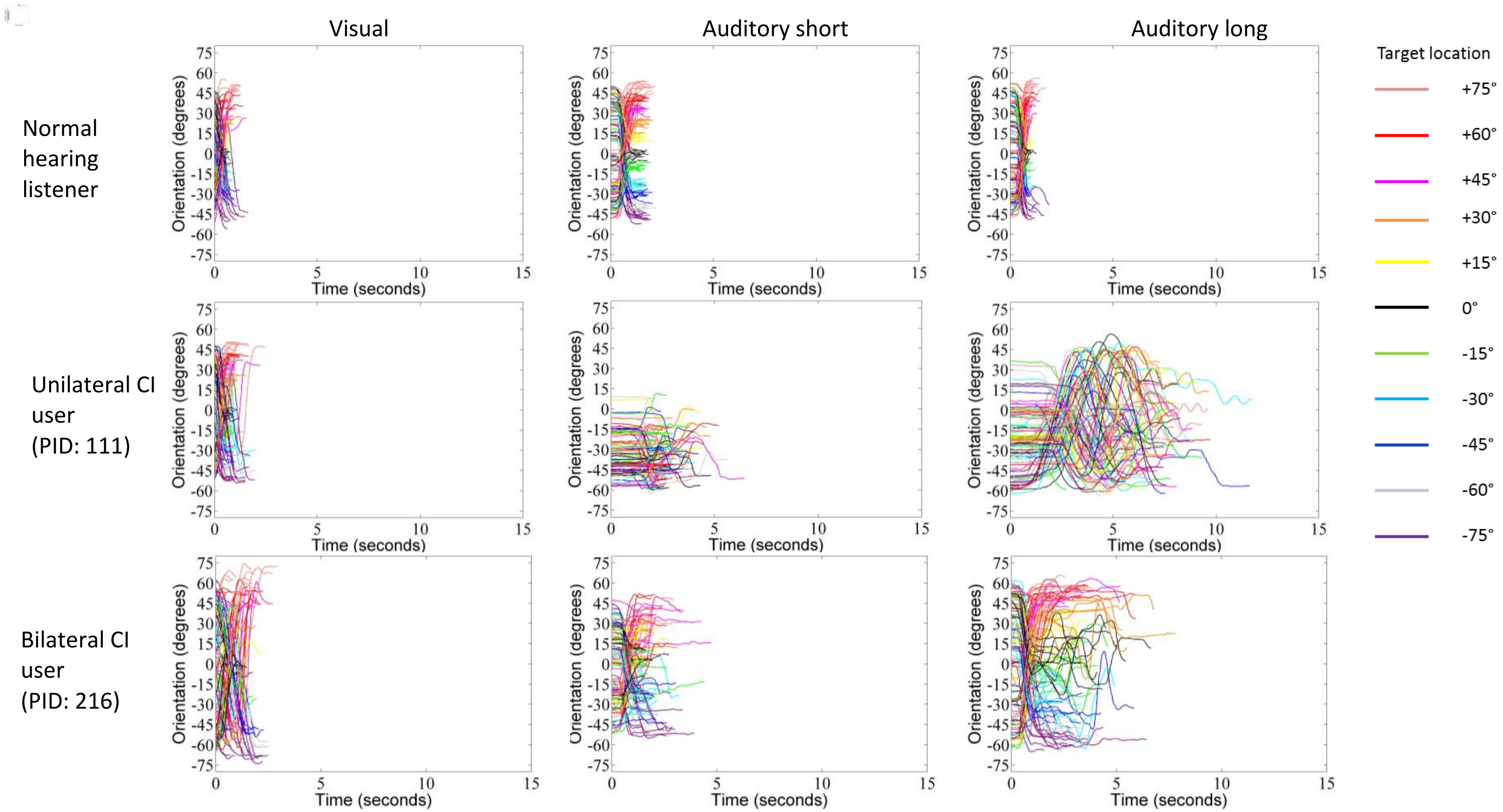


**Figure 7.9. Head movement trajectories made by a representative NH listener (top), unilateral CI user (middle) and bilateral CI user (bottom) in the visual (left), auditory short (centre) and auditory long (right) conditions. Each line corresponds to a single trial from target onset to participant response. The colour of the line corresponds to the location of the target stimulus.**

### *7.2.5.1 Reversals*

Figure 7.10 shows the mean number of reversals per trial for each condition by each listener group. A linear mixed model showed significant fixed effects of group (F(2,70.802) = 112.962, p<.001) and condition (F(2,59.023) = 160.802, p<.001) and a significant group by condition interaction (F(4,59.023) = 38.582, p<.001). The interaction was investigated by examining the simple effects of group and condition at each level of the other factor. A significant simple effect of group was found for the three conditions (all p<.01). Pairwise comparisons revealed that in the visual condition the bilateral CI users made more reversals than the NH listeners (p=.003). In both the auditory short and auditory long conditions the NH listeners made fewer reversals than the bilateral and unilateral CI users (all p<.001). The simple effect of condition was found for each level of group (all p<.001). Pairwise comparisons revealed that for all listener groups, significantly fewer reversals were made in the visual condition than both auditory conditions (all p≤.001, see Figure 7.10). For both the bilateral and unilateral CI users, fewer reversals were made in the auditory short condition than the auditory long condition (p<.001 and p=.013 respectively).

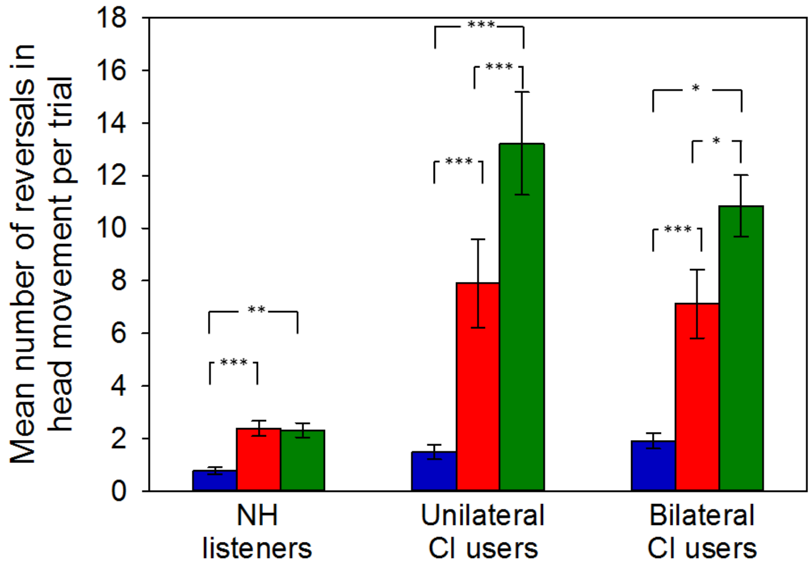


**Figure 7.10. Mean number of reversals in head movement per trial by NH listeners, unilateral CI users and bilateral CI users in the three conditions. Blue bars represent the visual condition, red bars represent the auditory short condition and green bars represent the auditory long condition. Error bars represent ±1SE. Asterisks indicate significant differences between conditions (*** p<.001, ** p<.01, * p<.05).**

### *7.2.5.2 Length of head movement per trial*

Figure 7.11 shows the mean absolute length of head movement per trial for each condition by each listener group. A linear mixed model showed significant main effects of group (F(2,39.890) = 13.703, p<.001) and condition (F(2,39.269) = 11.621, p<.001) and a significant group by condition interaction (F(4,39.269, p=.001). The interaction was investigated by examining the simple effects of group and condition at each level of the other factor. A simple effect of group was found for the visual condition (F(2,32) = 6.075, p=.006) and auditory long condition (F(2,32) = 12.832, p<.001) but was not found for the auditory short condition (F(2,32) = .551, p=.582). Pairwise comparisons revealed that in the visual condition, the mean length of movement made by the NH listeners was significantly shorter than that made by the bilateral CI users (p=.007). In the auditory long condition the mean length of movement made by the NH listeners was significantly shorter than that made by the unilateral CI users (p<.001). The simple effect of condition was only found for unilateral CI users (F(2,37.997) = 14.097, p<.001). Pairwise comparisons revealed that the mean length of movement in the auditory long condition was significantly longer than both the visual and auditory short conditions (both p<.001, see Figure 7.11).

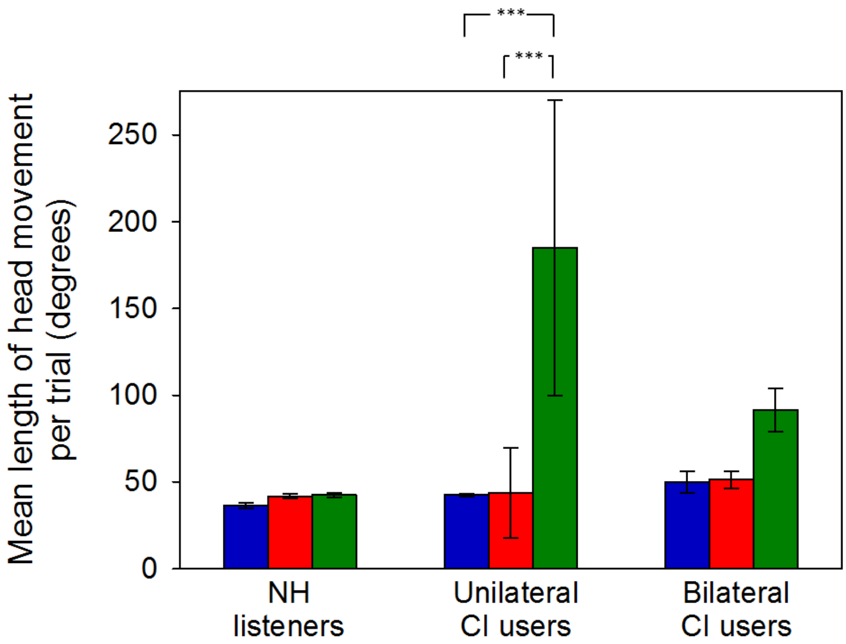


**Figure 7.11. Mean length of head movement per trial (degrees) by NH listeners, unilateral CI users and bilateral CI users in the three conditions. Blue bars represent the visual condition, red bars represent the auditory short condition and green bars represent the auditory long condition. Error bars represent ±1SE. Asterisks indicate significant differences between conditions (*** p<.001).**

#### *7.2.5.3 Latency*

Initial latency

Figure 7.12 displays the mean initial latency of the three listener groups in the three conditions. A linear mixed model showed significant fixed effects of group (F(2,63.105) = 43.092, p<.001) and condition (F(2,47.422) = 120.268, p<.001) and a significant group by condition interaction (F(4,47.422) = 18.351, p<.001). The interaction was investigated by examining the simple effects of group and condition at each level of the other factor. The simple effect of group was found for all three conditions (all $p<.01$). Pairwise comparisons revealed that in the visual condition, initial latency was significantly shorter for the NH listeners than the bilateral CI users ($p=.003$). In both auditory conditions initial latency was significantly shorter by NH listeners than unilateral CI users (both $p<.001$). Furthermore, initial latency was significantly shorter by bilateral CI users than unilateral CI users in the auditory short ($p<.001$) and auditory long ($p=.027$) conditions. The simple effect of condition was found for each group (all $p<.001$). Pairwise comparisons revealed that for all groups, initial latency was significantly shorter in the visual condition than the two auditory conditions (all $p<.01$). No difference between auditory short and auditory long conditions was found for any of the groups.

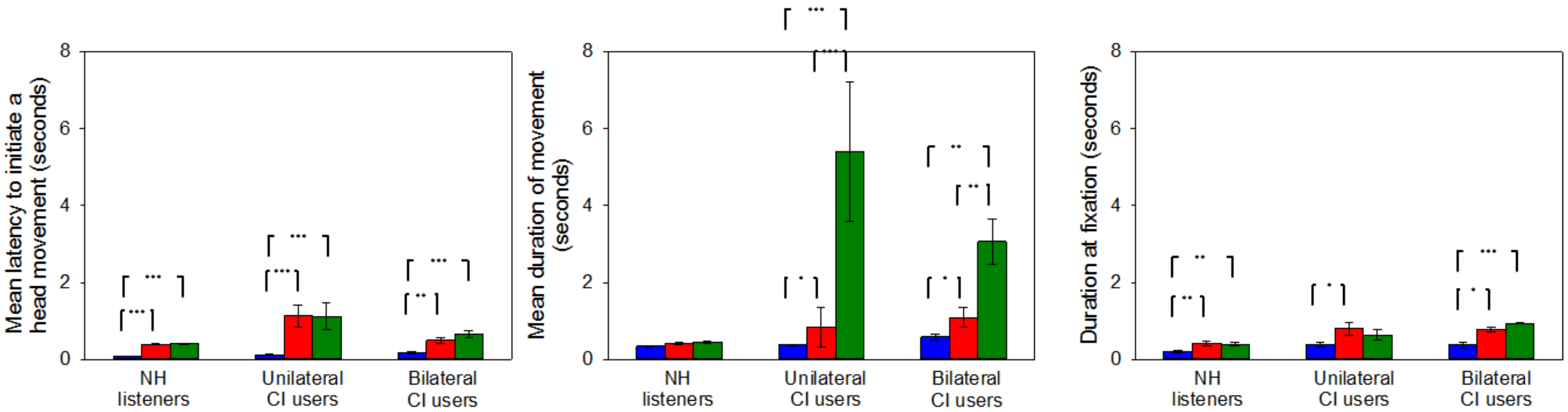


**Figure 7.12. Mean initial latency (left figure), duration of movement (middle figure) and latency at fixation (right figure) for the NH listeners, unilateral CI users and bilateral CI users in the three conditions. Blue bars represent the visual condition, red bars represent the auditory short condition and green bars represent the auditory long condition. Error bars represent ±1SE. Asterisks indicate significant differences between conditions (*** p<.001, ** p<.01, * p<.05).**

Duration of movement

Figure 7.12 displays the mean duration of movement of the three listener groups in the three conditions. A linear mixed model showed significant fixed effects of group ($F(2, 38.477) = 41.771$, $p<.001$) and condition ($F(2,35.754) = 44.968$, $p<.001$) and a group by condition interaction ($F(4,35.754) = 18.311$, $p<.001$). The interaction was investigated by examining the simple effects of group and condition at each level of the other factor. The simple effect of group was found for all three conditions (all $p<.01$). Pairwise comparisons revealed that in all three conditions the duration of movement by the NH listeners was significantly shorter than the duration of movement by the bilateral CI users (all $p<.01$). In the auditory long condition, the duration of movement made by the unilateral CI users was significantly longer than the NH listeners ($p<.001$) and bilateral CI users ($p=.025$). The simple effect of condition was found for the unilateral CI users ($F(2,34.202) = 39.026$, $p<.001$) and the bilateral CI users ($F(2,34.202) = 12.242$, $p<.001$) but was not found for the NH listeners ($F(2, 34.202) = .541$, $p=.587$). Pairwise comparisons revealed that for both CI groups, the duration of movement in the visual condition was significantly short than the duration of movement in both auditory conditions (all $p<.05$, see Figure 7.12). Furthermore, the duration of movement in the auditory short condition was significantly shorter than the auditory long condition (both $p<.01$).

Duration at fixation

Figure 7.12 displays the mean duration at fixation of the three listener groups in the three conditions. A linear mixed model with group (3 levels) and condition (3 levels) was conducted. A significant fixed effect of group was found ($F(2, 85.024) = 20.602$, $p<.001$). Pairwise comparisons revealed that duration at fixation was significantly shorter for the NH listeners than the unilateral and bilateral CI users (both $p<.001$). No difference between unilateral and bilateral CI users was found ($p=.838$). A significant fixed effect of condition was found ($F(2, 65.676) = 18.680$, $p<.001$). Pairwise comparisons revealed that duration at fixation was significantly shorter in the visual condition than the two auditory conditions (both $p<.001$, see Figure 7.12), however no difference between the two auditory conditions was found. No significant interaction was found ($F(4, 65.676) = 1.960$, $p.111$).

### 7.2.6 Discussion

#### *7.2.6.1 Accuracy*

As expected, and consistent with Brimijoin et al. (2010), NH listeners in the present study undershot both auditory and visual targets. The degree of undershoot increased the further the target was into the periphery. Figure 7.6 demonstrates the similarity between the results from the current study and the results reported by Brimijoin et al., with NH listeners in both studies undershooting targets by about 25° when the target was presented from the locations furthest into the periphery (±75°). This undershoot at the periphery can be explained by the limits of the human neck in rotating the head. Tousignant and Breton (2006) demonstrated that the maximum a human can turn their head comfortably to either side is about 56°. Thus for the peripheral targets in the current study, listeners were likely orienting their head most of the way but were then relying on eye gaze to fixate the target. However, this would not explain why there is an undershoot for targets close to the centre (e.g. there was an average of 3.97° and 4.56° undershoot for visual targets at -15° and +15° respectively). Brimijoin et al. also found a similar undershoot, and found no difference in performance between when participants could see the targets and when they were blindfolded and could not see the targets. Therefore a reliance on eye-gaze rather than head movement to fixate the target is unlikely to account for the undershoot found in the present stud and it is unclear why the undershoot arose. Nonetheless, the amount of undershoot systematically increased as the target location increased in angular distance from 0° azimuth. Importantly, as reported in Section 7.2.3.1, there was no difference in accuracy between the three groups for the visual targets. This result demonstrates that any difference in accuracy between the groups in the auditory conditions can be attributed to differences in hearing ability rather than other factors such as head movement restriction or age.

As shown in Figure 7.7, unilateral CI users performed poorly in both auditory conditions with the majority of stimuli perceived to originate from the same side as their implanted ear. Consistent with expectations, even when extra time was available in the auditory long condition (repetitive stimulus up to about 36 seconds), performance did not improve compared to the auditory short stimulus (mean duration 1.3 seconds). As hypothesised, bilateral CI users oriented significantly more accurately than unilateral CI users in both auditory conditions. The accuracy of bilateral CI users was slightly poorer than NH listeners in the auditory short condition; however their performance was as good as that of NH listeners in the auditory long condition. If accuracy was the only measure of performance, it would be reasonable to conclude that, with sufficiently long stimuli, bilateral CI users perform as well as NH listeners. However, as will be discussed below, despite similar levels of performance there were a number of differences between the two groups. The following discussion seeks to explain how bilateral CI users make use of extra time when it is available, in order to achieve normal levels of accuracy in final orientation.

#### *7.2.6.2 Latency to respond*

Whilst orientation accuracy was no different between NH listeners and bilateral CI users in the visual condition, bilateral CI users were significantly slower to respond in the visual condition than the NH listeners. This could be due to an age effect. The NH listeners were young (mean age = 22 years) whereas the bilateral CI group were older, ranging in age from 52.9 years to 71.6 years (mean = 62.4 years, see Table 7.1). Baron and Mattila (1989) demonstrated that older adults (aged 65-76 years) were slower to respond to auditory and visual stimuli than NH listeners (aged 18-25 years). Furthermore, Roggeveen, Prime and Ward (2007) found that when asked to respond to a moving visual stimulus, older adults (aged 65 to 81 years) were slower to respond than younger adults (aged 18 to 28 years). By using electroencephalography Roggeveen et al. were able to determine that the longer latency to respond by older adults was primarily due to slower motor processes compared to younger adults.

However, the unilateral CI users in the current study were similar in age (mean age = 67.7 years) to bilateral CI users yet bilateral CI users responded significantly faster than unilateral CI uses in the auditory long condition. This could be explained by higher uncertainty amongst the unilateral CI users. The bilateral CI users were as accurate as NH listeners in the auditory long condition, measured by their Final Orientation, suggesting that the time which they took to respond was sufficient to accurately locate the target (i.e. they did not require any more time to complete the task). The unilateral CI users however, performed poorly even when extra time was available. This suggests that they were uncertain where the target was located and so made use of the extra time to attempt to locate the target and hence took longer to respond.

#### *7.2.6.3 Maximum velocity*

No difference in maximum velocity was found between the three groups. However, the unilateral CI users had a significantly slower maximum velocity in the auditory short condition than the other two conditions. This could be due to uncertainty in the location of the stimulus and insufficient time to make a head movement whilst the stimulus was being presented. Indeed the mean initial latency (discussed in detail below) of the unilateral CI users in the auditory short condition was 1.13 seconds (SD = .56). As the duration of the stimulus in the auditory short condition was 1.32 seconds, this initial latency did not allow much time for a head movement to be made before the stimulus had finished.

#### *7.2.6.4 Trajectory complexity*

Trajectory complexity was assessed with five measures: number of head movement reversals, length of head movement, initial latency, duration of movement, and latency at fixation.

### Reversals

Both unilateral and bilateral CI users made significantly more head movement reversals than NH listeners in the two auditory conditions. This is somewhat consistent with the experiment reported by Mueller et al. (2014) who tracked the head movement trajectories of eleven NH listeners and seven bilateral CI users during a sound localisation task. Whilst they did not report the number of reversals listeners made, they did report the mean number of times during a trial that participants turned their head away from the target. They found that NH listeners made few head turns away from the target whereas the bilateral CI users made significantly more. However, in the present study bilateral CI users also made more reversals than NH listeners in the visual condition. This too could be due to age differences (discussed in Section 7.2.6.2).

### Length of movement

Whilst no difference between the bilateral CI users and NH listeners was found for the length of movement in the auditory conditions, in the visual condition bilateral CI users moved their heads significantly further than NH listeners. This is consistent with the reversal findings discussed above; if listeners make more reversals they will need to make longer head movement trajectories to correctly orient to the target. Despite the mean head movement trajectory length in the auditory long condition of the bilateral CI users (91.41°) being more than double that of the NH listeners (42.53°) this difference was not significant. The variance in performance was high among bilateral CI users (SD = 24.89) and the lack of a significant difference is likely due to the present study being underpowered with too few participants (see Section 7.2.6.5 for a full discussion on this issue).

### Initial latency

Unilateral CI users displayed longer initial latencies than both NH listeners and bilateral CI users in both auditory conditions. All listeners could be using this time to extract information from the environment to determine whether the sound source was on their left or right before making a movement to try and further resolve the location. With only one CI, and therefore unable to access interaural differences in level or timing, the unilateral CI users may take longer to try and extract as much information from the environment as possible. They may be attempting to judge the loudness of a stimulus with their heads still before moving their head to see how the loudness varies at their implanted ear. Consistent with the latency to respond analyses discussed above, bilateral CI users had a significantly slower initial latency than NH listeners. Regardless of the auditory condition, NH listeners took on average 0.4 seconds to initiate a head movement (consistent with Brimijoin et al., 2010 who also found an average initial latency of 0.4 seconds by NH listeners). Knowing that additional time was available in the auditory long condition did not result in either group of CI users taking longer to initiate a movement. Rather differences arose in the duration of movement, discussed below.

### Duration of movement

The duration of movement by NH listeners was significantly shorter than the bilateral CI users. Consistent with Brimijoin et al. (2010) and Mueller et al. (2014), the NH listeners in the present study typically made uniform head movements (as illustrated in Figure 7.8). Both Brimijoin et al. and Mueller et al. fitted polynomial functions to head movement trajectories in order to quantify the complexity. The order of the polynomial function was increased until the error estimate of the fit was below a specified threshold. This method yielded the lowest order polynomial required to adequately fit the data. Whilst this method is useful with typically sigmoidal functions (as was the case in Brimijoin et al., 2010) it becomes increasingly less meaningful with complex head trajectories such as some of the head trajectories displayed in Figure 7.9. As such, this method was not employed in the present study. However, duration of movement was considered. In the auditory long condition unilateral CI users had a longer duration of movement than both the NH listeners and bilateral CI users. However, despite making use of this extra time, the unilateral CI users did not improve their performance. Both CI groups had a longer duration of movement when time was available in the auditory long condition than the auditory short condition which is consistent with making more reversals in this condition as discussed above.

### Duration at fixation

Both CI groups displayed longer at fixation durations than the NH listeners. This effect was not specific to auditory conditions as no interaction was found, suggesting that this is not specific to hearing difficulties. This could be due to differences in age (as discussed above). No difference was found between the two CI groups further suggesting that hearing difficulty is not the reason behind this difference. Participants had shorter latencies at fixation with the visual stimulus than an auditory stimulus. This could be due to the location of the visual stimulus being more salient than the location of the auditory stimulus, with listeners taking some moments to check they are facing the correct location of the auditory target.

### Reasons for increased movement complexity

Brimijoin et al. (2010) proposed two explanations for moderately hearing impaired listeners having more complex head movement trajectories compared to NH listeners: uncertainty and learned behavioural search response. These two explanations are challenging to separate as it is possible that uncertainty in where the target is presented from results in users adopting searching strategies to extract as much information from the listening environment as possible to help reduce ambiguity. The search-like strategies could be used by listeners to maximise the ILD. These two interpretations could also be applied to the current dataset to explain why bilateral CI users made more complex head movement trajectories to achieve a similar level of performance to NH listeners. They may make more complex head movements to manipulate the interaural level of the signal to determine the location of the sound source more accurately. This would be beneficial to bilateral CI users as the direction of the sound source could be inferred from the ear which has the louder stimulus level. When the ILD is at its maximum for that stimulus, one can infer that the sound source is located in the direction in which the ear with the louder signal is pointing. However, head movement trajectories by bilateral CI users were also more complex than NH listeners in the visual control condition. Visual acuity was not measured however participants reported no difficulty in seeing the light stimulus used. Therefore it is possible that confounding variables such as age account for some of the differences. This cannot be confirmed from the present study.

#### *7.2.6.5 Strengths and limitations*

The inclusion of the visual condition enabled checks to be made that all groups were physically able to orient their heads to the different target locations and that any differences between the groups were not explainable by mobility constraints. However, although there was no difference in orientation accuracy between bilateral CI users and NH listeners in the visual condition, there were several differences in the trajectories made that distinguished the two groups. Bilateral CI users took longer to initiate a movement, made longer head movements, made more head movement reversals, and took longer when making head movements than NH listeners. In all cases the bilateral CI users were demonstrating slower, more complex movements than NH listeners. This could be due to the age difference between the two groups. If this suggestion is the case, it is likely that these age differences could also be contributing to differences in trajectory complexity in the two auditory conditions as well. Therefore it would be informative for future research to age match normal hearing listeners with bilateral CI users in order to separate age effects from effects driven by hearing difficulties.

A limitation of this study is that there were just four participants in each of the CI groups. This study is therefore likely to be underpowered. One approach one could take is to conduct a power analysis to determine a more appropriate minimum number of participants per group. One way to estimate required sample size is to use the effect sizes gathered from this study in a power analysis. A power analysis was conducted using G*Power Version 3.1.9.2 to determine the minimum sample size required given these measured effect sizes. Effect size 'Cohen's f' was calculated within G*Power from the $\eta_p^2$ calculated in SPSS from an ANOVA for accuracy. G*Power uses the conversion as outlined by Cohen (1988) shown below.

$$f = \sqrt{\frac{\eta_p^2}{1-\eta_p^2}}$$

Cohen's f for group, condition, and the group by condition interaction was large at 1.47, 1.16, and 1.40 respectively. Alpha was set at .05. To achieve a power of at least 80% would require 9 participants per group. The lack of significant differences between groups on some measures could be accounted for in part because of a lack of power to detect differences. Future research should compare performance from at least 9 participants in each group to disambiguate whether the non-significant differences found are due to insufficient participants tested in the current study or to no difference being present.

#### *7.2.6.6 Implications*

This study has demonstrated that the duration of a stimulus can influence the accuracy of performance by bilateral CI users which has implications for studying localisation accuracy. Although in a sound localisation task Mueller et al. (2014) found no benefit from increasing stimulus length for reducing RMS error, they did find that fewer front-back confusions occurred with a longer stimulus. Indeed 32% of confusions with a 0.5s stimulus decreased to 10% of confusions with a 2.2 second stimulus and 5.5% confusions with a 4.5 second stimulus. In comparing performance between different devices to determine clinical effectiveness, it is important that the test is adequately able to capture the benefits obtained. It may be that comparisons of localisation ability with monaural and binaural listening (such as the experiment reported in Chapter 5) will achieve more discriminatory results from using a longer stimulus. These results can be informative for determining the potential achievement users can obtain from interventions for hearing loss. In the present experiment CI users made more complex head movements in the auditory long condition compared to the auditory short condition, with bilateral CI users achieving a higher level of accuracy than unilateral CI users. Despite listeners being able to benefit from the additional time available, it may be that head movements contribute an important role in locating sources of sounds. This idea will be investigated further in an experiment reported in Section 7.3.

#### *7.2.6.7 Conclusion*

NH listeners are able to orient to an auditory or visual target stimulus but undershoot towards the periphery. Bilateral CI users perform slightly worse than NH listeners when asked to orient to an auditory stimulus of 1.3 seconds in duration. However, when more time is made available bilateral CI users are as accurate as NH listeners. Nevertheless, in order to achieve this level of performance the bilateral CI users make more complex head movements, with more reversals, longer trajectories and longer durations. Unilateral CI users are unable to accurately orient to a sound source even when sufficient time is available to make large head movements. Future research should use a larger sample of CI users and age-match NH controls to distinguish between effects due to hearing differences and age.

### 7.2.7 Summary

- Participants oriented their heads towards a visual stimulus, a short (1.3 second) auditory stimulus or a long auditory stimulus.
- No difference in accuracy by NH listeners was found between the three conditions although participants did undershoot by increasing amounts as the target location was presented from further in the periphery.
- With a long stimulus bilateral CI users oriented as accurately as NH listeners, but were less accurate when the stimulus duration was limited to 1.3 seconds.
- In order to achieve a similar level of accuracy to NH listeners, bilateral CI users made more complex head movements.
- Unilateral CI users made more complex head movements in the auditory long condition than the auditory short condition, however this did not improve performance, with accuracy remaining poor.

## 7.3 Sound localisation by cochlear implant users and normally hearing listeners: The role of head movements

### 7.3.1 Introduction

Previous research investigating the role of head movements in sound localisation was discussed in detail in Chapter 3 and why they may help listeners in Section 7.2. On the whole, previous research has demonstrated that head movements can help NH listeners improve localisation accuracy and reduce the number of front-back confusions made (Mueller et al., 2014; Perrett & Noble, 1997a, 1997b; Wightman & Kistler, 1999). However, this conclusion is caveated by the finding that head movements only improve performance if the sound stimulus is long enough (Mueller et al., 2014; Perrett & Noble, 1997a). With a 0.5 second stimulus both Mueller et al. and Perrett and Noble demonstrated that localisation in the horizontal plane was not improved from permitting natural head movements compared to no head movement. It was argued that 0.5 seconds was insufficient for a head movement to be made and completed before the cessation of the sound. In comparison, when a 2.18 second (Mueller et al.) or three second (Perrett and Noble) stimulus was used localisation performance by NH listeners improved when head movements were permitted.

Unilateral CI users have been shown to perform poorly even when head movements are permitted (Buhagiar et al., 2004; Tyler et al., 2006). Only one published study has directly assessed the role of head movements by bilateral CI users on localisation accuracy. In that study, Mueller et al. (2014) instructed participants to locate a target sentence in the presence of background noise. Both the target and background noise were presented in the horizontal plane and the target was short (0.5 seconds), medium (2.18 seconds) or long (4.45 seconds) in duration. Compared to NH listeners, the bilateral CI users made longer, more complex head movement trajectories. Consistent with the findings for NH listeners discussed above, the stimulus needed to be sufficiently long for listeners to benefit from permitting head movements. For instance, whilst the number of front-back confusions was reduced when head movements were permitted for the long and medium stimulus durations, there was no significant reduction in the number of front-back confusions made with the short stimulus. Mueller et al. calculated the RMS error made after accounting for front-back errors by projecting the locations behind the listener to the front of the listener to remove large RMS errors caused by front-back confusions. It was found that whilst head movements had helped to reduce the number of front-back confusions, they had not helped listeners to significantly reduce the angular error made. In the short-duration condition RMS error was around 31° both with and without head movements permitted, in the medium-duration condition RMS error was about 26° without head movement and 30° with head movement and in the long-duration condition, RMS error was about 28° without head movement and about 26° with head movement.

The current study sought to investigate the role of head movements for sound localisation in the horizontal plane by NH listeners and CI users. Head movement was either permitted or not permitted but, unlike Mueller et al., the current study used a localisation task without the presence of background noise. This study also investigated the impact that the duration of the stimulus has on the amount of benefit obtained from permitting head movements. Three durations were used; short (0.8 seconds, which is slightly longer than the 0.5 second stimulus used by Mueller et al; 2014 and Perrett & Noble; 1997a), medium (5.4 seconds, which is slightly longer than the 'long' stimulus used by Mueller et al.) and long (a continuous repeating stimulus). These durations were chosen to cover a broad range of durations to assess whether individuals make use of extra time when it is available (continuous stimulus) and whether this improves performance over a medium length stimulus similar in duration to Mueller et al's long stimulus. This study also tested two groups of CI users (bilateral and unilateral) to assess the benefit of head movements to each group.

It was hypothesised that both NH listeners and bilateral CI users would benefit from head movements in reducing the number of front-back confusions when the sound was long enough (medium and long stimulus duration conditions). However, it was anticipated that unilateral CI users would perform poorly even when head movements were permitted. Pilot research (Goman, Kitterick, & Summerfield, 2013) had suggested that the angular accuracy of locating sources in the horizontal plane by NH listeners was not improved by permitting head movements. However, despite no change in performance, self-rated listening effort was reduced. This previous study had only tested participants on one half of auditory space (either front or rear) therefore the potential for head movements to reduce front-back confusions was not assessed. For this reason, the present study sought to investigate the potential for head movements to reduce front-back confusions. A self-rated listening effort scale was included to assess listening effort. It was hypothesised that listening effort would be larger in the front-and-back condition as there would be a greater number of location possibilities and a chance for front-back confusions to occur that would be absent from the front-only condition.

### 7.3.2 Method

#### *7.3.2.1 Participants*

Twenty-five NH adults (6 male, mean age = 22.1 years (SD=2.9) and eight CI users participated (4 unilateral and 4 bilateral, summary demographic information displayed in Table 7.1 in Section 7.2.2). All NH participants had pure-tone thresholds below or equal to 20 dB HL at 0.25, 0.5, 1, 2, and 4 kHz. NH participants were recruited from within the University of York. The Research Ethics Committee of the Department of Psychology at the University of York approved the study.

#### *7.3.2.2 Apparatus*

All stimuli were presented through an array of 10 loudspeakers (Bose Acoustimass 3 Series IV) positioned in a circular array with a radius of 1.5m (see Figure 7.13). Loudspeakers were positioned at a height of 1m and were separated by 15°. The array of loudspeakers was situated within an Industrial Acoustic Corporation (IAC) single-walled enclosure situated within a larger sound-treated room. The loudspeaker array was calibrated as described in section 7.2.2.2. Positioned just directly underneath each loudspeaker was a red light-emitting diode (LED), which could be turned on or off. The head tracking equipment as described in section 7.1 was used to measure the head movements of participants.

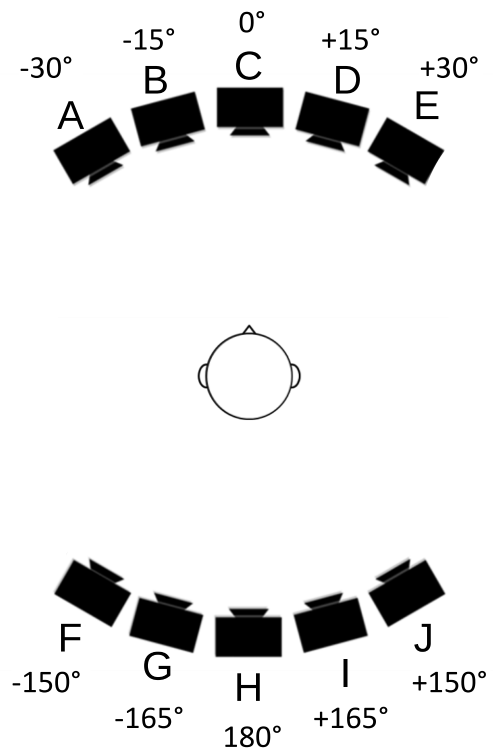


**Figure 7.13. Loudspeaker arrangement. In the front-only condition loudspeakers A-E were used. In the front-and-back condition loudspeakers A-J were used.**

#### *7.3.2.3 Design*

Three groups of participants were tested in a 2 (movement condition) by 2 (direction condition) by 3 (stimulus duration) blocked design. Participants were either instructed to keep their head still by maintaining their fixation on the loudspeaker directly in front of them (movement not permitted), or they were instructed that they could move their head as they wished (movement permitted). For the direction conditions the target was either presented from one of five loudspeakers in front of the participant (front-only condition) or was presented from one of the ten possible locations (front-and-back condition, see Figure 7.13). There were three stimulus durations; short (mean duration = 0.82, SD= 0.10), medium (mean duration = 2.54s, SD= 0.23), and long (continuous repetition until responded up to a maximum mean duration of 17.79s, SD= 1.60).

#### *7.3.2.4 Stimuli*

Coordinate-response-measure (CRM) sentences were used. Each sentence took the form “Ready CALL-SIGN go to COLOUR NUMBER now.” There were eight possible call signs (Arrow, Baron, Laker, Charlie, Hopper, Tiger, Eagle, and Ringo), four possible colours (blue, red, green and white), and four possible numbers (1, 2, 3, 4). Thus an example sentence is “Ready Charlie go to blue two now”. Target sentences were spoken by four male talkers. Three talkers were native British-English whilst one was a native Irish talker. Thus there were a total of 512 sentences (8 call signs x 4 colours x 4 numbers x 4 talkers). In the short-duration condition only the ‘Ready CALL-SIGN’ portion of the sentence was presented. In the medium-duration condition the full sentence was presented twice with the second instance presented immediately after the first. In the long-duration condition the sentence was repeated continuously until the participant made a response (up to a maximum of 7 presentations, or 17.79 seconds). All sentences were normalised to the same total RMS power. The average presentation level of sentences when presented from 0°azimuth was 60.0 dB SPL. The presentation level was randomly roved from trial to trial by ±5dB.

#### *7.3.2.5 Procedure*

On each trial the target sentence was presented from one loudspeaker. Throughout each condition the target sentence was presented from each of the possible locations 5 times resulting in 25 (front-only condition) or 50 (front-and-back condition) trials. The location of the target was randomly selected on each trial. Prior to the experimental conditions, a practice run was included of a movement-permitted, front-and-back-long-duration condition. Prior to each block, to familiarise participants with the condition, a brief practice period was included where stimuli were presented from each possible location once.

For each trial the participant had two tasks:

1. As soon as they knew *where* the sound was coming from they were instructed to press a button on a handheld Nintendo Wii Remote. This was used as a measure of response latency.
2. They then indicated where they judged the sound to be coming from, using a touchscreen in front of them which had labels indicating the possible locations (A-J, see Figure 7.13). In addition, a '?' button was also displayed which participants could use if they were unable to judge where the sound was coming from. These responses were scored to provide a measure of accuracy of localisation.

At the end of each condition participants rated how much listening effort they had needed to expend on a scale from 0 ('None at all') to 100 ('Extremely great' amount of effort).

#### 7.3.2.6 Analyses

Individual trials were excluded from the analysis if the there was a gap in the head tracking recordings for 300ms or more. Any trials in the "head-movement-not-permitted" conditions that had head movements greater than ±5 ° were excluded. Head movement trajectories were smoothed with a 50ms Hanning window as described in Section 7.1.2.2.

To ensure that measurements by the head tracking equipment matched where the participant was actually facing, the head tracking equipment was calibrated immediately before and immediately after each condition. For this, a light was presented below loudspeakers A to E in turn from left to right and back to left. The participant was instructed to turn to face the light and then when satisfied that their nose was pointing at it, press a handheld response button. After a response was made the next light was presented. The mean yaw head orientations when the participant responded to a light at 0° azimuth (4 instances per condition) were extracted and averaged to produce a calibration yaw. This value was used to correct each recorded head position for that condition as described in section 7.1.2.2.

Outcome measures and a corresponding description are shown in Table 7.6. For all outcome measures (except listening effort), only data from participants who had 40% or more of trials included were included in the group analyses. As not all conditions by all CI users met this criterion, fixed effects linear mixed models were calculated with maximum likelihood estimation. All pairwise comparisons reported are Bonferroni corrected.

**Table 7.6. Description of outcome measures.**

| Outcome measure | Definition |
|---|---|
| Accuracy | Percent correct. |
| Number of unknown responses | Number of trials where participants responded with a '?' to indicate they did not know where the target was located. |
| Same-sector error | Error made within the same half of auditory space as the target. |
| Number of front-back confusions | Number of trials in which a target in the front sector was perceived as coming from the back sector (and vice versa). |
| Angular error | RMS error of participant response after correcting for front-back confusions. |
| Latency to respond | The time (seconds) taken from the target onset until the participant pressed the response button. |
| Length of movement | Absolute length of the head trajectory (°). |
| Maximum velocity | Maximum speed (°/s) at which the participant moved during a trial. The average maximum velocity from each participant for each condition was calculated. |
| Reversals | A change in the direction of head movement (e.g. a change from leftward movement to rightward movement) was counted as a 'reversal'. The number of reversals per trial was counted and an average per participant for each condition was calculated. |
| Listening effort | Rating on a scale from zero ("No effort") to 100 ("Extremely great amount of effort"). |

### 7.3.3 Results

One NH participant was excluded from the analysis due to a lack of data recorded from the head tracking equipment. The remaining participants were included in the following analyses.

#### *7.3.3.1 Accuracy*

Percent correct

The percentage of correct trials were calculated for each participant in each condition. Figure 7.14 shows the mean localisation accuracy for each group averaged across duration conditions.

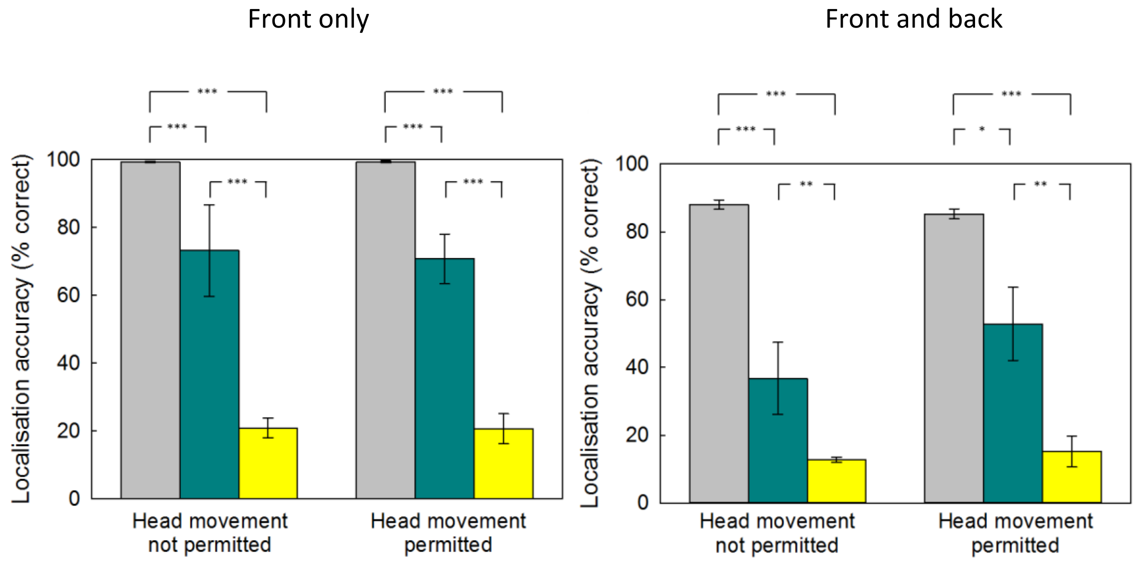


**Figure 7.14. Mean localisation accuracy for NH listeners (grey bars), bilateral CI users (green bars) and unilateral CI users (yellow bars) in the front-only condition (left figure) and front-and-back condition (right figure). Error bars show ±1SE. Asterisks indicate significant differences between the groups (*** p<.001, ** p<.01).**

A linear mixed model analysis was performed with fixed effects of group (3 levels), direction (2 levels), duration (3 levels), and movement (2 levels). Significant main fixed effects were found for each factor except movement. A significant group by direction by duration by movement interaction was also found (see Table 7.7). The four way interaction was examined by investigating the simple effects of each factor at all combinations of the other three factors.

**Table 7.7. F test results from mixed linear model investigating localisation accuracy. Significant effects are emboldened.**

| Tests of fixed effects | F | df | p |
|---|---|---|---|
| **Group** | **1860.134** | **2,329** | **<.001** |
| **Direction** | **160.929** | **1, 330.037** | **<.001** |
| **Duration** | **3.347** | **2, 218.035** | **.037** |
| Movement | 3.136 | 1, 330.037 | .077 |
| **Group x direction x duration x movement** | **2.432** | **4, 217.394** | **.049** |

### Simple effect of group

A simple effect of group was found to be significant at all combinations of the other three factors (all p<.001). Pairwise comparisons showed that NH listeners were significantly more accurate than bilateral CI users and unilateral CI users at all combinations of the other three factors (all p<.05). In addition bilateral CI users were significantly more accurate than unilateral CI users at all combinations of the other three factors (all p<.01).

### Simple effect of movement

For the NH listeners, no simple effect of movement was found (all $p>.05$). For the bilateral CI users a simple effect of movement was found in the front-only-short-duration condition ($p=.028$) and the front-and-back-long-duration condition ($p=.001$). Pairwise comparisons revealed that in the front-only-short-duration condition, accuracy was significantly higher when head movements were not permitted but in the front-and-back-long-duration condition, accuracy was significantly better when head movements were permitted. For the unilateral CI users the simple effect of movement was found in the front-only-short-duration condition with more accurate performance when head movements were permitted ($p=.016$).

### Simple effect of direction

For the NH listeners, the simple effect of direction (more accurate performance in the front-only condition) was evident at all combinations of the other factors (all $p<.001$). For the bilateral CI users the simple effect of direction was significant at all combinations of other factors (all $p<.001$) except the head-movement-permitted-long-duration condition ($p=.542$). For unilateral CI users, the simple effect of direction was only evident in two combinations of conditions; head-movement-not-permitted-medium-duration ($p=.007$), and head-movement-permitted-long-duration ($p=.040$).

### Simple effect of duration

For the NH listeners there was no simple effect of duration at any combination of conditions (all $p>.05$). For the bilateral CI users, the simple effect of duration was evident in the front-only-head-movement-not-permitted condition ($p=.003$). Pairwise comparisons revealed that accuracy was significantly better in the short-duration condition than the medium-duration and long-duration conditions ($p=.017$ and $p=.018$ respectively, see Table 7.8). No significant difference between the medium-duration and long-duration conditions was found. In addition for the bilateral CI users the simple effect of duration was evident in the front-and-back-head-movement-permitted condition ($p<.001$). Pairwise comparisons revealed that accuracy was significantly better in the long-duration condition than the short-duration and medium-duration conditions ($p=.001$, and $p=.002$ respectively). For unilateral CI users, the simple effect of duration was only evident in the front-only-head-movement-not-permitted condition ($p=.001$). Pairwise comparisons revealed that accuracy in the short-duration condition was significantly worse than accuracy in the medium-duration and long-duration conditions ($p=.008$, and $p=.010$, respectively).

**Table 7.8. Mean percent correct localisation accuracy for bilateral and unilateral CI users in both direction and movement conditions across the three duration conditions. SD in parentheses.**

| | | Head movement not permitted | | | Head movement permitted | | |
|---|---|---|---|---|---|---|---|
| | | Short | Medium | Long | Short | Medium | Long |
| Bilateral | Front-only | 83.09 (14.87) | 67.04 (30.12) | 69.39 (25.56) | 72.63 (19.16) | 72.58 (24.94) | 67.00 (17.09) |
| | Front-and-back | 33.74 (12.19) | 42.24 (10.97) | 42.76 (27.25) | 44.82 (22.94) | 43.42 (18.72) | 70.54 (14.73) |
| Unilateral | Front-only | 11.46 (6.25) | 26.80 (10.85) | 24.25 (5.68) | 22.52 (14.92) | 18.18 (7.13) | 28.75 (12.37) |
| | Front-and-back | 11.03 (7.35) | 12.05 (4.67) | 15.16 (7.65) | 15.10 (3.37) | 14.32 (10.97) | 16.14 (13.73) |

## Types of error

The following sub-sections focus on only the error trials.

### *Front-only condition*

NH listeners performed at ceiling. All errors made by bilateral CI users were same sector errors. The majority of errors by unilateral CI users were in the same sector (see Table 7.9) however they did use the unknown response occasionally.

**Table 7.9. Percentage of error trials made by unilateral CI users in the front-only conditions due to same sector errors. SD in parentheses.**

| Head movement not permitted | | | Head movement permitted | | |
|---|---|---|---|---|---|
| Short | Medium | Long | Short | Medium | Long |
| 82.88 (21.16) | 82.88 (21.16) | 82.88 (21.16) | 90.63 (18.75) | 90.63 (18.75) | 90.63 (18.75) |

### *Front-and-back condition*

The majority of errors made by NH listeners in the front-and-back condition were same-sector errors, whereas about half of the errors made by CI users were front-back confusions (see Table 7.10).

**Table 7.10. Percentage of error trials that were due to a front-back confusion and 'unknown location' responses by the three groups of participants in the front-and-back conditions. The rest of the error trials were same sector errors. SD in parentheses.**

| | | Head movement not permitted | | | Head movement permitted | | |
|---|---|---|---|---|---|---|---|
| | | Short | Medium | Long | Short | Medium | Long |
| NH listeners | Front-back error | 9.14 (17.48) | 1.39 (6.80) | 5.02 (20.47) | 2.69 (7.97) | 1.45 (6.95) | 1.11 (4.25) |
| | Unknown location response | 0 | 0 | 0 | 0 | 0 | 0 |
| Bilateral CI users | Front-back error | 58.54 (9.45) | 50.38 (10.63) | 63.82 (11.67) | 45.47 (9.01) | 21.79 (25.61) | 0 |
| | Unknown location response | 0 | 0 | 0 | 0 | 0 | 0 |
| Unilateral CI users | Front-back error | 44.76 (17.15) | 50.60 (19.18) | 46.29 (5.81) | 45.64 (9.86) | 30.74 (20.81) | 32.29 (21.59) |
| | Unknown location response | 14.67 (29.35) | 13.69 (25.82) | 0 | 8.39 (13.66) | 4.89 (9.78) | 5.11 (10.23) |

*Did the proportion of front back errors differ by condition?*

A 3 (group) by 3 (duration) by 2 (movement) mixed linear model found a significant main effect of group (F(2,118.960) = 143.845, p<.001), duration (F(2,84.959) = 4.276, p=.017) and movement (F(1, 118.567) = 35.703, p<.001) and a significant group by duration by movement interaction (F(4,84.715) = 3.467, p<.001). The interaction was investigated by examining the simple effects of each factor at each combination of the other factors.

Simple effect of group:

The simple effect of group was significant at each combination of the other factors (all p<.01). Pairwise comparisons showed that the proportion of errors that were front-back confusions was significantly lower for NH listeners than unilateral CI users (all p<.01). and bilateral CI users in all but one condition (all p<.05 except the head-movement-permitted-long-duration condition where p>.05). No differences between bilateral and unilateral CI users were found except in the head-movement-permitted-long-duration condition where the proportion of errors that were front-back confusions was significantly higher for unilateral CI users (p<.001).

Simple effect of duration:

The simple effect of duration was significant only for unilateral and bilateral CI users in the head-movement-permitted condition. Pairwise comparisons demonstrated that for unilateral CI users the effect did not survive Bonferroni correction. For bilateral CI users, significantly more front-back confusions were made in the short-duration condition than the medium- duration and long-duration conditions (both $p<.01$), and significantly more in the medium-duration condition than the long-duration condition ($p<.05$).

Simple effect of movement:

The simple effect of movement (fewer errors made when head movements were permitted) was significant for unilateral and bilateral CI users in the medium-duration condition and bilateral CI users only in the long-duration condition (all $p<.01$).

*Angular error*

Focusing on the error trials only, this section sought to ascertain what the RMS error was after correcting for front-back errors. Of those trials in which a front-back error was made, this was corrected for by projecting the response from one hemifield to the other (for instance a front-back error in which a -165° response was made was converted to a -15° response). A 3 (group) by 2 (direction) x 3 (duration) by 2 (movement) mixed linear model found a significant main effect of group ($F(2,72.182) = 584.841$, $p<.001$) with pairwise comparisons revealing significantly lower RMS error for NH listeners (mean = 14.51°, SE = .335) than both CI groups. Furthermore, bilateral CI users (mean = 21.04°, SE = .36) had significantly lower RMS errors than unilateral CI users (mean = 31.28°, SE = .36). A significant interaction between group and direction ($F(2,72.182) = 4.840$, $p=.011$) was also found. The interaction was investigated by examining the simple effects of each factor at each level of the other factor. The simple effect of group was found for both directions (all $p<.001$). A simple effect of direction was found only for bilateral CI users, with a slight but significantly higher RMS error in the front-only condition (mean = 22.09°, SE = .66) than the front-and-back condition (mean = 20.00°, SE = .39, $p=.008$).

#### *7.3.3.2 Latency to respond*

The mean latency to respond to each condition by each group is shown in Table 7.11. A 3 (group) by 2 (direction) x 3 (duration) by 2 (movement) mixed linear model found a significant main effect of group ($F(2,224.918) = 782.658$, $p<.001$), direction ($F(1,226.217) = 30.132$, $p<.001$), duration ($F(2,166.211) = 294.259$, $p<.001$) and movement $(1,226.217) = 10.075$, $p=.002$). The main effect of movement showed that latency to respond was significantly slower in the head-movement-permitted condition (mean = 3.10s, SE = .074) than the head-movement-not-permitted condition (mean = 2.81s, SE = .06). A significant group by direction by duration interaction was found (F(4, 187.913) = 3.438, p=.010). The interaction was investigated by examining the simple effects of each factor at each combination of levels of the other factors.

Simple effect of group:

The simple effect of group was significant at each combination of the other factors (all p<.001). Pairwise comparisons demonstrated that latency to respond by NH listeners was significantly faster than unilateral and bilateral CI users at all levels (all p<.001). In the front-only condition, unilateral CI users were significantly slower to respond than bilateral CI users in the short-duration condition, but were significantly faster to respond in the long-duration condition.

Simple effect of direction:

The simple effect of direction (faster to respond in the front-only condition) was found for the NH listeners at all duration levels (all p<.01), unilateral CI users for the long-duration condition (p=.004) and bilateral CI users for the short-duration and medium-duration conditions(both p<.01).

**Table 7.11. Mean latency to respond (seconds) by the three groups of listeners in the twelve listening conditions. SD in parentheses.**

| | | Head movement not permitted | | | Head movement permitted | | |
|---|---|---|---|---|---|---|---|
| | | Short | Medium | Long | Short | Medium | Long |
| NH listeners | Front-only | .72 (.27) | .79 (.41) | .73 (.44) | .76 (.31) | .79 (.35) | .73 (.28) |
| | Front-and-back | .90 (.30) | 1.06 (.40) | 1.10 (.34) | 1.03 (.28) | 1.45 (.65) | 1.54 (.77) |
| Bilateral CI users | Front-only | 1.30 (.12) | 3.91 (.46) | 5.00 (1.41) | 1.56 (.84) | 3.96 (.70) | 5.99 (1.92) |
| | Front-and-back | 2.23 (.05) | 5.00 (.35) | 4.74 (.64) | 2.05 (.72) | 5.43 (1.77) | 5.50 (2.09) |
| Unilateral CI users | Front-only | 2.23 (.87) | 4.14 (1.41) | 4.75 (1.73) | 2.27 (.73) | 4.95 (1.14) | 3.90 (.04) |
| | Front-and-back | 2.29 (.29) | 4.52 (.93) | 4.99 (.76) | 2.60 (.69) | 5.15 (.98) | 6.09 (2.07) |

Simple effect of duration:

The simple effect of duration was found in the front-and-back condition for NH listeners ($p=.002$) but not the front-only condition. Pairwise comparisons revealed that latency to respond in the short-duration condition was significantly faster than both medium-duration and long-duration conditions (both $p<.05$), however there was no difference between medium-duration and long-duration conditions. The simple effect of duration was found for both direction conditions by unilateral and bilateral CI users (all $p<.001$). Pairwise comparisons revealed that for unilateral CI users, latency to respond was significantly faster in the short-duration condition than the medium and long-duration conditions for both directions (all $p<.001$). However, no difference between medium and long-duration conditions was found. For bilateral CI users latency to respond was significantly faster in the short-duration condition than the medium-duration and long-duration conditions for both directions (all $p<.001$). Latency to respond in the medium-duration condition was significantly faster than the long-duration condition for the front-only ($p<.001$) condition but there was no significant difference in the front-and-back condition.

#### *7.3.3.3 Movement trajectory*

Figure 7.15 shows the head movements made by one representative NH listener, one bilateral CI user and one unilateral CI user in the front-only condition when head movements were permitted. Little movement was made by the NH listener in any of the three duration conditions. However, when more time was available the bilateral CI user made use of it, turning to the left and right periphery. The unilateral CI user also made use of the extra time available though they did not turn as far as the bilateral CI user shown. The head movement trajectories made by the same listeners in the front-and-back condition are displayed in Figure 7.16. This time listeners made larger head movements (as shown by the larger range on the y axis). When time was available for a head movement to be completed whilst the stimulus was still presented, the NH listener turned their head in the direction of the target in a smooth manner. The bilateral CI user initially made a head movement in the direction of the target but then moved their head to the other side of the hemispace before returning to the hemispace containing the target location. The unilateral CI user made fewer movements into the far periphery, rather the majority of the head movements were within the hemispace in which their implanted ear was on. The following sections seek to quantify the complexity of the head movements made in terms of the number of reversals in head movement made, the length of movement, and the maximum velocity.

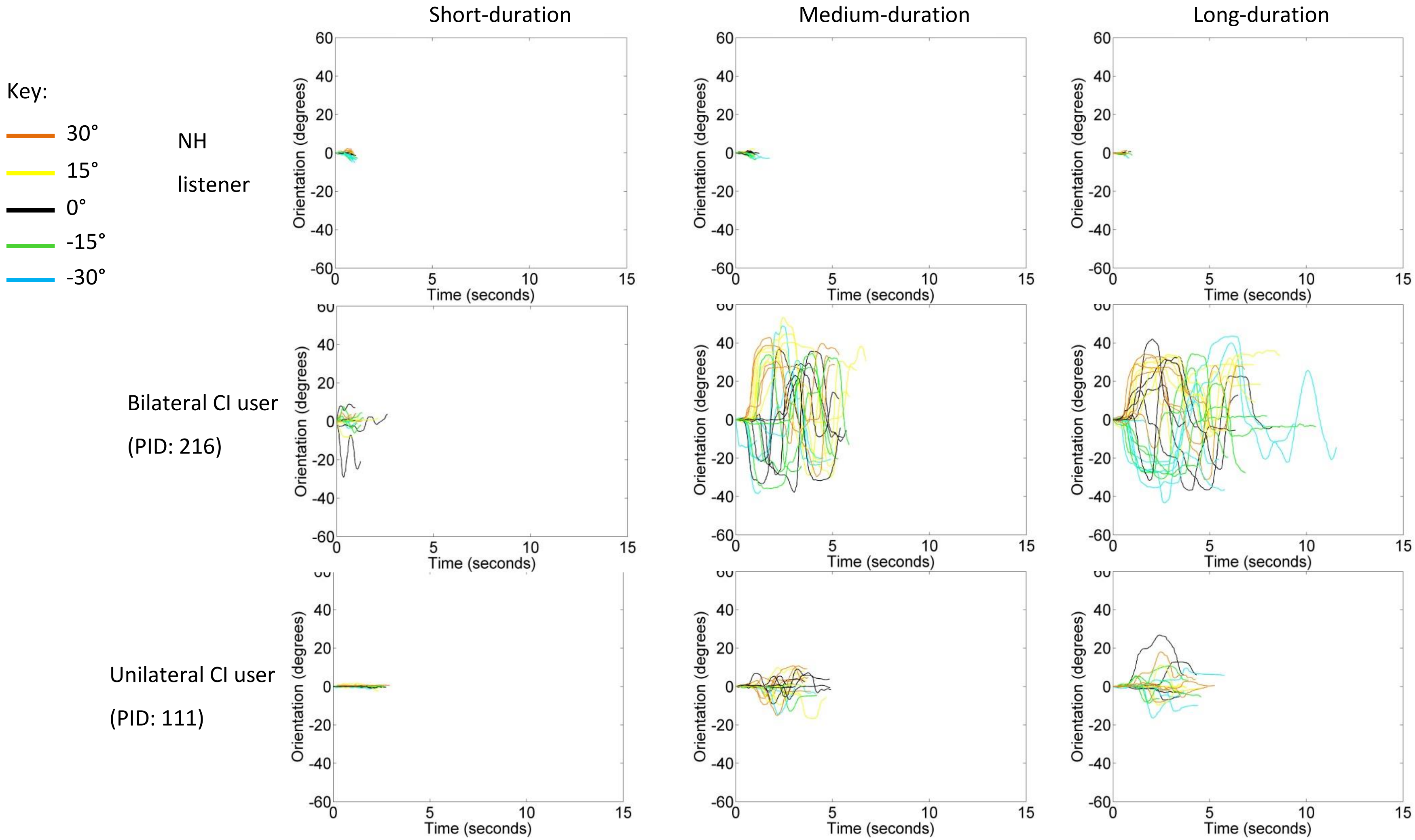


**Figure 7.15. Head movement trajectories in the front-only condition by a representative NH listener, a bilateral CI user and a unilateral CI user in the short, medium and long-duration conditions. Each line represents one trial. The colour of the line indicates the target location for that trial (see key).**

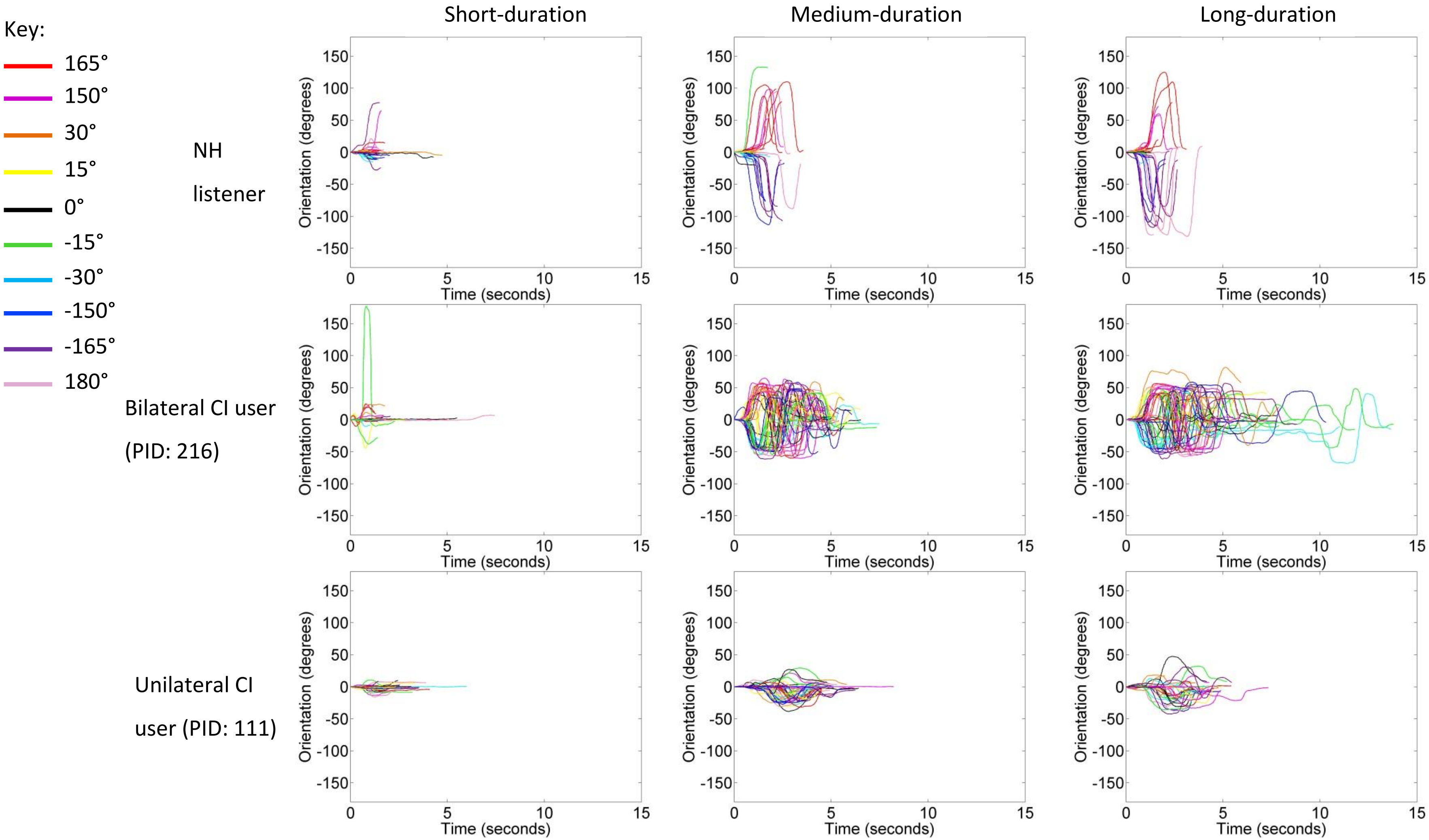


**Figure 7.16. Head movement trajectories in the front-and-back condition by a representative NH listener, a bilateral CI user and a unilateral CI user in the short, medium and long-duration conditions. Each line represents one trial. The colour of the line indicates the target location for that trial (see key).**

Reversals

The mean number of reversals per trial for the three groups collapsed across duration is displayed in Figure 7.17. A 3 (group) by 2(direction) by 3 (duration) mixed linear model was conducted. Significant fixed effects of group ($F(2,126.035) = 126.277$, $p<.001$) and duration ($F(2,91.945) = 36.143$, $p<.001$) were found. A significant group by direction by duration interaction was found ($F(4,109.056) = 3.674$, $p=.008$). The interaction was investigated by examining the simple effects of each factor at each combination of levels of the other factors.

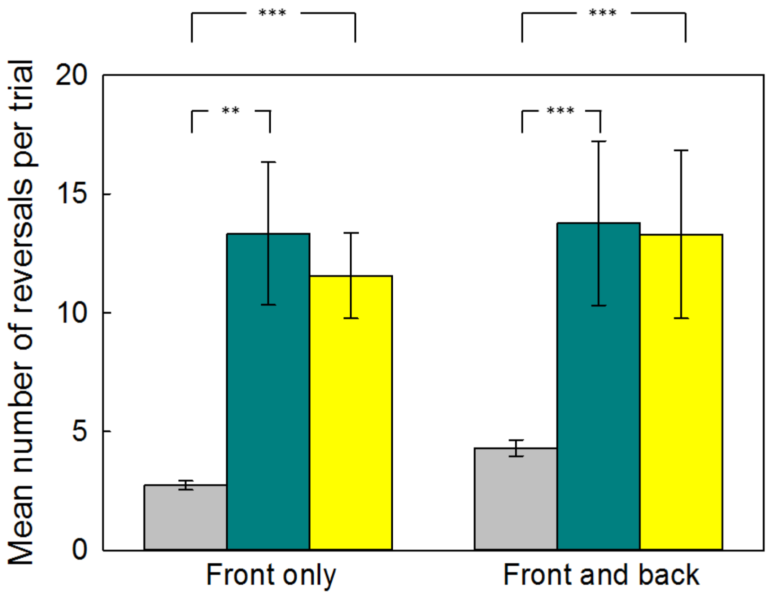


**Figure 7.17. Mean number of reversals per trial for NH listeners (grey bars), bilateral CI users (green bars) and unilateral CI users (yellow bars) in the movement-permitted-front-only condition (left) and movement-permitted-front-and-back condition (right). Error bars show ±1SE. Asterisks indicate significant differences between the groups (*** p<.001, ** p<.01).**

*Simple effect of group:*

The simple effect of group was significant at each combination of the other two factors (all $p<.001$). Pairwise comparisons showed that NH listeners made significantly fewer reversals than unilateral CI users at all combinations (all $p<.001$) except the front-only-long-duration condition ($p=.051$). NH listeners made fewer reversals than bilateral CI users at all combinations (all $p<.05$). Unilateral CI users made significantly fewer reversals than bilateral CI users in the front-only-long-duration condition ($p=.013$). No other significant differences were found.

*Simple effect of direction:*

Bilateral CI users made significantly more reversals in the front-and-back condition in the medium-duration condition ($p=.030$) but significantly fewer reversals in the front-and-back condition for the long-duration condition ($p=.013$). No other significant differences were found.

*Simple effect of duration:*

The simple effect of duration was found in both direction conditions for unilateral CI users (both $p=.001$) and bilateral CI users (both $p<.001$). Pairwise comparisons showed that for unilateral CI users in both directions, significantly fewer reversals were made in the short-duration condition than the medium-duration condition (both $p<.001$). Furthermore, unilateral CI users made significantly fewer reversals in the short-duration condition than the long-duration condition in the front-and-back condition ($p=.003$). For bilateral CI users in both direction conditions significantly fewer reversals were made in the short-duration condition than the medium-duration condition (both $p<.01$). In the front-only condition, significantly fewer reversals were made in the medium-duration condition than the long-duration condition ($p=.005$) and significantly fewer reversals were made in the short-duration condition than the long-duration condition ($p<.001$).

### Length of movement per trial

The mean length of movement per trial for the three groups collapsed over duration is displayed in Figure 7.18. A 3 (group) by 2(direction) by 3 (duration) mixed linear model was conducted. Significant fixed effects of group ($F(2,91.511) = 26.799$, $p<.001$), direction ($F(1,91.056) = 13.128$, $p<.001$), and duration ($F(2,78.643) = 20.107$, $p<.001$) were found. A significant two way interaction was observed (group x duration: $F(4,79.452) =6.262$, $p<.001$).The interaction was investigated by examining the simple effects of each factor at each combination of the other factor.

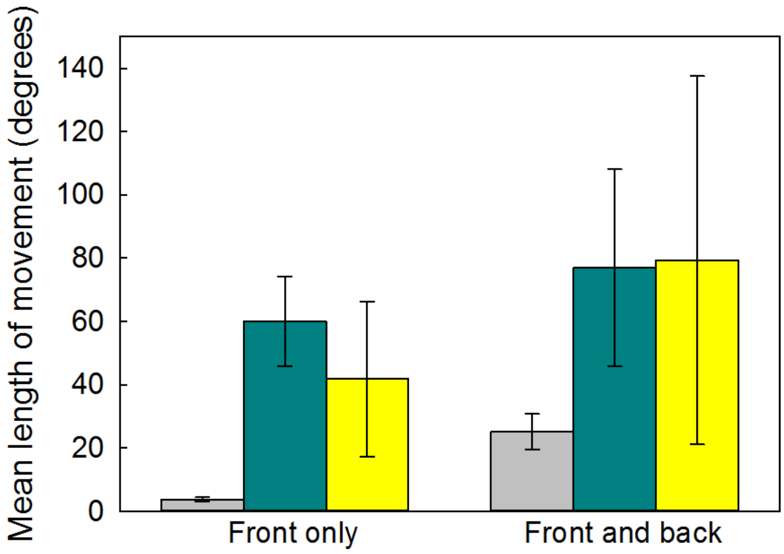


**Figure 7.18. Mean length of head movement per trial for NH listeners (grey bars), bilateral CI users (green bars) and unilateral CI users (yellow bars) in the head-movement-permitted-front-only condition (left) and the head-movement-front-and-back condition (right). Error bars show ±1SE.**

The simple effect of group was found at all levels of duration (all $p<.05$). Pairwise comparisons showed that length of movement was significantly shorter for NH listeners than unilateral CI users at all three durations (all $p<.05$). Movement was significantly shorter for NH users than bilateral CI users in the medium-duration ($p=.004$) and long-duration ($p<.001$) conditions. There was no difference between unilateral and bilateral CI users. The simple effect of duration was significant for unilateral and bilateral CI users (both $p<.01$) but not NH listeners. Pairwise comparisons demonstrated that for unilateral CI users, length of movement was significantly shorter in the short-duration condition than the medium-duration condition ($p=.016$). For bilateral CI users length of movement in the short-duration condition was significantly shorter than both medium-duration ($p=.005$) and long-duration ($p<.001$) conditions.

### Maximum velocity

A 3 (group) by 2(direction) by 3 (duration) mixed linear model was conducted. Significant fixed effects of group ($F(2,99.802) = 18.237$, $p<.001$), direction ($F(1,99.334) = 14.921$, $p<.001$) and duration ($F(2,82.189) = 5.190$, $p=.008$) were found. Pairwise comparisons revealed that the mean maximum velocity of movement by NH listeners (mean = 34.83°/s, SE = 3.645) was significantly slower than unilateral (mean = 59.26°/s, SE = 9.05) and bilateral (mean = 95.89°/s, SE = 9.93) CI users. Maximum velocity was significantly faster in the front-and-back condition (mean = 81.25°/s, SE = 8.85) than the front-only condition (mean = 45.40°/s, SE = 2.80). Pairwise comparisons revealed that the mean maximum velocity was significantly slower in the short-duration condition than the medium-duration condition (p=.034) and long-duration condition (p=.028). No interactions were observed.

#### *7.3.3.4 Listening effort*

A3 (group) by 2(direction) by 3 (duration) by 2 (movement) mixed linear model was conducted on listening effort ratings. A significant fixed effect of group ($F(2,358.656) = 36.033$, $p<.001$) was found. Pairwise comparisons revealed that listening effort ratings were significantly lower (less effort) for NH listeners (mean = 44.12, SE = 1.50) than unilateral (mean = 56.32, SE = 3.35) and bilateral (mean = 81.58, SE = 4.33) CI users (both $p<.001$). Furthermore, listening effort by bilateral CI users was significantly higher (more effort) than unilateral CI users ($p<.001$). A significant main effect of direction ($F(1,358.656) = 13.983$, $p<.001$) was also found, with higher listening effort ratings in the front-and-back condition. No other significant main effects or interactions were observed.

### 7.3.4 Discussion

#### *7.3.4.1 Accuracy*

As expected, localisation accuracy by unilateral CI users was significantly poorer than bilateral CI users and NH listeners. Furthermore, accuracy by bilateral CI users was significantly worse than NH listeners. This pattern is consistent with previous research (see Chapter 2) which has demonstrated that whilst localisation with bilateral CIs is better than with one CI, performance does not reach NH levels. This is likely due to the bilateral CI users having restricted access to the cues which NH listeners use. Whilst bilateral CI users have good access to ILDs they are limited in their ability to use ITDs due to the restricted ability of CIs to encode temporal information (Laback, Majdak, & Baumgartner, 2007; van Hoesel, Ramsden, & O'Driscoll, 2002). Furthermore, they have to integrate the signals from two different processors, and from electrodes which may have been installed to different depths and which may not have been mapped identically, which could impair performance.

NH listeners did not benefit from head movement in the front-only condition as they were already at ceiling when movement was not permitted. This result is consistent with Cooper, Carlile, and Alais (2008) who found NH listeners can localise sound sources in the frontal plane within ±30° very well without movement. NH listeners in the present study did perform worse in the front-and-back condition than the front-only condition. Cooper et al. (2008) found that NH listeners made more location errors in the rear than in the front. They presented a visual stimulus to the left or right (in the frontal hemifield) and the participant’s task was to turn rapidly to this location. During the head turn a 0.8 second stimulus was presented from one of 74 locations around the participant. More errors for locations in the rear hemifield were found and the authors suggested this was due to the visual target (in frontal horizontal plane) capturing attention resulting in better spatial attention in this area. Whilst the present study used the same length of stimulus (in the short-duration condition) as Cooper et al., movement in the present study did not start until after the onset of the target whereas in Cooper et al.'s study movement had already been initiated before the onset of the stimulus. However, the present study did not use a visual stimulus, therefore the attentional facilitation effect proposed by Cooper et al. cannot explain why accuracy performance in the front-and-back condition was worse than the front-only condition.

Mixed findings were observed on the effect of movement with the bilateral CI users: In the front-only condition, listeners performed more accurately when head movements were not permitted (only significant for the short-duration condition), whereas in the front-and-back condition performance was better when head movements were allowed (only significant for the long-duration condition). The effect in the front-only-short-duration condition could be due to head movements impairing performance when there is insufficient time to complete a movement. For instance, Mueller et al (2014) encouraged bilateral CI users to make head movements when locating the source of a short stimulus (0.5 seconds). However, some listeners reported that performance was hindered when making head movements due to the short-duration of the stimulus. The short-duration stimulus in the present study was a little longer at 0.8 seconds therefore bilateral CI listeners may have begun a head movement before the stimulus ceased. The present study used a blocked design so participants knew in advance how long each stimulus would be. However, it may be that failure to complete a movement actually worsened performance. The mean length of movement by bilateral CI users in the front-only-short-duration condition was 15.21° (SD = 10.36) demonstrating that they did make a movement in this condition. However, this explanation does not extend to unilateral CI users. Based on previous research, it had been hypothesised that unilateral CI users would not benefit from head movements. However, unilateral CI users did benefit from head movements in the front-only-short-duration condition with an accuracy of 23% compared to 12% when head movements were not permitted. Whilst this was a significant improvement, performance was still poor, near the chance level of 20% correct. Performance might have been below chance in the front only short-duration condition when head movements were not permitted because unilateral CI users were less willing to make a guess of the location in this condition. This is shown in Table 7.9, with more unknown responses when head movements were not permitted. By selecting a target location unilateral users have a one in five chance of selecting the correct answer, which is not the case when participants select the 'unknown' response.

Front-back confusions

It had been hypothesised that both NH listeners and bilateral CI users would make fewer front-back confusions when head movements were permitted when the stimulus was long enough to make a head movement (medium-duration and long-duration conditions). This was not found for NH listeners. NH listeners made few errors and whilst the proportion of errors that were front-back confusions in the head movement conditions were overall numerically less than in the head-movement-not-permitted condition (see Table 7.10)., there was no significant simple effect of duration or movement. This is likely due to the small numbers of errors made.

However, the hypothesis was supported for bilateral CI users. When head movement was permitted, bilateral CI users benefitted from additional time, and made significantly fewer front-back confusions as the length of the stimulus increased; from 45% in the short-duration condition, to 22% in the medium-duration condition and to no front-back errors in the long-duration condition (see Table 7.10). Furthermore, bilateral CI users benefitted from head movements with fewer front-back confusions made in the head-movement condition than the head-movement-not-permitted condition for medium-duration and long-duration stimuli. As expected, the effect was not found for short stimuli. This could be due to insufficient time to make informative head movements whilst the stimulus is being presented. For instance, the stimulus in the short-duration condition was about 0.8 seconds in duration yet bilateral CI participants required, on average, a total duration of 1.3 seconds (front-only condition) to respond (see Table 7.11).

#### *7.3.4.2 Latency to respond*

NH listeners responded faster than both CI groups. This could be due to better hearing or other differences between the groups. One confounding factor is age, with the CI users being much older than the NH listeners. The implications of this difference on reaction times were discussed in detail in Section 7.2.6. so will be acknowledged here but not discussed further. The CI users may have taken longer to respond due to being less certain than the NH listeners of the location of the stimulus. The bilateral CI users could have made use of the extra time available to integrate information from both processors, to make more movements (when permitted to do so) to vary the ILDs to determine where the sound was presented from. Unilateral CI users could have used the extra time to make more movements to vary the level of the stimulus at their implanted ear. The movements made by listeners will be discussed in the next section.

In the majority of conditions there was no significant difference in response latency between the two CI groups. However, in the front-only conditions unilateral CI users took longer to respond than the bilateral CI users to stimuli with short-durations but responded faster in the long-duration conditions. Mean response time for both groups in the front-only-short-duration condition was after the stimulus had ceased. However, in the front-only-long-duration condition both groups responded within the time the stimulus was presented. The reason why unilateral users responded quicker may be that, despite additional time being available they were not getting sufficient information from the stimulus to determine its location as they do not have access to ILDs like the bilateral CI users. Therefore, they may have chosen to make a guess (as evidenced by their low accuracy results discussed in Section 7.3.4.1) whereas bilateral CI users made use of the extra time available using interaural level differences to help guide their decision.

NH listeners were faster to respond in the front-only condition than the front-and-back condition. This is likely due to a combination of the reduced number of response options in the front-only condition (five compared to ten) and listeners taking longer in the front-and-back condition to reduce the likelihood of front-back confusions occurring.

#### *7.3.4.3 Trajectory complexity*

Maximum velocity

In both direction conditions, the mean maximum velocity was slower for NH listeners (mean = 34.83°/s) than both CI user groups (bilateral mean = 95.89°/s; unilateral mean = 59.26°/s). NH listeners made less use of head movements than CI users with fewer reversals and shorter head movements (discussed in detail below). With fewer search like movements there was less opportunity to move the head at a fast speed like the CI users did. CI users may have been using rapid head turns to vary the level of the signal at the CI (unilateral CI users) or vary the ILD (bilateral CI users) or to reach a position for which the ILD could be maximised (bilateral CI users). However, rapid head turns have been shown to distort cues (such as interaural differences) listeners use to locate sound sources. Cooper et al. (2008) instructed NH listeners to turn rapidly towards a visual stimulus located to their left or right in the frontal horizontal plane. During the head turn a 0.8 second stimulus was presented from one of 74 locations around the participant. They found that localisation performance with rapid head turns was worse than no movement particularly for sources in the middle of the frontal horizontal plane (such as the locations used in the present study). The possibility of distorted spatial cues from rapid head turns could a possible explanation for poorer performance by CI users as they made faster head turns than NH listeners.

### Reversals

NH listeners made fewer reversals than either CI group. This result is consistent with the findings reported in Section 7.2.5.1. Furthermore, CI users made use of extra time when it was available making more reversals in the medium-duration and (sometimes) long-duration conditions than the short-duration conditions. This result is also consistent with the results reported in Section 7.2.5.1. where both CI groups made more reversals in a continuous stimulus condition than a short (1.3 second) stimulus condition. The finding is also consistent with Mueller et al. (2014) who found bilateral CI users made more head turns away from the target location than NH listeners for all stimulus durations tested.

### Extent of movement

NH listeners made less extensive movements than unilateral CI users at all durations and less extensive movements than bilateral CI users in the medium-duration and long-duration conditions. This result is not consistent with the results from the experiment reported in Section 7.2. In that experiment there was no difference in the length of movement made by bilateral CI users and NH listeners when the stimulus was long. The reason why a difference between these groups was found in the present study could be because of the locations of the sources (with some being behind the listeners). Support for this suggestion can be found in the study reported by Mueller et al. (2014). In their study they conducted a sound localisation task using a 360° array of loudspeakers and found that the extent of head movements made by bilateral CI users was significantly greater than NH listeners for a 4.45 stimulus (the longest used in their experiment and slightly shorter than the medium-duration condition stimulus used in the present study) but there was no difference for stimuli of 0.5s and 2.18s in duration. This pattern of results is consistent with the present study's finding of no difference in the extent of movement made between bilateral CI users and NH listeners for the short-duration stimulus, which at 0.8 seconds was in between the two durations used by Mueller et al.

There was no difference in the extent of movement between unilateral and bilateral CI users. Both CI groups made use of extra time when it was available, making longer movements in the medium-duration condition than the short-duration condition. However, despite this similarity, performance by the bilateral CI users was significantly better than unilateral CI users (as discussed in 7.3.4.1).

### Reasons for increased movement complexity

Similar to the discussion in Section 7.2.6.4 it is difficult to distinguish between an uncertainty explanation and a learned behavioural response explanation for increased head movement complexity. Mueller et al. (2014) argued that the reason why bilateral CI users made more complex head movements than NH listeners was due to uncertainty in the location of the stimulus. This could explain why the unilateral and bilateral CI users who took part in the present study displayed more complex head movement trajectories than the NH listeners. CI users may have used head movements to vary the loudness at the CI (unilateral CI users) or vary the ILD (bilateral CI users) in an attempt to reduce the uncertainty. However, Brimijoin, McShefferty, and Akeroyd (2010) found moderately hearing impaired listeners made more complex head movements than NH listeners in a sound orientation task and they suggested this could be a learned behavioural response to extract as much information as possible from the environment. This too could explain the results of the present study. However, as discussed in Section 7.2.6.4 it is difficult to separate these two explanations given the data available.

#### *7.3.4.4 Listening effort*

Listening effort ratings were not consistent with accuracy results. NH listeners displayed the least amount of listening effort , followed by unilateral CI users and then bilateral CI users. It was expected that NH listeners would require less listening effort than CI users due to having normal levels of listening ability. However, it was anticipated that unilateral CI users would find the task difficult, performing poorly, and therefore require more listening effort than bilateral CI users. Using the SSQ, Noble, Tyler, Dunn, and Bhullar (2008) compared self-ratings of listening effort between 70 unilateral CI users and 36 bilateral CI users and found that listening effort ratings were significantly higher (more effort) for unilateral CI users (mean = 5.1 on a 0-10 scale) than bilateral CI users (mean = 6.1). The listening effort rating in Noble et al.'s study was derived from answers to three questions which focused on concentration when listening to someone or something, when in conversation with others, and ignoring other sounds when trying to listen to something. The question used in the present study was less general and focused on the task the participant had just completed. The task was not easier for unilateral CI users as evidenced by their lower accuracy scores. It was suggested in Section 7.3.4.2 than unilateral CI users may have displayed giving up behaviour, ceasing to engage in the task as they could not do it. This could explain why listening effort ratings were lower. Bilateral CI users know that they ought to be able to localise with two devices and therefore they may have put effort into the task. On the other hand, unilateral CI users know that they should not be able to localise with just one device and therefore they do not put in as much effort.

As expected listening effort ratings were higher in the front-and-back condition than the front-only condition. This could be due to an increased number of possible responses (uncertainty).

However, it could also be due to the uncertainty in whether the stimulus was presented in front of or behind the listener. Indeed both unilateral and bilateral CI users had many trials resulting in front-back confusions (see Table 7.10).

#### *7.3.4.5 Strengths, limitations, and future research*

A strength of this study is that it assessed the impact of permitting head movement for sound source locations both in front of, and behind, the listener. The location of the loudspeakers enabled the potential benefit of head movements for reducing front-back confusions to be measured. However, the use of an unknown location response does not indicate to what degree of uncertainty participants perceived the sound as possibly coming from. Nevertheless, only the unilateral users made use of this response option and very few unknown location responses were made (see Table 7.10). Therefore it is unlikely to have influenced the findings. Similar to the previous experiment, this study is limited by insufficient power and age differences between the groups. These were discussed in detail in Section 7.2.6.5. This study has demonstrated that head movements can help bilateral CI users reduce the number of front-back confusions provided the stimulus is long enough. From the mean latency to respond data, this study suggests that the stimulus needs to be longer than 5 seconds for bilateral CI users to benefit.

It would be informative for future research to measure the certainty of participants in their response. This could shed light on whether certain locations are located with more confidence than others (for instance locations on the side of the CI for unilateral CI users). This could also attempt to disambiguate between an uncertainty explanation and a learned behavioural response explanation for increased head movement complexity. If increased head movement complexity was due to a learned behavioural response, head movement should be similar across certainty ratings. However, if increased head movement complexity was due to uncertainty, the amount and type of head movements made may differ across certainty ratings. This measure was not included in this study due to the experiment already encompassing several tasks for the participant (e.g. maintaining head position in the head movement not permitted conditions, responding to each trial with a handheld response button then responding using a touch screen). Having the additional confidence measure would have extended the 2 hour experimental session. With a longer session there were the risks of tiredness, fatigue, or disengagement with research tasks. This could be overcome in future studies by running multiple shorter sessions. CI users were already completing a four hour research session (or two 2-hour sessions which included the other two experiments reported in this chapter) therefore extending this experiment was not feasible within the time available.

#### *7.3.4.6 Conclusion*

In conclusion, unilateral CI users were unable to accurately locate the target location even when the stimulus was continuously repeated or when head movements were allowed. Head movements helped bilateral CI users by reducing the number of front-back confusions provided the stimulus was long enough. CI users made more complex head movements than NH listeners with more reversals, longer head movement trajectories, and faster movements. Listening effort was reduced in the front-only condition likely due to fewer location alternatives and no chance of front-back confusions occurring. Thus head movements have the potential to improve localisation performance for bilateral CI users.

### 7.3.5 Summary

- Localisation accuracy by NH listeners is at ceiling for sound sources in the frontal horizontal plane but is reduced when sources are located in both the front and rear horizontal plane.
- Unilateral CI users are unable to accurately localise the source of a sound.
- Bilateral CI users benefit from head movements when the stimulus is longer than 5 seconds in duration as front-back confusions are reduced.
- Both CI groups made more complex head movements than NH listeners with more reversals, longer head movement trajectories and faster head movements.
- Despite both CI groups making complex head movement trajectories, accuracy was significantly better for bilateral CI users.

## 7.4 Head orientation strategies for improving speech perception in noise

### 7.4.1 Introduction

When listening to speech in the presence of background noise, different head orientations can be adopted to potentially improve performance. Moving the head manipulates the level of a sound at each ear. In a speech in noise task, listeners may opt to orient to a position which maximises the level of the target at one or the other ear. However, changes in head orientation will also alter the noise level at each ear and thus the signal-to-noise ratio (SNR), therefore a more optimal head orientation may be to maximise the SNR. These two strategies were investigated by Brimijoin, McShefferty, and Akeroyd (2012) who monitored the direction in which asymmetrically moderately hearing impaired listeners oriented their head during a speech in noise task. In a blocked design, a target sentence was presented from one of five locations and speech-shaped noise was presented from one location which was separated from the target location by ±30°, ±90°, or 180°. If listeners sought to maximise the signal level, Brimijoin et al. (2012) demonstrated that the optimal head orientation strategy would be to turn to orient 60° to the side of the target irrespective of where the noise was presented from. If listeners opted to maximise the SNR Brimijoin demonstrated that they would need to orient differently depending on where the noise was presented from (relative to target: 0° for a separation of +30°, -150° for a separation of -30°, +35° for a separation of +90°, +155° for a separation of -90° and +65° for a separation of 180°). Brimijoin et al. (2012) found that listeners who had better hearing in their left ear oriented their head to the right of the target (median = +51.2°, IQR = +12.2° to +79.8°), whereas listeners who had better hearing in their right ear oriented their head to the left of the target (median -48.6°, IQR = -9.5° to -78.8°) irrespective of where the noise was presented from. This strategy served to maximise the signal level rather than the SNR.

Culling, Jelfs, Talbert, Grange, and Backhouse (2012) compared the benefits in spatial release from masking (SRM) from bilateral cochlear implantation to unilateral cochlear implantation in a modelling report. They modelled performance when speech and noise were presented concurrently at 0° azimuth and when speech was presented at 0° azimuth but noise was presented at +90° azimuth. Their model predicted that bilateral CI users would have an SRM of 3.5dB when facing the target. However, this could be increased to 7dB if the head was turned to the right by 20° or increased to 8.25dB if the head was turned to the right by 30°. A unilateral CI user (with a CI in the right ear) would need to turn to -150° to achieve the maximum benefit to SRM (about 10dB relative to looking at the target). Thus this model predicts that head orientation has the potential to improve performance. The current study sought to establish what orientation strategies NH listeners and unilateral and bilateral CI users adopt when completing a speech in noise task. Based on Brimijoin et al's findings it was expected that listeners would seek to maximise the signal level rather than maximise the SNR. If, on the other hand, listeners sought to maximise the SNR, based on the predictions from the model by Culling et al. (2012), it would be expected that unilateral CI users would orient further from the target than NH listeners and bilateral CI users.

### 7.4.2 Method

#### *7.4.2.1 Participants*

24 normally hearing adults (6 male, mean age=21.8 years, SD=2.4) participated. All had pure-tone thresholds below or equal to 20 dB HL at 0.25, 0.5, 1, 2, and 4 kHz. Participants were recruited from within the University of York. Four bilateral CI and four unilateral CI participants participated. Demographic information for these participants is displayed in Table 7.1 in Section 7.2.

#### *7.4.2.2 Apparatus*

Stimuli were presented through an array of 24 loudspeakers (Bose Acoustimass 3 Series IV) positioned in a 360° circular array with a radius of 1.5m. Loudspeakers were positioned at a height of 1m and were separated by 15°. The array of loudspeakers was situated within an Industrial Acoustic Corporation (IAC) single-walled enclosure situated within a larger sound-treated room. The loudspeaker array was calibrated as described in Section 7.2.2.2. Positioned just directly underneath each loudspeaker was a red light-emitting diode (LED), which could be controlled to be turned on or off. The head tracking equipment as described in section 7.1 was used to measure the head orientation and head movements of the participants.

#### *7.4.2.3 Design*

Three groups (NH listeners, unilateral CI users, and bilateral CI users) were tested in a blocked design. There were 5 levels of target location (-90°, -45°, -30°, 60°, and 105°) and 6 levels of separation (0°, 30°, -30°, 90°, -90°, 180°). The experiment was completed in sessions where participants also took part in one or both of the experiments reported earlier in this chapter. Therefore participants completed a subset of these conditions depending upon the time available in the experimental session. The number of participants who took part in each condition is given in Appendix F.

#### *7.4.2.4 Stimuli*

Coordinate-response-measure sentences were used. Each sentence took the form "Ready CALL-SIGN go to COLOUR NUMBER now." There were eight possible call signs (Arrow, Baron, Laker, Charlie, Hopper, Tiger, Eagle, and Ringo), four possible colours (blue, red, green and white), and four possible numbers (1, 2, 3, 4). Thus an example sentence is "Ready Charlie go to blue two now". Target sentences were spoken by four male and four female talkers. Seven were native British-English talkers, whilst one male was a native Irish talker. Thus the corpus consisted of 1024 sentences (8 call signs * 4 colours * 4 numbers * 8 talkers). Pink noise was used to provide consistency with the experiment reported in Chapter 5.

#### *7.4.2.5 Procedure*

Conditions were completed in blocks and the order of conditions was counterbalanced across participants using a Williams design latin square (Williams, 1948). This method ensured that for each condition, the preceding condition was different for each participant. On each trial a target sentence was selected randomly and presented from the target location. On each trial, pink noise was presented from a loudspeaker determined by the noise separation condition. The pink noise sample was 4.38s long and began 500ms before the sentence began. Participants sat on a rotating chair in the centre of the loudspeaker array and were given the following instructions: "In this experiment you are seated on a rotating chair. Feel free to turn the chair as you like." The participant was instructed to repeat back the colour and number that they heard. A trial was scored correct if both the colour and number were identified correctly.

Each condition began with an SNR of +6dB. The presentation level of the noise began at 60dB SPL, and the presentation level of the target sentence was 66dB. A one-up-one-down adaptive procedure was conducted whereby the SNR was increased or decreased by 2dB for 6 reversals. A reversal was defined as a change in direction of the SNR. If the participants reported the correct colour and number the SNR was reduced by 2dB. If either the colour or number were reported incorrectly, the SNR was increased by 2dB. SNRs less than 6dB were achieved by attenuating the level of the signal, whereas SNRs greater than 6dB were achieved by attenuating the level of the noise. Before and after each condition, calibration of the head tracking equipment was conducted as described in Section 7.3.2.5.

#### *7.4.2.6 Analysis*

Table 7.12 describes the measures used in this experiment. For each condition and each participant, trials before the second reversal were not included in the following analyses. This was to allow time for listeners to become familiar with the location of the target and the noise and adjust their head position if they wished. All correct trials from the second reversal onwards were included. Mixed linear models were computed because not all participants had completed all combinations of conditions. All pairwise comparisons reported are Bonferroni corrected.

**Table 7.12. Description of measures.**

| Measure | Description |
|---|---|
| SNR | Average signal-to-noise-ratio (SNR) of the trials included in the analyses |
| Final head position relative to the target | Final yaw (°) from the trial. Averaged over the trials included in the analyses |
| Final absolute head position relative to the target | Absolute value of final head position relative to the target (°). |
| Signal level optimization | For each condition participants were categorized into one of two groups: Signal-level optimizers and signal-level non-optimisers. Individuals who oriented their heads to a position which would maximise the signal level at one ear (defined below) were classified as signal-level optimisers. Participants who oriented their heads to other positions were classified as signal-level non-optimisers. |
| SNR optimization | For each condition participants were categorized into one of two groups: SNR optimizers and SNR non-optimisers. Individuals who oriented their heads to a position which would maximise the SNR at one ear (defined below) were classified as SNR optimisers. Participants who oriented their heads to other positions were classified as SNR non-optimisers. |
| Any optimization | Individuals who optimized the signal-level or the SNR were classified as optimizers and those who did not were classified as non-optimizers. |

### Signal level optimization

The range of head orientation positions which would optimize the signal level was determined from data courtesy of Pádraig Kitterick and Quentin Summerfield. They did not have a broadband measure like the stimuli used in the present experiment, but they did present an octave band of white noise centred on 2kHz from each of the same 24 loudspeakers used in the present experiment. Recordings were made using the in-ear microphones of a HATS. Figure 7.19 shows the relative attenuation of the signal-level as a function of loudspeaker position. This figure demonstrates that the optimal head orientation position to maximise the target signal at one ear lies in the region between 30° and 60° to the left or to the right of the target. The slightly higher levels of attenuation for the right ear shown in the figure are likely due to the room acoustics (A.Q. Summerfield, personal communication, November 21, 2014). The 'signal-level optimization zone' between 30° and 60° either side of the target has been highlighted in grey in the figures presented later in this report. Brimijoin et al. (2012) estimated the peak head orientation that would maximise the signal level to be ±60° relative to the target. This is at the higher end of the optimization zone defined above. The difference could be due to the room acoustics and signal used by Brimijoin compared to that used by Kitterick and Summerfield. The present study has used estimates from data by Kitterick and Summerfield as this was gathered in the same room that the present experiment was conducted in and it also incorporates the peak orientation estimated by Brimijoin.

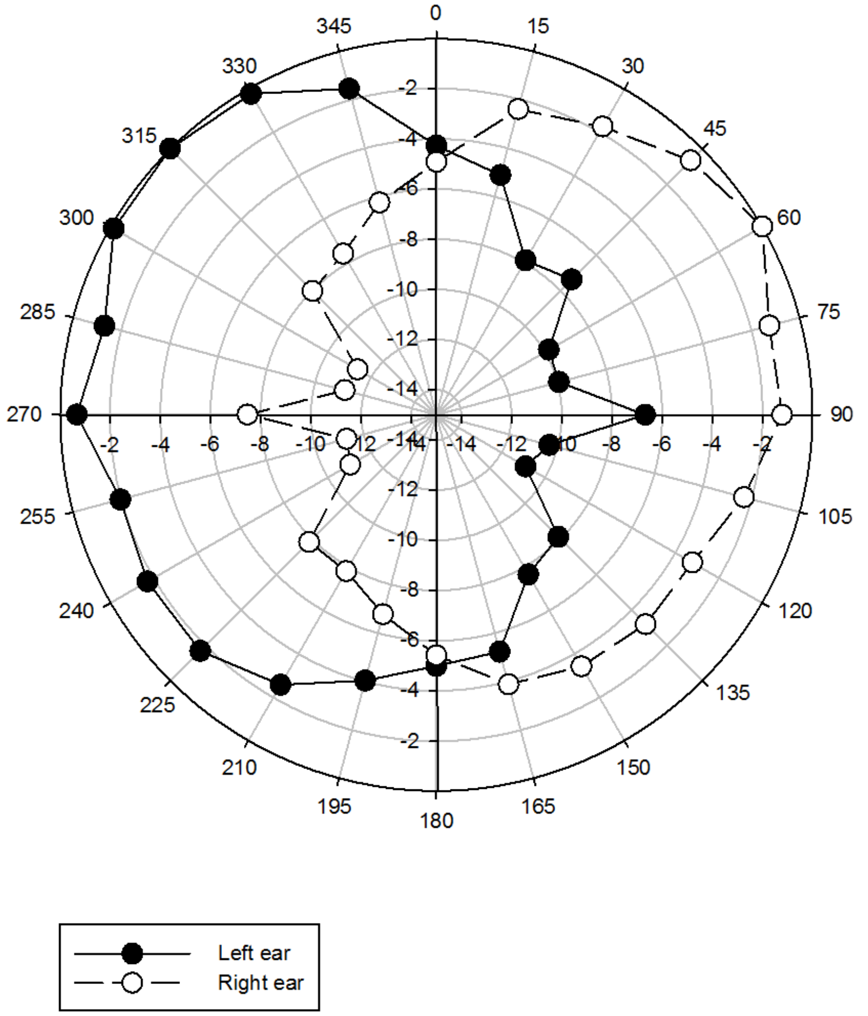


**Figure 7.19. Relative attenuation of a noise signal centred on 2kHz when presented from different locations. Figure demonstrates that the least attenuation of the signal is observed between ±30 and ±60 degrees to the side of the listener.**

### SNR optimization

The optimal head orientation position relative to the target to maximise the SNR was estimated from the same data set used to estimate signal-level optimisation. Figure 7.20 shows the optimal head orientation relative to the target location to maximise the SNR at each ear for each noise separation used in this experiment (excluding 0° of separation as this will have an SNR of 0dB). For each noise separation, the head orientation which resulted in the best SNR at either ear was taken as the optimal SNR position. A tolerance of ±10° was applied to create 'SNR-optimization zones'. This is highlighted in purple in the figures presented later in this report.

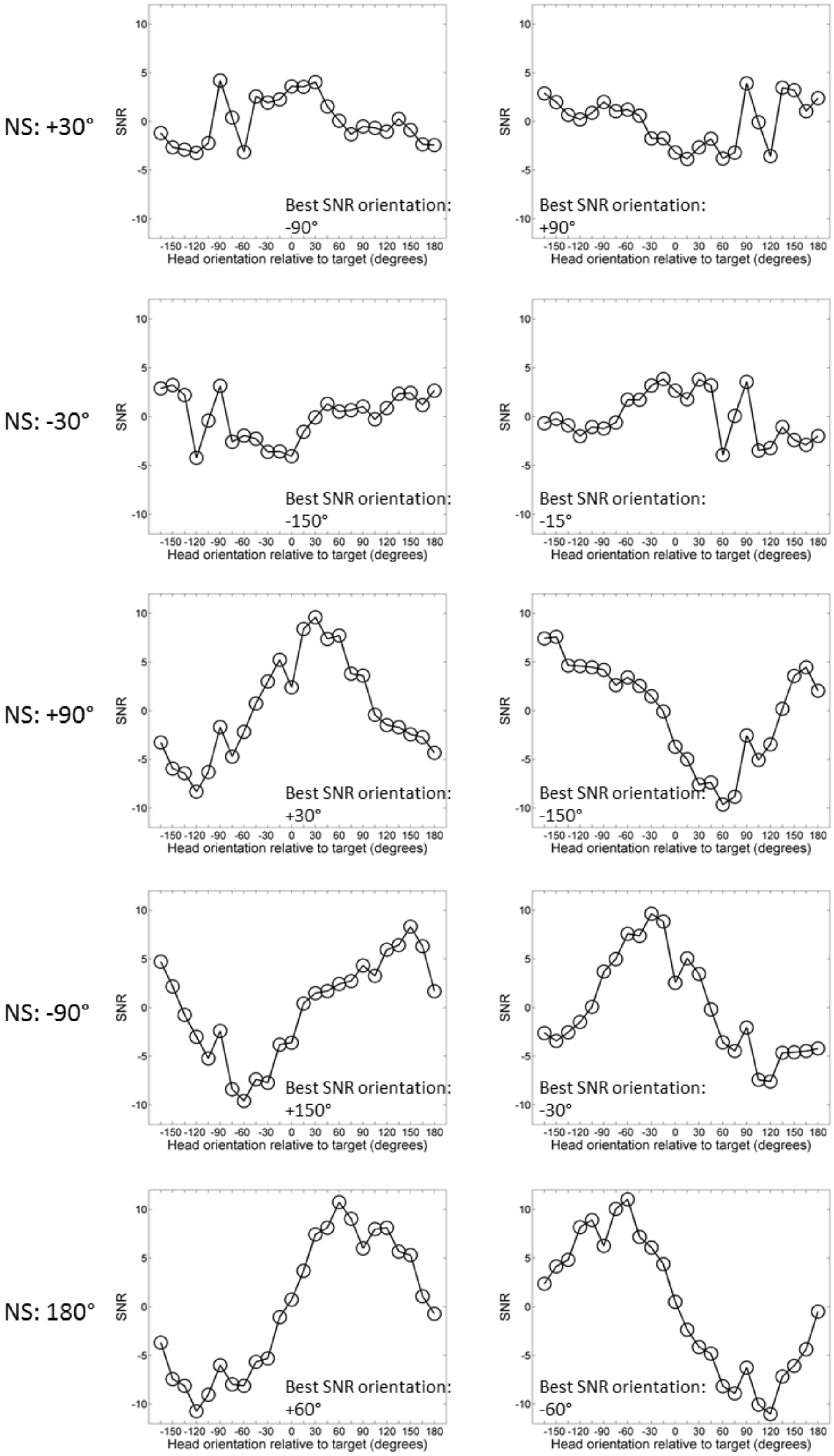


**Figure 7.20. SNR at each ear for each head orientation at each noise separation (NS) used in this experiment.**

### 7.4.3 Results

#### *7.4.3.1 Final head orientation relative to the target*

NH listeners

Figures 7.21 and 7.22 show the final head orientation by NH listeners in each condition. It can be seen that the mean head orientation for each target location did not vary as the noise location varied. However, participants did orient themselves differently for each target location. For some target locations (Figure 7.21) the mean head orientation was within the signal-level optimization zone. Thus participants oriented so as to maximise the signal level, although there was large variation, particularly when the target was presented from 105°. For target locations at -30° and -45°, the mean head orientation was for the most part not within either the signal-level or SNR optimization zone. Instead the majority of listeners oriented their head within ±30° of the target. As with the other conditions, they adopted a similar orientation irrespective of where the noise was presented from.

CI users

Figures 7.23 and 7.24 show the final head orientation by CI users in each condition. For target locations at -90°, 60° and -45° a similar pattern to NH listeners was found. In these conditions the majority of listeners oriented their heads within the signal-level optimization zone, maximising the level of the signal at one ear. However, when the target location was presented from 105°, all but one listener in one condition oriented to a position that was not within either the signal-level or SNR optimization zones.

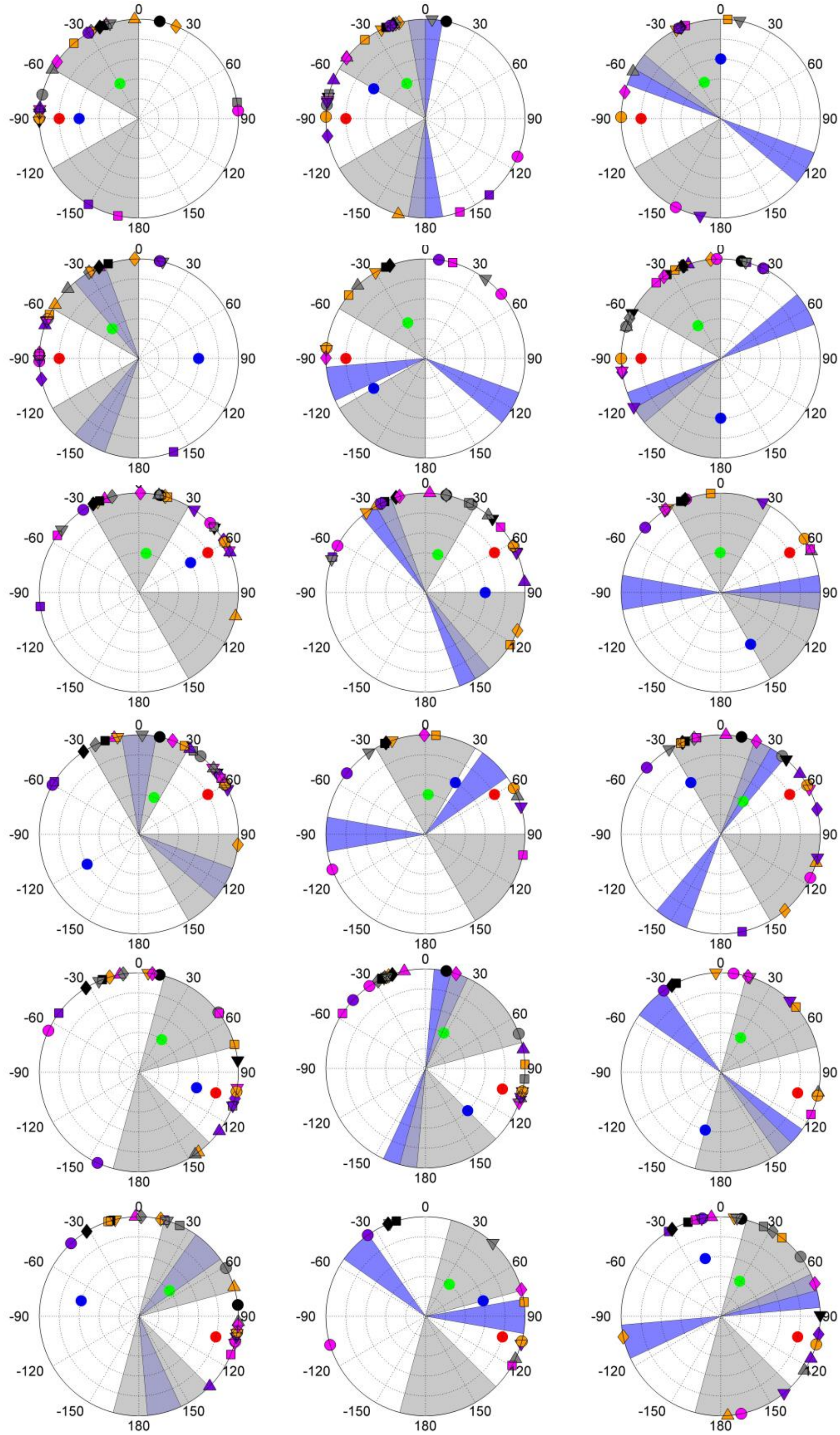

**Figure 7.21. Final head orientation by NH listeners. Grey areas represent optimal head position for maximising the signal level at either ear. Purple areas represent optimal head position for maximising the SNR at either ear. Red circle indicates the location of the target talker (in degrees azimuth). Blue circle indicates the location of the noise (in degrees azimuth). Green circle indicates the mean head orientation (in degrees azimuth). Coloured shapes at the periphery of each polar plot represent final head orientation data from individual participants.**

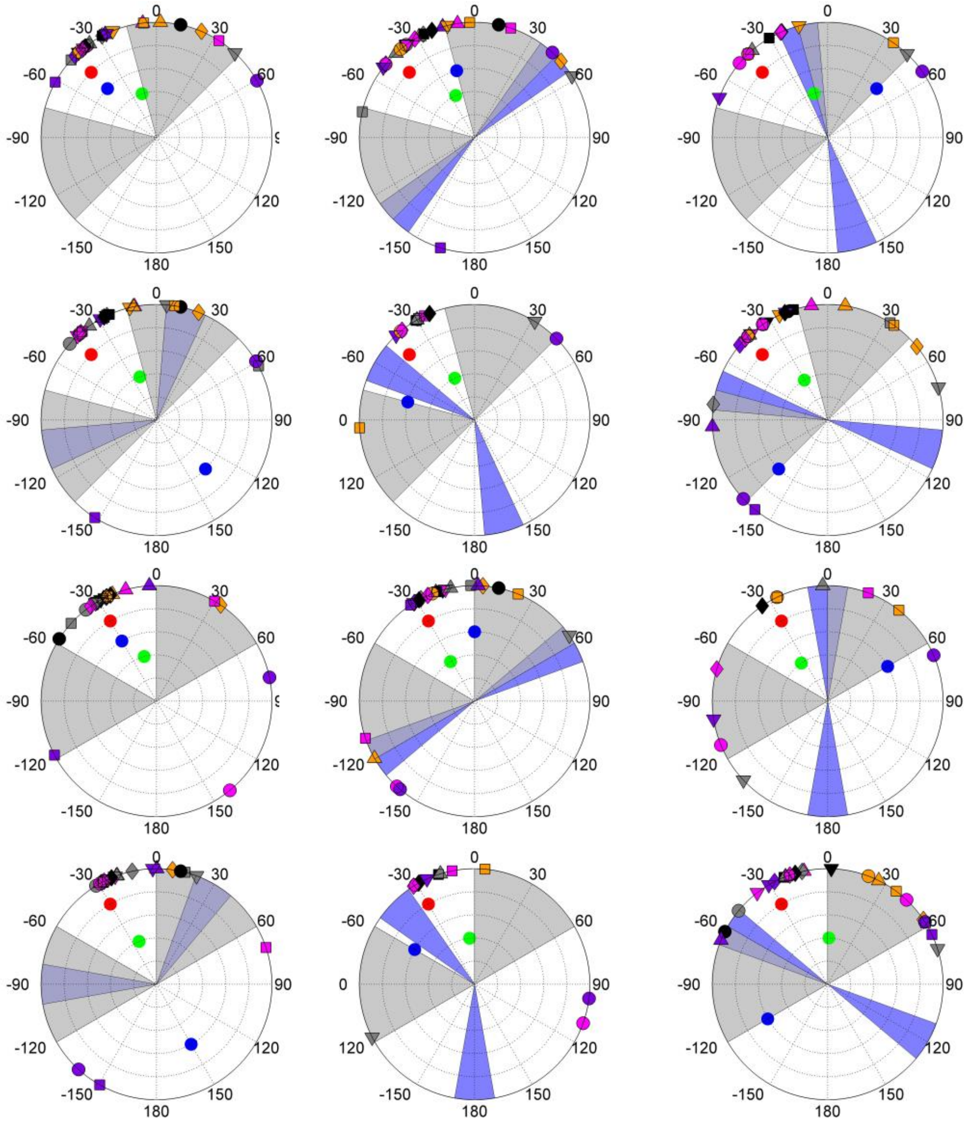

**Figure 7.22. Final head orientation by NH listeners. Shaded grey areas represent optimal head position for maximising the signal level at either ear. Shaded purple areas represent optimal head position for maximising the SNR at either ear. Red circle indicates the location of the target talker (in degrees azimuth). Blue circle indicates the location of the noise (in degrees azimuth). Green circle indicates the mean head orientation (in degrees azimuth). Coloured shapes at the periphery of each polar plot represent final head orientation data from individual participants.**

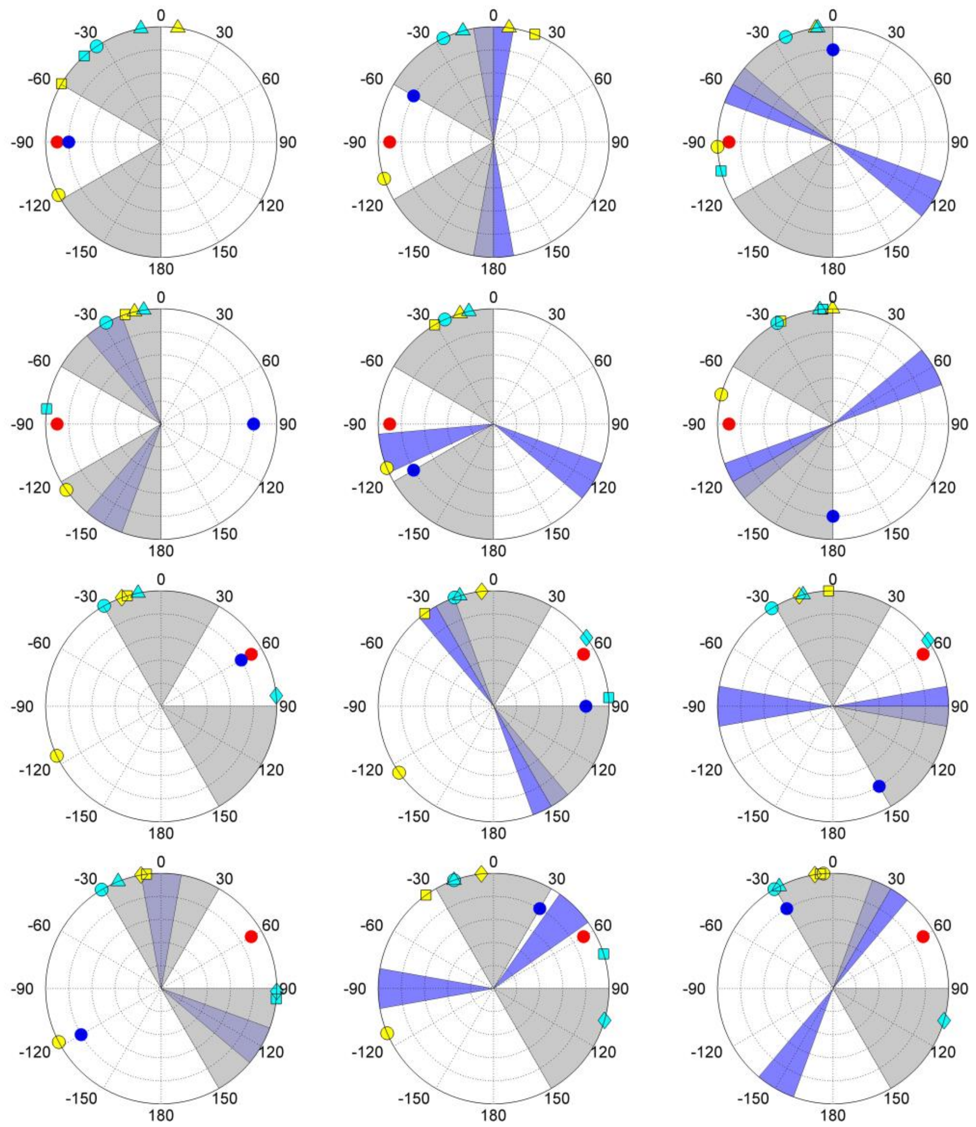

**Figure 7.23. Final head orientation by CI users. Shaded grey areas represent optimal head position for maximising the signal level. Red circle indicates the location of the target talker (in degrees azimuth). Blue circle indicates the location of the noise (in degrees azimuth). Coloured shapes at the periphery of each polar plot represent final head orientation data from individual participants. Yellow shapes indicate unilateral CI users, light blue shapes indicate bilateral CI users.**

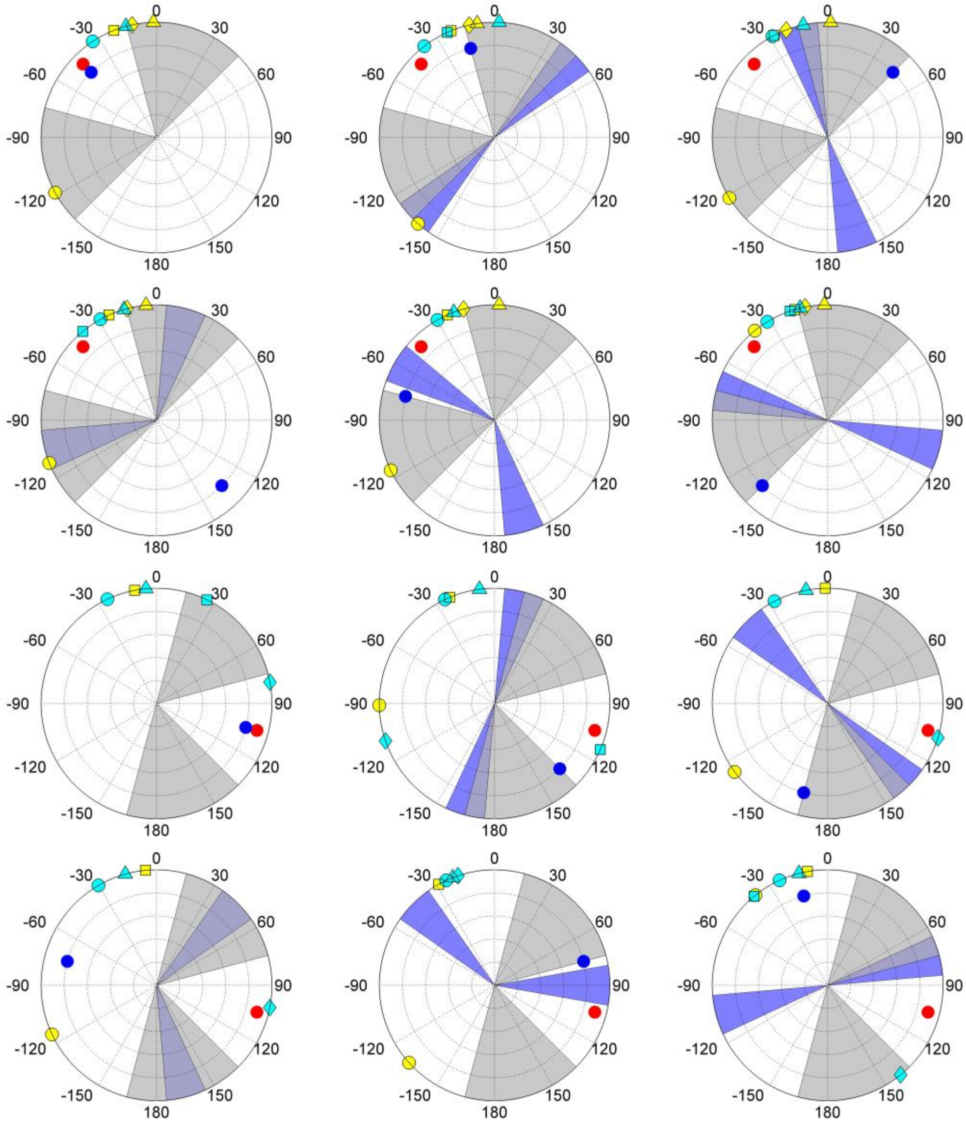


**Figure 7.24. Final head orientation by CI users. Shaded grey areas represent optimal head position for maximising the signal level. Red circle indicates the location of the target talker (in degrees azimuth). Blue circle indicates the location of the noise (in degrees azimuth). Coloured shapes at the periphery of each polar plot represent final head orientation data from individual participants. Yellow shapes indicate unilateral CI users, light blue shapes indicate bilateral CI users.**

#### *7.4.3.2 Does the absolute final head orientation relative to the target differ depending upon the target location and noise location?*

A 3 (group) by 5 (Target location) by 6 (separation) mixed linear model was calculated which found fixed effects of group ($F(2,414.686) = 7.741$, $p=.001$), target location ($F(4,175.687) = 30.926$, $p<.001$) and a significant group by target location interaction ($F(6,251.852) = 3.557$, $p=.002$). No other significant effects were found. The interaction was investigated by examining the simple effects of group and target location at each level of the other factor. The simple effect of group was found only for target locations at 60° ($F(2,131.911) = 8.138$, $p<.001$) and 105° ($F(2,135.158) = 7.574$, $p=.001$). Pairwise comparisons demonstrated that for the 60° target location unilateral CI users oriented their heads further from the target than NH listeners (p<.001) and bilateral CI users (p=.011). For the 105° target location, unilateral CI users oriented their heads further from the target than NH listeners (p=.003). No other significant differences were found. The simple effect of location was found for all three groups (all p<.001). Pairwise comparisons demonstrated that for NH listeners, there was no difference between the absolute head orientation relative to the target when the target was presented at -30° or -45°. There was also no difference in the absolute head orientation when the target was presented from -90°, 60°, or 105°. However, orientations with targets at -90°, 60° and 105° were significantly further from the target than head orientations when the target was presented from-30° and -45° (see Table 7.13). Unilateral CI users oriented their heads further from the target when it was presented from 105° than when it was presented from -90° or -45°. Also, unilateral CI users oriented themselves further from the target when it was presented from 60° than when it was presented from -45°. For bilateral CI users, head orientations were closer to the target when it was presented from -45° than when the target was presented from the other locations. Bilateral CI users oriented themselves further from the target when it was presented from 105° than when it was presented from 60°. No other significant differences were found.

**Table 7.13. Mean absolute head orientation relative to the target location. SE in parentheses.**

| Target location | NH | Unilateral CI | Bilateral CI |
|---|---|---|---|
| -90 | 63.99 (4.96) | 56.36 (12.88) | 63.83 (13.20) |
| -45 | 32.29 (2.77) | 39.97 (5.97) | 21.71 (7.61) |
| -30 | 36.45 (4.00) | - | - |
| 60 | 55.92 (3.69) | 96.02 (9.25) | 59.30 (8.27) |
| 105 | 71.38 (4.76) | 127.06 (15.60) | 98.30 (10.96) |

#### *7.4.3.3 Do 'optimizers' perform better?*

An independent t-test found no significant difference in mean SNR between signal-level non-optimizers (mean = -10.01, SD = 5.87) and signal-level optimizers (mean = -10.10, SD = 5.73), t(733) = -.147, p=.883. An independent t-test found no significant difference in mean SNR between SNR non-optimizers (mean = -10.45, SD = 5.98) and SNR optimizers (mean = -12.00, SD = 6.81), t(591) = -1.329, p=.184. Furthermore an independent t-test found no significant difference in SNR performance between individuals who did not optimize their head orientation (mean = -10.48, SD = 6.00) and individuals who either optimized the signal level or SNR (mean = -10.68, SD = 6.12).

#### 7.4.3.4 *Is performance different between groups and target and noise locations?*

A 3 (group) by 5 (Target location) x 6 (noise separation) mixed linear model was calculated using SNR as the dependent variable. Fixed main effects of group ($F(2,522.832) = 628.460$, $p<.001$) and noise separation ($F(5,185.180) = 4.441$, $p=.001$) were found as was a significant group by noise separation interaction ($F(10,184.062) = 2.204$, $p=.019$). No other significant effects were found. The interaction was investigated by examining the simple effects of group and noise separation at each level of the other factor. A simple effect of group was found at all noise separations (all $p<.001$). NH listeners performed significantly better than both CI groups at all noise separations (see Table 7.14). Bilateral CI users performed significantly better than unilateral CI users at the larger noise separation of 180° ($p=.029$). No other significant differences were found. The simple effect of noise separation was found only for NH listeners ($F(5,176.852) = 35.421$, $p<.001$). SNR significantly improved as the noise separation increased, up to 90° (see Table 7.14). Pairwise comparisons demonstrated that there was no difference in performance for separations of the same magnitude but different directions ( i.e. between +30 and -30 separations, and between +90° and -90° separations). Performance with no separation was significantly poorer than all other conditions. A separation of ±30° was poorer than ±90° and 180°. There was no difference between 180° and ±90°.

**Table 7.14. Mean SNR for each noise separation for each group. SE shown in parentheses.**

| Noise separation | NH | Unilateral | Bilateral |
|---|---|---|---|
| 0 | -9.43 (.26) | 0.10 (.97) [1] | -0.77 (.86) [1] |
| -30 | -11.37 (.33) | -0.52 (.83) [1] | -.77 (.88) [1] |
| 30 | -11.61 (.31) | 0.77 (.94) [1] | -1.18 (.93) [1] |
| -90 | -13.20 (.34) | 0.66 )1.10) [1] | -2.78 (1.02) [1] |
| 90 | -14.14 (.44) | -0.37 (1.13) [1] | -2.03 (1.04) [1] |
| 180 | -14.00 (.31) | 0.28 (1.05) [1] | -3.52 (.99) [1] |

### 7.4.4 Discussion

#### 7.4.4.1 *Listeners orient their heads depending upon the target location and not the noise location*

This study found no effect of noise separation, for each target location the mean head orientation did not vary as the noise location varied. Section 7.4.3.2 demonstrated that NH listeners adopted

[1] Based on modified population marginal mean

two different strategies. In three out of five target locations (-45°, -30°, and 60°), listeners oriented their heads in a way that would optimise the level of the signal at one ear. This finding is consistent with Brimijoin et al. (2012) who found that participants with moderate asymmetrical hearing loss oriented their heads within the 'signal-level optimization zone' defined in this study. In the present study, mean head orientation for targets presented from -90° were just outside the signal-level optimization zone. However, when the target location was presented from 105° the data were more heterogeneous. On average, orientation relative to the target was beyond the signal-level optimization zone, with a mean relative head orientation of 71°. It is unclear why this was the case for this target location. As the order of conditions was counterbalanced it cannot be explained by novelty of the task. Whilst not the most optimal position, an orientation of 71° relative to the target will provide 3-4dB of benefit compared to orienting towards the target (see Figure 7.19). Testing was not conducted in an anechoic chamber so effects of reverberation may account for some of these differences in head orientations between target locations.

For the most part, head orientation relative to the target by CI users was similar to NH listeners. Unilateral CI users optimized the signal level when the target was presented from -45° or -90°. Bilateral CI users optimized the signal level when the target was presented from 60°, although oriented just beyond the signal-level optimization zone when the target was presented from -90°. Similar to NH listeners, both CI groups oriented their heads beyond the signal-level optimization zone when the target was presented from 105°. Modelling by Culling et al. (2012) predicted that unilateral CI users would orient their heads further from the target than bilateral CI users and NH listeners. Some support was found for this prediction as unilateral CI users oriented their heads further than both groups when the target was presented from 60°, and further than the NH listeners when the target was at 105°. However, for the other two target locations, unilateral CI users performed similarly to the other two groups.

#### *7.4.4.2 Optimization does not improve performance*

Consistent with data reported by Brimijoin et al. (2012), there was a range of final head orientations with sometimes large inter-subject variation (see Figure 7.21). To assess whether a strategy to maximise the signal level improved performance, for each condition listeners were grouped as 'signal-level optimizers' and 'signal-level non-optimizers' based on whether or not their final head orientation relative to the target was within the signal level 'optimization zone'. However, no difference was found between the two groups suggesting that maximising the signal level did not result in benefits to speech perception in the presence of noise. Orienting to a position which optimized the SNR was adopted by a few participants in some conditions.

However, their performance did not differ from those who did not orient to optimise the SNR. Furthermore, when performance by participants who optimised either to maximise the signal-level or the SNR was compared to non-optimisers, no difference in performance was found.

One possibility is that those individuals who optimized did so because they found the task difficult, whereas those who did not optimize, performed the task well enough that they did not need to optimize. This is similar to the suggestion made by Wightman and Kistler (1999) in relation to head movements and sound localisation discussed in Chapter 3. They found that when locating the source of a sound when head movements were not permitted some individuals made many front-back confusions whereas other individuals made very few. Of interest to the present discussion, is that individuals who made many front-back confusions when head movements were not permitted, made large head movements when they were allowed to do so, whereas individuals who made few errors made limited head movements when allowed to do so. To test whether this was the case in the present experiment, a future study could test participants in two conditions. In one condition, like the present study, participants would be able to orient their heads as they wished whilst performing the task. In another condition participants would be instructed to orient their heads to a position outside of the optimization zone. Participants could be divided into two groups (optimizers or non-optimizers) based on their behaviour in the former condition. Performance in the latter condition could then be compared between optimizers and non-optimisers. If performance by optimizers in the latter condition was worse than non-optimizers, it would support the proposal that some individuals who find the task challenging optimize their head orientation position to maximise the signal level to improve performance. Thus it could be that head orientation could improve speech in noise performance for some individuals. Of further interest is whether “forced” optimization results in an improvement to performance. Participants could be instructed to orient to a theoretically optimal or theoretical sub-optimal position which would either maximise the SNR or not. Performance could then be compared between these conditions.

#### *7.4.4.3 NH listeners perform better with increasing target to noise spatial separation*

This experiment found that NH listeners’ performance improved as the spatial separation between the target and noise increased. This finding is consistent with previous research into the cocktail party problem (Cherry, 1953; Bronkhorst, 2000). The cocktail party problem refers to the challenge of hearing out a target in the presence of background interference (i.e. noise or other speech). In a review of the literature, Bronkhorst (2000) demonstrated that when speech was presented at 0° azimuth, performance improved as the location of background noise increased in azimuthal distance from the speech. This increase reached a peak around 120° (with an SRM of 10dB) then decreased to an SRM of 0dB at a separation of 180°. The maximum azimuthal separation in the present study (180°) did not improve performance over a separation of ±90° but neither did performance decrease.

However, this effect was not found for CI users, who performed similarly at all noise separations (see section 7.4.3.4). This is somewhat surprising as previous research has demonstrated that speech perception performance in the presence of competing noise by CI users is better when speech and noise are spatially separated than when they are spatially concurrent (e.g. Loizou et al., 2009). In a study reported by Loizou et al. (2009), stimuli were presented directly to the processor of CIs so listeners could not move their heads to alter the signal input. In the virtual space, a target was presented from in front of the listener at 0° azimuth and speech modulated noise was presented from either 0°, -30°, +60°, and +90°. They found that when listening with either a unilateral CI or bilateral CIs SRTs in the separation conditions were about 4dB better than performance in the no separation condition. However, Loizou et al. (2009) found that there was no difference in performance between bilateral CI listening and listening with a unilateral CI (when the noise was presented contralateral to the CI). This finding is similar to the present study which found no difference in performance between bilateral and unilateral CI users at any separation condition. However the present study is limited by a small sample of CI users.

In the present study, final head orientations relative to the target did not differ depending upon the location of the noise (see section 7.4.3.2), which cannot account for why there was limited spatial release from masking. When the noise separation was +90° and -90°, bilateral users achieved 1.7dB and 2.59dB better performance than when the speech and noise were presented concurrently. These values are similar to the levels of spatial-release-from-masking obtained with a larger sample of bilateral CI users (2.55dB and 2.26dB for each ear) in the experiment reported in chapter 5.

#### *7.4.4.4 Conclusion*

Listeners oriented differently depending upon the location of the target. The noise separation did not affect head orientation showing that the majority (96%) of listeners did not seek to maximise the SNR. For NH listeners, performance improved as the separation between the target sentence and the background noise increased in azimuth consistent with research into the cocktail party phenomenon. This effect was not found for CI users. Listeners who oriented to maximise either the signal level or the SNR did not perform better than those who did orient to maximise the signal level or SNR. In conclusion, listeners orient their heads differently depending upon where the target is presented from irrespective of where background noise is presented from.

### 7.4.5 Summary

- A target sentence was presented from one of five locations and pink noise was presented from one of 6 separations.
- Head orientation was monitored in a blocked design.
- Although there was inter-subject variability, behaviour was consistent across noise separations with listeners not demonstrating an orientation pattern consistent with maximising the SNR.
- Individuals who oriented to a position which would maximise the signal level of the target did not perform any differently to individuals who did not orient to maximise the signal level.

# 8 Development and validation of a measure of "hearing related quality of life" sensitive to binaural hearing in adults

## 8.1 Introduction

With limited resources available to fund healthcare, policy makers must prioritise the treatments to which they allocate funding. Analyses of incremental cost-effectiveness can inform the setting of priorities by ranking treatments in terms of the cost of gaining increments in health-related quality of life. Generic health-related quality of life measures (such as questionnaires) can be used to measure the effectiveness component for use in a cost-effectiveness analysis. As discussed in Chapter 4, one widely used generic questionnaire, the EuroQol (EQ5D, Brooks, 1996; The Euroqol Group, 1990) lacks sensitivity to differences between groups of people with differing hearing difficulties (Barton, Bankart, & Davis, 2005; Grutters et al., 2007). Another widely used generic questionnaire, the Health Utilities Index Mark 3 (HUI3, Boyle, Furlong, Feeny, Torrance, & Hatcher, 1995; Feeny et al., 2002; Torrance, Furlong, Feeny, & Boyle, 1995) is sensitive to differences between groups of people with 'no hearing' compared to 'some hearing' but lacks sensitivity to differences in quality of life between groups of people with 'some hearing' compared to 'more than some hearing', such as unilateral CI users and bilateral CI users (Lovett et al., 2010; United Kingdom CI Study Group, 2004). Two alternative interpretations can be put on this result. One is that the self-reported and behavioural benefits obtained from a second CI (as demonstrated in chapters 5, and 6) do not lead to an increase in health related quality of life. The second interpretation is that the benefits do improve health-related quality of life but that current instruments are not sufficiently sensitive to detect differences between the quality of life associated with monaural, compared with binaural hearing.

The purpose of the current study was to distinguish between these two alternatives. Firstly this study aimed to use the time-trade off method to test whether members of the public are willing to trade years of life to improve listening skills which particularly benefit from binaural hearing. If so, the second aim was to establish whether patients with one or two CIs show significant differences in utility and whether the differences are large enough, in principle, for the provision of a second CI to be a cost-effective use of resources. To address these aims, this study adopted a similar approach to what was used in the development of the EQ5D (Brooks, 1996). Firstly, areas in which binaural hearing provides benefit were identified. Secondly, members of the public used the time-trade off method to value these areas. Thirdly, a questionnaire was created in which patients can describe their own level of hearing ability on each area. Fourthly, using valuations gathered from members of the public, a utility value was assigned to each patient based on their level of function described in the questionnaire. Finally, the questionnaire was used to test whether there are significant differences between patients with a unilateral CI, bimodal devices, and bilateral CIs. This can be used to infer whether the size of the difference is large enough to mean that bilateral cochlear implantation could, in principle, be a cost-effective use of resources. This new questionnaire is a means of establishing values of "hearing-related quality of life" which could be used to inform cost-effectiveness analyses in the same way that measures of health-related quality of life currently do.

### 8.1.1 Advantages of binaural listening over monaural listening

There are a number of advantages from binaural hearing compared to monaural listening. However, in order to keep the length of the questionnaire short enough so that it could reasonably be administered to patients alongside existing questionnaires, only a limited number of dimensions could be included. Following a review of the literature the three dimensions identified were: the ability to understand speech presented in spatially-separated noise, the ability to localise sounds, and a reduction in effort and fatigue. These dimensions were chosen because they are aspects of listening that are commonly encountered in daily life, they can be improved from listening with two ears compared to one, and they also correspond to the three sections of the SSQ which addresses everyday listening scenarios. This correspondence provides the opportunity to assess the construct validity of the new questionnaire by assessing the relationship between self-ratings on the SSQ and YHRQL questionnaires.

#### *Speech in noise*

Three mechanisms contribute to improved speech understanding in spatially-separated noise when listening with two ears rather than one: The head shadow effect, binaural redundancy, and binaural squelch. A full description of these can be found in Chapter 2. Compared to unilateral CI users, bilateral CI users can benefit from the head shadow, binaural squelch and binaural redundancy when listening to speech in noise (Müller et al., 2002; Schafer et al., 2011; Schleich et al., 2004) although the head shadow has been shown to account for the majority of the benefit (Müller et al., 2002; Schleich et al., 2004). Furthermore bimodal listeners have been shown to benefit from the head shadow and binaural summation (Ching, 2005) with better speech perception in noise compared with unilateral CI listening (Carroll, Tiaden, & Zeng, 2011; Ching, Incerti, & Hill, 2004; Ching, van Wanrooy, Hill, & Dillon, 2005; Zhang et al., 2010).

#### *Sound localisation*

Being able to localise sources of sound enables listeners to locate potential hazards and to know where to look to see who is talking. Binaural listening can provide listeners with access to interaural differences in level (ILDs) and timing (ITDs). Users of bilateral CIs have access to ILDs, but have access to ITDs only in the envelope of the signal, not the temporal fine structure (Ching, van Wanrooy, & Dillon, 2007). Bilateral CI users are more accurate at localising sounds in the horizontal plane than unilateral CI listening (Dunn, Tyler, Oakley, Gantz, & Noble, 2008; Kerber & Seeber, 2012; Litovsky, Parkinson, & Arcaroli, 2009; van Hoesel & Tyler, 2003). Mixed findings have been reported for horizontal localisation with bimodal devices. In a small sampled study, Tyler et al. (2002) found that compared to performance with a single CI, two out of three patients benefitted from using a contralateral acoustic hearing aid. Dunn, Tyler, and Witt (2005), found that localisation ability was very varied in a group of twelve bimodal users, and whilst three participants could localise fairly well, the majority of participants were unable to locate the source of the sounds accurately. Thus binaural hearing has the potential to improve spatial listening skills for some listeners.

### *Effort and fatigue*

Listening effort refers to the need for cognitive resources to be utilised to direct attention during a listening task (Hicks & Tharpe, 2002) and can be measured either subjectively (through the use of self-reports) or objectively (using either a dual-task paradigm or physiological measures). Using a dual-task paradigm, individuals perform a listening task whilst simultaneously performing a secondary task (such as responding to a visual stimulus). The assumption is that increases in listening effort due to the listening task will manifest themselves in longer reaction times to respond to the secondary task (Hicks & Tharpe, 2002). Using a dual-task method in which a speech in noise task was performed whilst simultaneously responding to a probe light, Hicks and Tharpe (2002) found that hearing impaired children took significantly longer to respond to the probe than normal hearing children. In a comparison between 42 bilateral hearing aid users and 118 unilateral hearing aid users who completed the Speech, Spatial and Qualities of hearing scale (SSQ), Noble & Gatehouse (2006) demonstrated that self-reported effort of conversation was significantly lower with two hearing aids compared to one. In a comparison of listening effort between unilateral and bilateral CI users, it was found that, at the group level, listening effort was reduced with binaural hearing (Hughes & Galvin, 2013). However, in this dual-task paradigm only three out of eight listeners showed this effect individually. Fatigue can incorporate both physical and mental exhaustion and increases in listening effort have been suggested to exacerbate fatigue (Hornsby, 2013; McGarrigle et al., 2014; Nachtegaal et al., 2009). Thus, binaural hearing may have an important role in reducing listening effort and fatigue.

### 8.1.2 Existing questionnaires

***Binaural listening***

The aim of this study was to develop and validate a questionnaire that is sensitive to the benefits of binaural hearing. Previous research developing questionnaires sensitive to binaural benefits include the SSQ (Gatehouse & Noble, 2004), and the Spatial Hearing Questionnaire (Tyler et al., 2009). The SSQ is a 50-item questionnaire split into three sections: listening to speech, spatial listening, and other qualities of hearing and listening. The authors emphasised that the questionnaire was designed to be sensitive to the benefits of binaural listening but also incorporated some questions related to monaural listening. The instrument has shown better self-rated ability with binaural devices compared to monaural devices (bilateral hearing aids vs. unilateral hearing aids: Gatehouse & Akeroyd, 2006; Noble & Gatehouse, 2006, bilateral CIs vs. unilateral CI: Summerfield et al., 2006; Tyler et al., 2009). The Spatial Hearing Questionnaire is a shorter instrument comprising 24 items, which assesses eight aspects of listening (understanding male voices, female voices, and children's voices, perception of music, source localisation, understanding speech in quiet, in spatially concurrent noise, and in spatially separated noise). Tyler et al. administered the questionnaire to 100 unilateral and 42 bilateral CI users and found that overall self-rated spatial listening was significantly higher for the bilateral group.

***Quality of life amongst CI users***

Two questionnaires which were specifically designed to assess quality of life amongst CI users are the Nijmegen cochlear implant questionnaire (NCIQ, Hinderink, Krabbe, & Van Den Broek, 2000) and the comprehensive cochlear implant questionnaire (CCIQ, King, Nahm, Liberatos, Shi, & Kim, 2014). The NCIQ has 60 questions and covers three broad domains (physical, psychosocial and social). The questions are answered on a 5-point Likert scale from 'Never' to 'Always.' Similarly the CCIQ contains 28 questions over three domains (hearing and balance, psychological and social) and responses are made using the same 5-point Likert scale. Despite being sensitive to differences between clinically distinct groups these questionnaires were not developed following the principles for measuring utility. For instance, each question on the NCIQ can result in a score out of 100, with the score for each sub-group being the mean score of the questions in that group. The CCIQ results in a mean score between 1 and 5. Therefore scores from these questionnaires are not suitable for incorporation in the type of cost-effectiveness analyses required by NICE (2013) as the scores cannot be interpreted in terms of quality adjusted life years.

***Questionnaires for us in cost-effectiveness assessment***

Two previous studies have developed questionnaires to inform analyses of the cost-effectiveness of cochlear implantation. Summerfield, Lovett, Bellenger, & Batten (2010) sought to estimate the cost-effectiveness of cochlear implantation for pre-lingually deafened children. They created a questionnaire which described a hypothetical child born profoundly deaf with one of four different listening scenarios (using no devices, benefiting from a unilateral CI, benefiting from bimodal devices, and benefiting from bilateral CIs). Each scenario described spatial listening abilities, speech understanding, school performance, language development, family strain and potential future job opportunities. Respondents consisted of clinicians, students and members of the public who read each scenario imagining that they were 33 years old and the scenario was describing their hypothetical six-year-old daughter. Using the time-trade off technique they were asked to imagine they had 50 years of remaining life and could trade some of their own life years to relieve difficulties for their daughter. It was found that respondents valued bilateral CIs to have on average a 0.11 higher utility value (with a wide range of valuations from 0.00 to +0.60) than a unilateral CI. Furthermore, the study demonstrated differences between types of binaural hearing; bilateral cochlear implantation was valued with a utility value 0.05 higher than that of bimodal listening (also with a wide range of valuations from -0.06 to +0.40).

Although influential (the findings contributed to NICE's (2013) decision to fund bilateral cochlear implantation for children) the focus was to estimate the cost-effectiveness of cochlear implantation in pre-lingually deafened children. There are aspects included in their questionnaire that are not relevant to post-lingually deafened adults, namely school performance and language development. One study which did focus on adults was that of Summerfield, Marshall, Barton, & Bloor (2002). They used the time-trade off technique with a group of normally hearing adults to estimate the cost-effectiveness of providing bilateral CIs to profoundly deafened adults. The increase in utility from providing a second CI to users of a unilateral CI was estimated at +0.03, which the authors concluded was not large enough to mean that bilateral cochlear implantation would be judged to be cost-effective. This conclusion was supported by Bond et al (2009) which demonstrated that at a willingness-to-pay threshold of £30,000 (typical of NICE, 2013), the gain would need to be about +0.05 (see Chapter 4).

### 8.1.3 Current study

The rather lengthy scenarios described in Summerfield et al. (2002; 2010) were useful in creating a picture of what it may be like to have those hearing difficulties but it was not the authors intention that they be used directly with patients. Therefore the research reported in this chapter sought to bridge a gap in the literature and develop a questionnaire that would be (1) sensitive to benefits in binaural hearing obtained by adults, and (2) observe the principles used in compiling current generic health related quality of life instruments to enable estimates of hearing related quality of life to be measured, and (3) be short enough that it could feasibly be administered to patients alongside existing generic instruments. The style of the questionnaire was based on the style of the EQ5D. The EQ5D is the preferred evaluation questionnaire by NICE (2013)and includes three levels of difficulty for each domain: No difficulty, some difficulty, and great difficulty. The scenario descriptors provided informants with an insight into how a hearing difficulty could impact everyday life so that they could make an informed evaluation. Previous research using the time-trade off technique has also used vignettes to describe the potential challenges of hearing difficulties (Summerfield et al., 2010). However, unlike Summerfield et al., the descriptions in the present study were kept short enough so that the questionnaire could be administered alongside existing instruments. Furthermore, this approach ensured that the utility values assigned to patients were based on the same descriptors used to elicit valuations. The first study outlines the development of this questionnaire (the York hearing related quality of life questionnaire, YHRQL), and study two outlines the validation of this new instrument with an opportunity sample of adult CI users.

## 8.2 Study 1: Questionnaire development

### 8.2.1 Materials and methods

#### *Participants*

The opportunity sample of 361 adults consisted of students, clinicians, and members of the general public. Demographic information is displayed in Table 8.1.The Research Ethics Committee of the Department of Psychology at the University of York approved the study.

**Table 8.1. Summary demographic data of participants.**

| Group | N | Minimum age (years) | Mean age (years) | Maximum age (years) | Females (%) |
|---|---|---|---|---|---|
| Clinicians | 51 | 23 | 45.10 | 62 | 86 |
| Students | 154 | 18 | 20.54 | 26 | 79 |
| Non-students | 156 | 22 | 46.48 | 79 | 53 |
| All | 361 | 18 | 35.22 | 79 | 69 |

### *Levels of function*

Three levels of function on each dimension were defined corresponding to ‘No difficulties’, ‘Some difficulties’, and ‘Great difficulties’ (see Table 8.2). These levels of difficulty were selected to cover a broad range of listening challenges, whilst limiting the number to three kept the possible combinations of difficulties to a reasonable number (27) so that all combinations could be valued by the same informants.

**Table 8.2. Scenario descriptors by dimension and difficulty.**

| Level of function | Speech in noise | Localisation | Effort and fatigue |
|---|---|---|---|
| No difficulty | When a friend speaks to you while the TV is on or other people are chatting in the same room, you can hear your friend speaking easily, usually picking up all of the words they say. | You can work out where sounds are coming from accurately. You can point to where a sound is coming from easily. | You have to concentrate a little when you are trying to hear something or someone. You can hear what people are saying with only a little effort. By the end of the day, you are not mentally or physically tired because of your hearing. |
| Some difficulty | When a friend speaks to you while the TV is on or other people are chatting in the same room, you can hear your friend speaking, but you can only pick out some of the words they say. This can lead to confusion if you miss an important word. Sometimes you need them to repeat themselves or to turn the volume down for you to understand them. | You have some difficulty working out where sounds are coming from. You can usually tell if a sound is coming from the right- or left-hand side, but you cannot be more accurate than that. As a result, you are not always sure who is speaking when you are in a group with several people. | You have to concentrate quite hard when you are trying to hear something or someone. You have to put in some effort to hear what people are saying. By the end of the day, you are moderately mentally and physically tired because of your hearing. |
| Great difficulty | When a friend speaks to you while the TV is on or other people are chatting in the same room, you find it very difficult to hear your friend speaking. You are usually unable to pick out the words they say. This regularly leads to misunderstanding and confusion. The room needs to be completely quiet for you to understand them. | You have great difficulty working out where sounds are coming from. You cannot even tell if a sound is coming from the right- or left-hand side without looking around. As a result, you find it very difficult to tell who is speaking when you are in a group with several people. You are also worried about your safety outdoors because of your difficulty working out where sounds are coming from. | You have to concentrate very hard when you are trying to hear something or someone. You have to put in a great deal of effort to hear what people are saying. By the end of the day, you are extremely mentally and physically tired because of your hearing. |

### *Questionnaire creation*

A questionnaire was compiled in which all 27 (3 x 3 x 3) combinations of difficulties were evaluated using the time-trade off technique. Respondents were instructed to imagine that the descriptions were describing their own hearing abilities. For each combination of difficulties, participants were given a choice: either live with the difficulties for the rest of their life or live a shorter period of time (f) but with perfect hearing. Participants were told that any life given up would be taken from the end of their life.

Two different time-trade-off methods were used, instructions for which can be found in Appendix G. One group (50-year condition, n = 250, clinicians, students and non-students) were instructed to imagine that they were 30 years old and that they would live for 50 more years (y=50) until they were 80 years old. They were asked to state how many years of their remaining life they would give up (L) in order to have perfect hearing (f = y-L). The other group of respondents (10-year condition, n= 111, students and non-students) were instructed to imagine that they had 10 years of life remaining (y=10) and were asked to indicate the number of years with perfect hearing (f) that they judged was equivalent to living for 10 years with the difficulties described in the scenario. Group 2 responded by placing a cross anywhere on an 11 point scale from 0 years to 10 years.

The questionnaire included two unrelated examples to familiarise participants with the response method. One example described a scenario that many would consider to be a major problem (suffering from a stroke and as a result struggling to cope with day-to-day living). The other example described a scenario that many would consider to be a minor problem (either suffering from hayfever or having a cut on your hand). Following the examples, participants valued the 27 scenarios, which were presented in one of four random orders. The assignment of scenario order to participant was randomly allocated. A value of hearing related quality of life (Hearing Utility) was calculated as f/y for each scenario for each participant. Analyses were conducted on the hearing utility values. A brief demographic questionnaire gathered information concerning each participant's age, gender, experience of personal hearing loss, family hearing loss, working with hearing loss, own disabilities, and family disabilities.

### 8.2.2 Analyses

All analyses were conducted with IBM SPSS Statistics 21. Mauchly's test was used to assess sphericity, if the assumption of sphericity was violated, the degrees of freedom were corrected using a Huynh-Feldt correction. All pairwise comparisons reported are Bonferroni corrected.

#### *Missing data and zero traders*

A small minority of responses were missing (6 missing values for the 50-year condition and 9 missing values for the 10-year condition). These were imputed based on the available data as:

$$Missing\ value = \frac{(S\ x\ P)}{G}$$

Where S is the average utility value for the scenario as judged by the other participants in the group, P is the average utility value for all scenarios by the participant who has a missing value and G is the grand mean of utility values by scenario and participants (Raaijmakers, 1999).

The majority of respondents were willing to trade quantity of life to have perfect hearing (see Table 8.3). Twenty-eight participants were unwilling to trade years of life in any of the scenarios. No significant difference was found between the number of people (24) who were unwilling to trade life years in the 50-year condition and the number of people unwilling to trade life years in the 10-year condition (4) ($p$=.055, Fisher's exact test).

The proportion of non-traders between the three groups (students, non-students, and clinicians) was significantly different ($p$<.001, Fisher's exact test). Subsequent 2 x 2 post-hoc analyses with a Bonferroni correction were conducted to investigate this difference. It was found that the proportion of non-traders was significantly smaller in the student group than the non-student group ($\chi^2$= 15.971, $p$<.001) and the clinician group ($p$<.001, Fisher's exact test). No significant difference between the proportion of non-traders in the non-student and clinician groups was found ($\chi^2$= 1.264, $p$=.1.00). All participants, including zero-traders were included in the subsequent analyses.

**Table 8.3. Proportion of zero-traders by the three participant groups.**

| Group | Number of participants | Number of zero-traders |
|---|---|---|
| Student | 154 | 1 |
| Non-student | 156 | 18 |
| Clinician | 51 | 9 |

### 8.2.3 Results

A 3 (speech in noise) x 3 (localisation) x 3 (effort and fatigue) x 2 (method) mixed ANOVA was conducted.

#### *Hearing utility*

Figure 8.1 shows the mean hearing utility value for each of the 27 scenarios as valued by the 50-year condition and the 10-year condition.

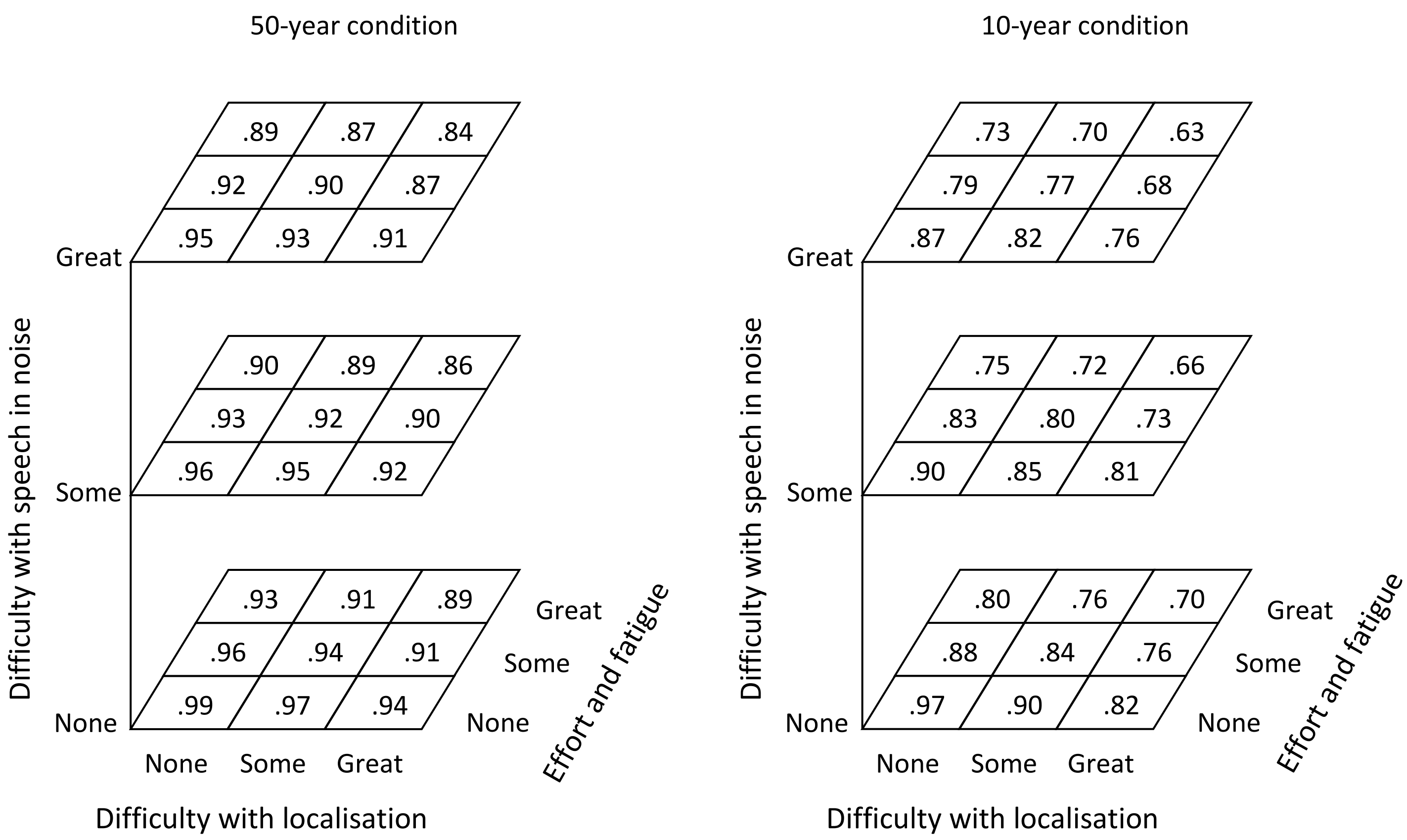


**Figure 8.1. Mean hearing utility valuations for the 27 scenarios by the 50-year condition (left) and the 10-year condition (right).**

### Effect of the time-trade off method used

A significant main effect of method was found ($F(1,359) = 121.232$, $p<.001$, $\eta_p^2 = .481$) with participants in the 10-year condition willing to trade proportionately more life years (mean utility across scenarios: .787, SD = .14) than those in the 50-year condition (mean utility across scenarios = .917, SD = .08). A significant speech in noise x localisation x method interaction was found ($F(3.801, 3.743) = 5.711$, $p<.001$, $\eta_p^2 =.016$) and a significant localisation x effort and fatigue x method interaction was found ($F(3.851, 1382.358) = 5.946$, $p<.001$, $\eta_p^2=.016$). These interactions were investigated further by evaluating the simple effects of method separately for each combination of localisation and (either) speech in noise and effort and fatigue. The simple effect of method was found for each combination of the other levels (all $p<.001$). However, as can be seen from Figure 8.2 the difference between the two methods increased as difficulty on the dimensions increased. When there was no difficulty with localisation, the mean difference between the two methods varied between 0.53 and .145 depending upon the level of difficulty on the other levels. However, when there was great difficulty with localisation, the difference between the two methods was greater (between .129 and .195).

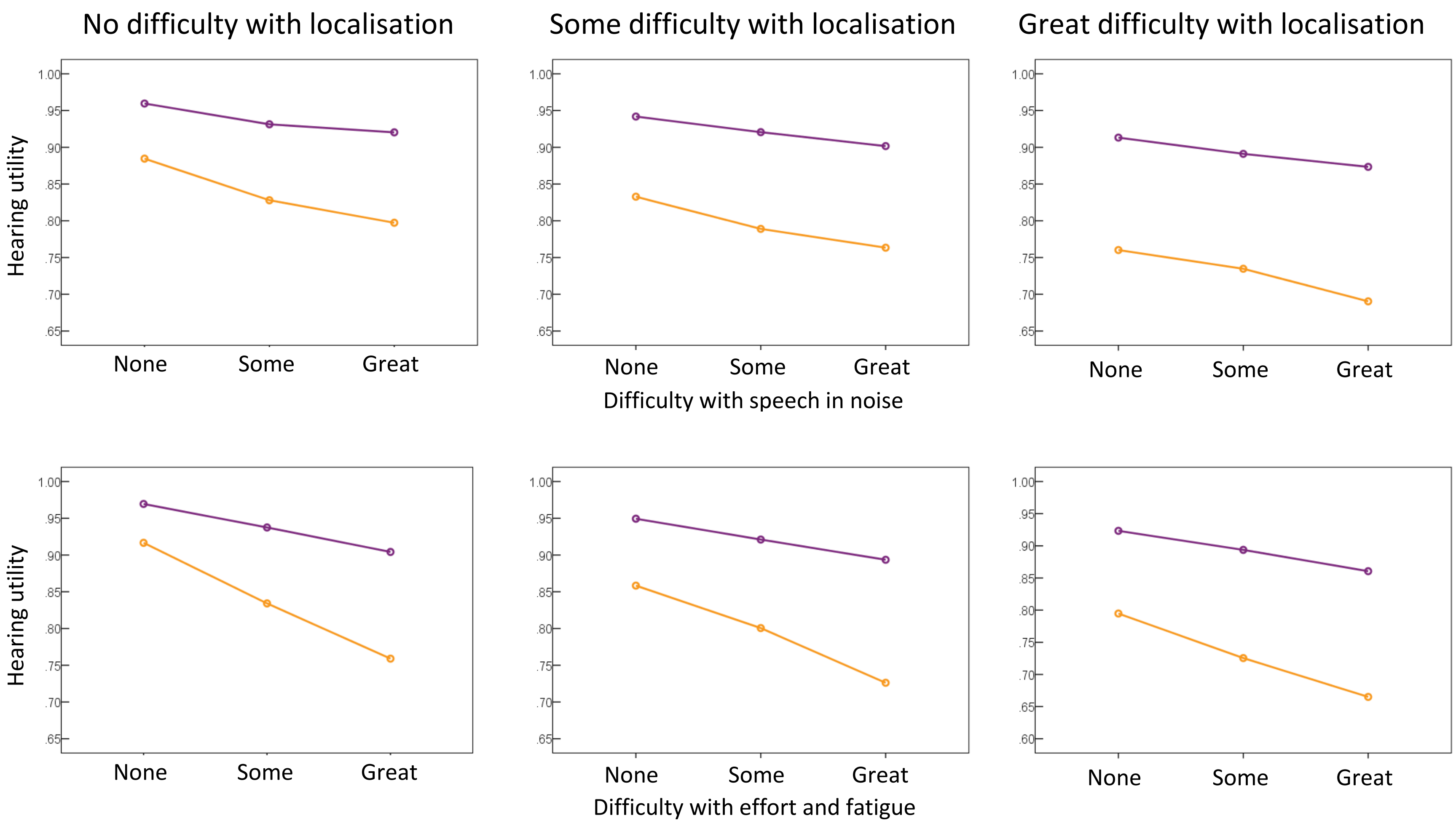


**Figure 8.2. Mean utility values for both method conditions at each level of the three dimensions. Purple line indicates 50-year condition and orange line indicates 10-year condition.**

### Are there systematic differences in hearing utility values between scenarios?

Significant main effects were found for each dimension (speech in noise: $F(1.501, 539.029) = 262.076$, $\eta_p^2 = .422$, localisation: $F(1.335, 479.434) = 338.260$, $\eta_p^2 = .485$, effort and fatigue: $F(1.323, 475.028) = 402.464$, $\eta_p^2 = .529$, all $p<.001$). Pairwise comparisons demonstrated that utility values decreased significantly as difficulty on each dimension increased (all $p<.001$). A significant speech in noise x localisation x effort interaction was also found ($F(6.880, 2469.954) = 2.896$, $p=.005$, $\eta_p^2 = .008$). This interaction was investigated further by evaluating the simple effects of each dimension at each combination of the other dimensions. Significant simple effects were found for all combinations of levels (all $p<.001$) and pairwise comparisons demonstrated that utility values decreased significantly as difficulty on each dimension increased (all $p<.01$). However, the difference between the levels varied depending upon the difficulty of the other two levels. For example, Figure 8.3 shows the interaction between speech in noise and effort and fatigue at each level of localisation. As difficulty in localisation increased, utility values decreased. When there was 'no difficulty' with localisation, utility values at each level of effort and fatigue, decreased more sharply between 'no difficulty' and 'some difficulty' than they did between 'some difficulty' and 'great difficulty'. As localisation difficulty increases however, this effect becomes less pronounced and starts to go in the opposite direction when localisation difficulty is great.

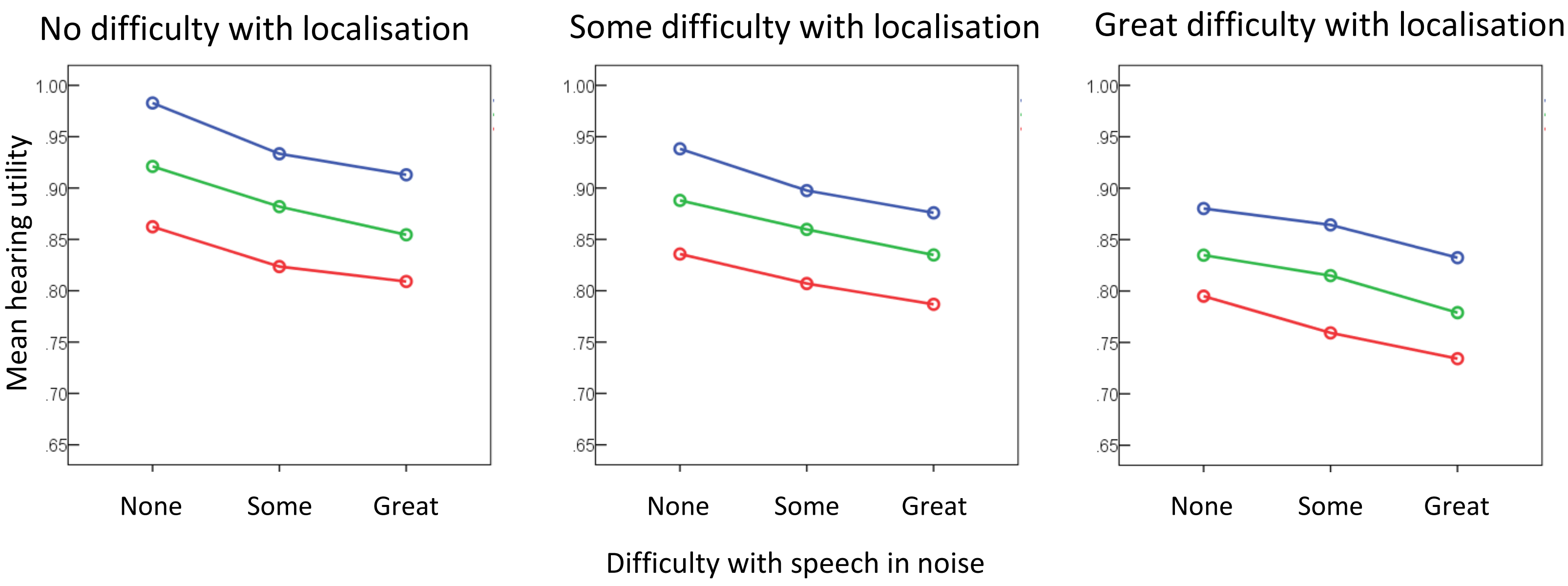


**Figure 8.3. Mean hearing utility values for each level of speech in noise and each level of effort and fatigue (blue line = 'No difficulty', green line = 'Some difficulty', red line = 'Great difficulty') at each level of localisation (left = 'No difficulty', middle = 'Some difficulty', right = 'Great difficulty').**

### Importance of each dimension

Average differences between no difficulty and great difficulty were calculated for each of the three dimensions (average of the nine scenarios with no difficulty minus the average of the nine scenarios with great difficulty) for both time-trade off methods. This created two 'dimension difference' values (one for each time-trade off method) which are displayed in Table 8.4. A 3 (dimension) x 2 (method) mixed ANOVA was conducted. A significant main effect of dimension was found ($F(1.695, 608.425) = 51.804$, $p<.001$). Pairwise comparisons demonstrated that the effort and fatigue dimension difference value was significantly larger than the localisation and speech in noise dimension difference values (both $p<.001$). In addition, the localisation dimension difference value was significantly larger than the speech in noise dimension difference value ($p<.001$). A main effect of method was found with the dimension difference scores being significantly higher in the 10-year valuation group ($F(1,359) = 94.505$, $p<.001$). A significant dimension x method interaction was also found ($F(1.695, 608.425) = 13.184$, $p<.001$). A simple effects analysis of this interaction, demonstrated that in the 50-year condition there was no significant difference between dimension difference scores for speech in noise and localisation ($p=.558$) but there were significant differences between speech in noise and effort and fatigue ($p<.001$) and localisation and effort and fatigue ($p=.006$). For the 10-year valuation group there were significant differences between all dimensions ($p<.001$).

**Table 8.4. Mean dimension difference scores for both method conditions. SE in parentheses.**

| | Speech in noise | Localisation | Effort and fatigue |
|---|---|---|---|
| 50-year condition | .040 (.004) | .045 (.004) | .061 (.005) |
| 10-year condition | .075 (.005) | .108 (.006) | .140 (.008) |

### Influence of demographic variables

40.2% of participants indicated that they had worked with people who had a hearing loss. An independent samples t-test showed that average valuations were significantly higher amongst those who had worked with individuals with hearing loss ($M=.91$, $SD = .10$) than those who had not worked with individuals with hearing loss ($M=.86$, $SD = .13$, $t(353.156 = 3.957$, $p<.001$). Just under half of the sample (47.1%) indicated that some members of their close family had a hearing loss but only 8.6% indicated that they had a hearing loss themselves. No significant differences between these groups were found. A Kendall's tau correlation demonstrated that age was significantly positively correlated with average hearing utility values ($\tau = .274$, $p<.001$).

A multiple linear regression analysis on the average hearing utility with the enter method found that method and age explained 31.3% of the variance in willingness to trade. The method significantly predicted willingness to trade as did age. However, when working with hearing loss was added, the model was not significantly improved ($R^2$ change = .006, see Table 8.6).

### Age weighting

As age was found to significantly predict willingness to trade, in order to appropriately represent the responses across ages, the valuations for the combinations of difficulties were age weighted using UK population estimates from the Office for National Statistics (2013). Age-weighted valuations for the 27 scenarios from both groups are shown in Figure 8.4.

**Table 8.5. Summary of regression analysis for variables predicting willingness to trade (N=361). *** indicates p<.001.**

| Predictor | Model 1 | | | Model 2 | | | Model 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | B | SE | β | B | SE | β | B | SE | β |
| Method | .003 | .00 | .502 | .003 | .00 | .464 | .003 | .00 | .454 |
| Age | | | | .002 | .00 | .258 | .002 | .00 | .241 |
| Worked with hearing loss | | | | | | | .019 | .01 | .078 |
| $R^2$ | | .250 | | | .313 | | | .317 | |
| F change | | 121.218*** | | | 34.016*** | | | 3.019 | |

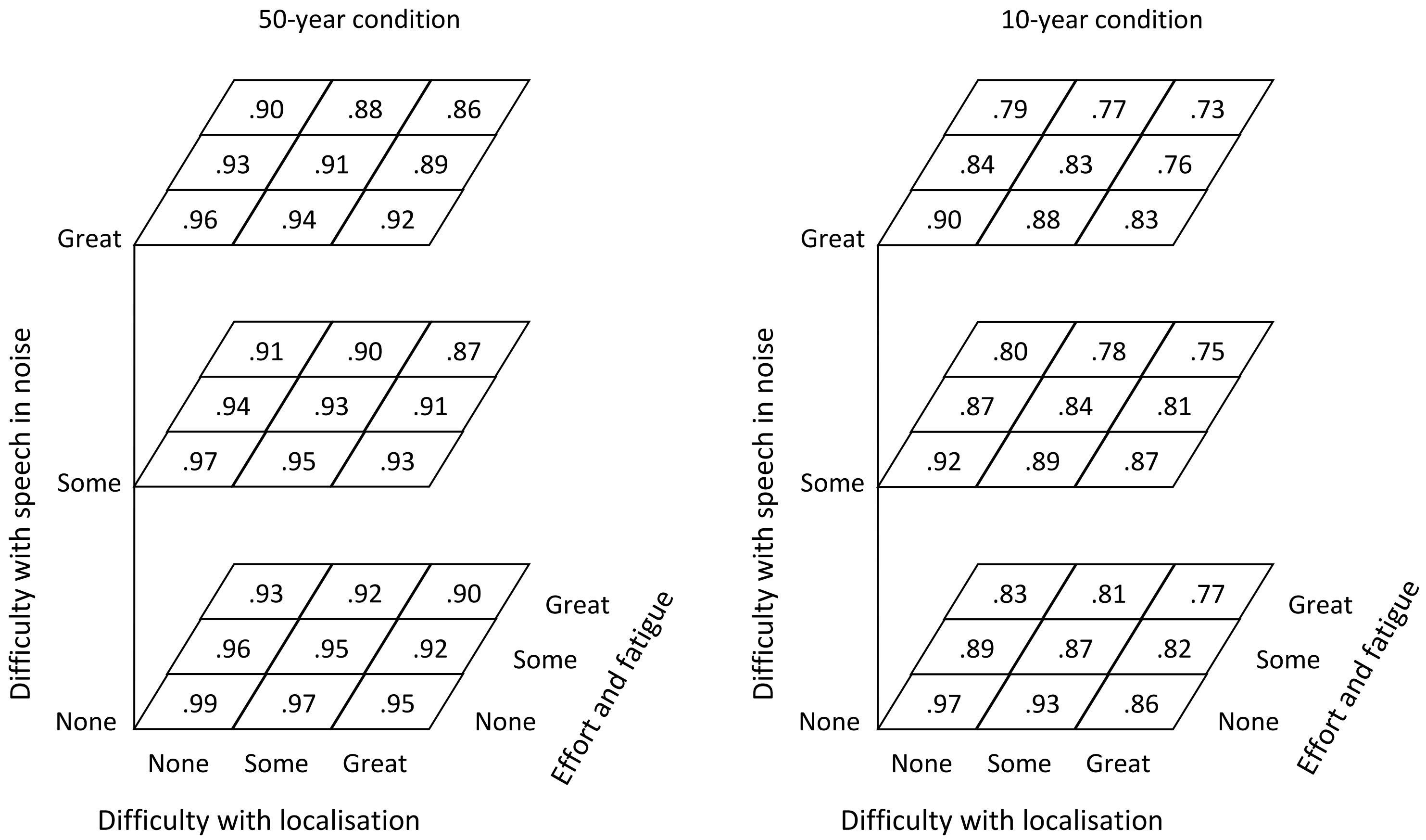


**Figure 8.4. Age weighted hearing utility valuations for the 27 scenarios by the 50-year condition (left) and the 10-year condition (right).**

### 8.2.4 Discussion

#### *Systematic differences*

There were systematic differences in the number of years traded for the different scenarios. Consistent with Summerfield et al. (2002; 2010) as difficulties increased in severity, participants were willing to trade more years of life to relieve the difficulties. This result confirms that participants understood the task for both methods. Some participants were willing to trade years of life in the condition where no difficulties were described (as can be seen from the mean utility values being less than 1 in Figure 8.4). This is likely to be due to the wording used in the scenarios (see Table 8.2). In the 'no difficulty' description of effort and fatigue the description mentioned that 'you have to concentrate a little' and in the speech in noise dimension the description was 'usually picking up all of the words'. The wording of the descriptions for this scenario were chosen to be closely matched to everyday listening by normal hearing listeners, however it is possible that participants perceived perfect hearing to be better than this; not needing to concentrate at all and picking up all the words said and were therefore prepared to trade years of life to achieve this level of performance.

#### *Importance of dimensions*

Effort and fatigue was found to be the most important dimension with participants willing to trade more years of life to relieve difficulties on this dimension than on either of the other two dimensions. There are three possible explanations for this result. (1) Effort and fatigue may be considered to be more important due to familiarity with difficulties in this dimension. Responses to the demographic questionnaire indicated that the majority of participants had no difficulties with their own hearing therefore for many, they may not have had much experience with difficulty localising sound sources or understanding speech in the presence of background noise. Effort and fatigue on the other hand encompasses many aspects of life which participants are likely to have experienced. As a result participants may be more able to appreciate difficulties in this dimension over the other dimensions and therefore more willing to trade years of life to relieve difficulties. (2) Effort and fatigue may be considered to be the most important dimension due to an additive effect. Although consideration was made to keep the three dimensions separate from each other, the description of effort and fatigue may have overlapped with the other two dimensions. For example 'You have to put in some effort to hear what people are saying' may have combined with the speech in noise dimension. (3) Effort may be considered to be the most important dimension due to the position in the questionnaire. A limitation of the current study was that the three descriptions for each scenario were viewed in the same order:

speech in noise, localisation, and effort and fatigue. It may be that participants placed more weight on the latter simply because it was the most recent description before they answered.

The majority of research investigating the benefits of binaural hearing has focused on listening performance and self-rated listening ability, with less emphasis on the cognitive demands that are associated with monaural hearing, such as increases in effort and fatigue (see Noble, 2006; and Sammeth et al., 2011 for reviews). However, it may be that the reduction in cognitive demands from binaural hearing has a greater impact on quality of life than has previously been considered. Neither the HUI3 nor the EQ5D include direct questions on effort and fatigue. Thus the YHRQL enables a test of this hypothesis. If reductions in effort and fatigue are valued as being more important than listening ability the YHRQL offers a way to measure the impact of this on hearing related quality of life.

### *Effect of the time-trade off method used*

No evidence of constant proportional trade-off was found. Two different versions of the time-trade-off method were used: One group of respondents were asked to imagine that they were 30 years old and had **50 years** to live and were instructed to indicate how many years of life they would **give up** in order to have perfect hearing. Another group of respondents were asked to imagine that they had **10 years** of life remaining and were instructed to indicate how many years living with perfect hearing they thought was **equivalent** to living 10 years with the difficulties described in the scenario. Two methods were chosen as there is no consensus on what the most appropriate time-trade off method is (Arnesen & Trommald, 2005; Attema, Edelaar-Peeters, Versteegh, & Stolk, 2013). Respondents in the 10-year condition were willing to trade proportionately more years than respondents in the 50-year condition. There were four differences between the two valuation methods that could account for this difference.

The first difference is the time horizon used: 10 years or 50 years. The fact that participants were willing to trade proportionately more in the shorter time frame is consistent with Attema and Brouwer (2010) who found participants were willing to trade a higher proportion of life to be relieved of back pain when there were 14 years left than when there were 27 years left. However, this finding is not consistent with others such as Dolan and Stalmeier (2003) who found participants traded a greater proportion of life with a longer time horizon. Attema and Brouwer may have found conflicting results to Dolan and Stalmeier due to the second difference in the present study: differences in the way in which participants were instructed to respond. For instance, Attema and Brouwer asked participants to indicate how many years in full health they considered to be equivalent to living a fixed period of time (either 14 or 27 years) in a described health state. Dolan and Stalmeier on the other hand, asked participants to state how many years of their remaining life (which was either 10 or 20 years) they would give up in order to have perfect health. In the present study, the shorter time frame asked respondents to indicate equivalence (consistent with Attema & Brouwer, 2010) whereas the longer time frame asked respondents to give up years of life (consistent with Dolan & Stalmeier, 2003). The equivalence method is more conceptually demanding than simply stating the number of years one would give up. Thus it is unclear whether differences between the two methods arose due to the different time frames used or the method of responding.

However, there is a third difference in that the concept of foregoing life years was not as explicit in the equivalence version as it was in the give up version. This could account for the fact that people were willing to trade proportionately more life years when using the equivalence version of the method. van Nooten et al. (2013) demonstrated that when the time horizon is made explicitly clear, individuals are less willing to trade. In the present study participants in the 50-year ('give-up') condition received instructions that were more explicit than those in the 10-year ('equivalence') condition. Instructions for the 50-year condition stated "imagine that you are 30 years old and that you will live for **50 more years**, until you are 80 years old." (emphasis in original instructions, see Appendix G) whereas the 10-year condition had instructions which stated "Now imagine that you have 10 years left to live." The forth difference between the valuation methods was the age at which the traded years would be lost. Both groups were instructed that any years lost would be taken from the end of their remaining life but respondents in the 50-year condition were trading years from 80 years old, whereas respondents in the 10-year condition were trading years from 10 years from their current age. No participant was over the age of 80 so no participant was trading years that they had already lived. One might have expected participants in the 50-year condition to trade more due to frailty and declining health in older age, whereas in 10-year time horizon, participants will be likely to be fairly healthy. However, although the questionnaire did not make this explicit, participants may have perceived hearing loss to be part of older age in which they could have time to adapt, whereas in the next 10 years it would have a more sudden impact on their current activities and they may therefore have been more willing to trade years in the 10-year condition.

Thus, consistent with previous research, this study has demonstrated that the time-trade-off method used, and the way in which it is described does influence the number of years people are willing to trade and therefore utility values associated with a health state.

### *Zero-traders*

A minority of respondents from each group were unwilling to trade any life years to relieve difficulties, with the proportion of non-traders being higher in the 50-year condition. A zero-trade can indicate that the participant is indifferent between the two options, does not understand the question, or is unwilling to trade (Arnesen & Trommald, 2004, 2005). Including zero-traders in the analyses can result in high utility values (as a zero trade corresponds to a hearing utility value of 1). However, excluding zero-traders can have the opposite effect and indicate a lower utility value than may be the case. There is no consensus in the literature as to whether non-traders should be included or excluded from analyses (Arnesen & Trommald, 2005).

This study sought to establish whether the dimensions in which binaural hearing can provide benefit matter to informants. It was possible that these dimensions would not be valued as important and therefore informants would have declined to trade life years to alleviate difficulties with some or all of the dimensions. Hence, excluding zero-traders would bias the analyses in favour of the hypothesis that binaural hearing results in gains of quality of life rather than there being no difference. Therefore both traders and zero-traders were included in the analyses in this study. No difference was found between the proportion of non-traders in the 50-year and 10-year conditions which demonstrate that the difference in utility values between the two time-trade-off methods was not due to a difference in the proportion of zero-traders.

The student group of respondents had proportionately fewer traders than the non-student and clinician groups. Students are likely to be more familiar with research participation and therefore more likely to engage. Furthermore, they were younger than the other two groups (see Table 8.1). Previous research has demonstrated that younger respondents are more willing to trade years of life than older respondents (e.g. van Nooten et al., 2009, 2013).

### *Influence of demographic variables*

Those informants who had worked with people with hearing loss were less willing to trade than those informants who had not worked with people with hearing loss. It may be that these individuals are more familiar with the difficulties faced by hearing impaired individuals and the options available to them and therefore do not view the difficulties as being as impactful on daily life as those who have not worked with hearing loss. However, a regression analysis indicated that experience working with hearing loss did not significantly explain more variance over method and age. It was found that older adults were willing to trade fewer years than younger adults which is consistent with previous research (e.g. van Nooten et al., 2009, 2013). A larger, more representative sample of respondents would improve the valuations of utility. Age weighting using the most up to date population statistics available served to appropriately represent valuations from all ages. It is these values that were used in Study 2.

## 8.3 Study 2: Questionnaire validation

It is important to assess the validity of new instruments by determining whether they are measuring what they intended to measure (construct validity, Cronbach & Meehl, 1955) and whether they are also capable of detecting differences between clinically distinct groups (sensitivity). This study sought to validate the YHRQL by assessing the construct validity and sensitivity of this questionnaire. To do this, firstly the YHRQL was administered to three groups of adult CI users: unilateral CI users, users of bimodal aiding, and users of bilateral CIs. The bilateral CI users and bimodal users completed the questionnaire twice, once considering their life if they only had their first (or only) CI, and again considering their life with their two devices. Utility values gathered from study one were assigned to each patient for each listening condition based on their responses. To assess the construct validity of the YHRQL, correlations were conducted between YHRQL utility values and scores on the SSQ and performance on listening tasks. To assess the sensitivity of the new questionnaire, comparisons were made between utility values for monaural and binaural hearing, and also between different types of binaural hearing (bimodal devices and bilateral CIs).

### 8.3.1 Method

***Participants***

The questionnaire was mailed to 31 CI users who had participated in a previous research project at the University of York (see Table 5.1). Implicit consent was obtained by the returning of the questionnaire. 27 participants completed and returned the questionnaire. A further bilateral CI participant completed the questionnaire whilst taking part in another experiment being conducted at the University of York. All participants were adults living in the UK. Summary demographic data of these participants is shown in Table 8.6. The average duration for which the bilateral participants had used two CIs was 8.4 years (SD = 4.4). The Department of Psychology Ethics Committee at the University of York approved the study.

**Table 8.6. Summary demographic data of participants.**

| Group | N | Gender (n female) | Mean age in years (SD) | Years of first implant use (SD) |
|---|---|---|---|---|
| Unilateral | 8 | 1 | 70.6 (17.6) | 10.9 (3.6) |
| Bimodal | 9 | 6 | 64.3 (9.4) | 7.4 (3.4) |
| Bilateral | 11 | 5 | 64.9 (8.0) | 12.4 (5.4) |

### *Materials*

A questionnaire consisting of three questions was created (see Figure 8.5). The questions asked participants about their everyday hearing on the three dimensions defined in study one. Respondents complete the questionnaire by selecting one of five descriptions. The wording of descriptions 1, 3 and 5 was intentionally exactly the same as that used to describe the “No difficulty”, “Some difficulty”, and “Great difficulty” scenarios in the first study (see Table 8.2) so that the wording used to elicit valuations from informants was the same as the wording that patients used to describe their own hearing ability. In addition to the three levels of function used in study one, the questionnaire contained two further levels, one between ‘No difficulty’ and ‘Some difficulty’ (worded as “Between 1 and 3”) and one between ‘Some difficulty’ and ‘Great difficulty’ (worded as “Between 3 and 5”). These levels were included to allow for a greater sensitivity of differences to be detected.

By placing a tick in one box under each heading below, please indicate which statement best describes your own hearing **when using your two cochlear implants together.**

Please do not tick more than one box under each heading.

Date:

P/N:

**Understanding speech when there is background noise**

- ☐ 1. When a friend speaks to you while the TV is on or other people are chatting in the same room, you can hear your friend speaking easily, usually picking up all of the words they say.
- ☐ 2. Between 1 and 3.
- ☐ 3. When a friend speaks to you while the TV is on or other people are chatting in the same room, you can hear your friend speaking, but you can only pick out some of the words they say. This can lead to confusion if you miss an important word. Sometimes you need them to repeat themselves or to turn the volume down for you to understand them.
- ☐ 4. Between 3 and 5.
- ☐ 5. When a friend speaks to you while the TV is on or other people are chatting in the same room, you find it very difficult to hear your friend speaking. You are usually unable to pick out the words they say. This regularly leads to misunderstanding and confusion. The room needs to be completely quiet for you to understand them.

**Working out where sounds are coming from**

- ☐ 1. You can work out where sounds are coming from accurately. You can point to where a sound is coming from easily.
- ☐ 2. Between 1 and 3.
- ☐ 3. You have some difficulty working out where sounds are coming from. You can usually tell if a sound is coming from the right- or left-hand side, but you cannot be more accurate than that. As a result, you are not always sure who is speaking when you are in a group with several people.
- ☐ 4. Between 3 and 5.
- ☐ 5. You have great difficulty working out where sounds are coming from. You cannot even tell if a sound is coming from the right- or left-hand side without looking around. As a result, you find it very difficult to tell who is speaking when you are in a group with several people. You are also worried about your safety outdoors because of your difficulty working out where sounds are coming from.

**Effort and fatigue**

- ☐ 1. You have to concentrate a little when you are trying to hear something or someone. You can hear what people are saying with only a little effort. By the end of the day, you are **not** mentally or physically tired because of your hearing.
- ☐ 2. Between 1 and 3.
- ☐ 3. You have to concentrate quite hard when you are trying to hear something or someone. You have to put in some effort to hear what people are saying. By the end of the day, you are moderately mentally and physically tired because of your hearing.
- ☐ 4. Between 3 and 5.
- ☐ 5. You have to concentrate very hard when you are trying to hear something or someone. You have to put in a great deal of effort to hear what people are saying. By the end of the day, you are extremely mentally and physically tired because of your hearing.

Questionnaire **Please check you have filled in the other side as well** VO1a

**Figure 8.5. YHRQL with instructions for bilateral two implant listening. Participants responded by ticking a box for each question next to the description that best described their hearing ability.**

The questionnaire was one page in length. Unilateral CI users received a single sided sheet whereas bimodal and bilateral CI users received a double-sided sheet. The wording of the instructions differed slightly for each combination of devices. On one side the participants were asked to “indicate which statement best describes your own hearing **when using your cochlear implant**’ (unilateral), ‘**when using your cochlear implant on its own**’ (bimodal) or ‘**when using your first cochlear implant on its own**’ (bilateral). The other side contained the same questions but asked the participant to ‘indicate which statement best describes your own hearing **when using your cochlear implant together with your hearing aid**’ (bimodal) or ‘**when using your two cochlear implants together**’ (bilateral).

### *Procedure*

Participants completed the questionnaire in their own time. One participant completed the questionnaire during one of the sessions of the experiments reported in Chapters 5 and 6. The rest of the participants completed the questionnaire on average 2 years later. Two hearing utility values were assigned to each unilateral CI user using the valuations from study one (one from the 50-year condition and the other from the 10-year condition). For the bimodal and bilateral CI users, four hearing utility values were assigned: two when they answered considering their own hearing with their first (or only) CI (one from each valuation group), and two when they answered considering their own hearing with both their devices (one from each valuation group).

To examine the test-retest reliability of the questionnaire, 14 months after the questionnaire had been completed another copy of the questionnaire was sent to the 27 participants originally contacted by post (re-test reliability could not be assessed with the one participant who completed the questionnaire whilst taking part in another experiment at the University of York due to insufficient time passing). 25 participants returned the completed questionnaire (one unilateral CI user and one bimodal user did not).

### *Analyses*

#### Utility values for intermediary states

There were no valuations derived from study one which considered the between level responses (between ‘No difficulty’ and ‘Some difficulty’ and between ‘Some difficulty’ and ‘Great difficulty’). Therefore utility values for these responses were interpolated using the available valuations gathered in study one.

To calculate the utility when responses included one between level response, utility values for responses either side of the between level were averaged. For instance, using the response numbers to the three questions shown in Figure 8.5, to calculate the utility value for a 121 response (no difficulty with speech in noise, between no difficulty and some difficulty with localisation, and no difficulty with effort and fatigue) the utility value of 111 and the utility value of 131 (.97 and .93 respectively with valuations from the 10 year condition) were averaged to produce the new utility value (.95). This method produced 54 between level utility values for each valuation method.

When there were two between level responses, four utility values gathered from study one were averaged to produce the new utility value. These were the four utility values either side of the between level responses. For instance to calculate the utility value for a 122 response, utility values from 111 ,113, 131, and 133 (.97, .89, .93, and.87 respectively with valuations from the 10 year condition) were averaged to produce the new utility value (.92). This method produced 36 between level utility values for each valuation method.

To calculate the utility when responses to all three questions were between the three levels, eight utility values were averaged. For instance to calculate the utility value for a 222 response utility values from 111, 113, 131, 133, 311, 313 , 331, and 333 (.97, .89, .93, .87, .92, .87, .89, and .84 respectively with valuations from the 10 year condition) were averaged to produce the new utility value (.90). This method produced 8 between level utility values for each valuation method. Appendix H contains a full table of utility values for both the 50-year and 10-year valuations.

All of the following analyses were conducted with IBM SPSS Statistics 21.

### Monaural listening

This study asked bimodal and bilateral participants to complete the YHRQL considering their life if they only had their first (or only) CI. There is a risk that these responses will be biased to report greater difficulty with one CI than is actually the case due to being unfamiliar to listening with just one CI. To check that this was not the case a between subjects ANOVA was conducted between the three groups when considering their hearing with their first (or only) CI.

### Construct validity

Participants had previously completed the SSQ and a battery of listening tests on average two years earlier (see Chapters 5 and 6). The listening test battery contained a variety of tests. Of interest to the present study were the results of tests of sound localisation and speech perception in the presence of one, six or twelve other talkers. These tests were most closely related to the dimensions included in the YHRQL. Correlations between participants' hearing utility values and participants' scores on the SSQ and between participants' hearing utility values and participants' performance on the listening tasks were calculated to assess the construct validity of the questionnaire. Participants had previously completed the HUI3 and EQ5D questionnaires (see

Chapter 6). To enable comparisons with the new questionnaire, correlations were also conducted between the health utilities measured with the HUI3 and EQ5D with SSQ scores and performance on listening tasks. . All correlations were calculated on scores obtained from participants when considering their experience in their normal configuration (two CIs for bilateral CI users, one CI and a contralateral acoustic hearing aid for bimodal users and one CI for unilateral CI users).

#### Sensitivity

To assess whether the YHRQL could distinguish between clinically distinct groups a Wilcoxon signed rank test was conducted to examine the difference in hearing related quality of life between using one device and two devices. In addition, a Mann Whitney U test was conducted to test for differences in the benefit from a second device between the bimodal and bilateral groups.

#### Reliability

To examine the test-retest reliability of the YHRQL, Pearson correlations were calculated between utility values obtained from the initial completion of the questionnaire and utility values obtained from the completion of the questionnaire 14 months later.

### 8.3.2 Results

***Monaural listening***

A between-subjects ANOVA found no significant main effect of group using utility values from the 10-year valuations ($F(2,25) = .721$, $p=.496$) or the 50-year valuations ($F(2,25) = .794$, $p=.463$).

***Construct validity***

#### Relationship to SSQ scores

Correlations are shown in Table 8.7. Strong positive correlations between SSQ scores and hearing utility values obtained from the YHRQL using the two different valuations were found. Health utility scores measured by the EQ5D and HUI3 did not distribute normally so Kendall’s tau correlations were calculated. No relationship was found between SSQ scores and the health utility values from the EQ5D. Moderate positive correlations were found between SSQ scores (with the exception of the spatial section) and the health utility values from the HUI3.

**Table 8.7. Pearson's product moment (or Kendall's tau) correlation coefficients between measures of utility (YHRQL, 10-year valuations and 50-year valuations; EQ5D;HUI3) and SSQ scores.**

| Measure | SSQ average | SSQ speech | SSQ spatial | SSQ qualities |
|---|---|---|---|---|
| YHRQL (10-year valuations) | .660*** | .627*** | .652*** | .552** |
| YHRQL (50-year valuations) | .644*** | .609*** | .632*** | .546** |
| EQ5D | .214† | .192† | .243† | .195† |
| HUI3 | .390†** | .391†** | .344†* | .366†* |

**p*<.05, ***p*<.01, ****p*<.001. Bonferroni corrected, †Non-parametric Kendall's tau correlation coefficient.

### Relationship to listening performance

Scores on the listening measures did not distribute normally so Kendall's tau correlations were calculated. The results of these correlations are shown in Table 8.8. Moderate to strong positive correlations were found between hearing utility values on the YHRQL and localisation performance. No other significant relationships were found.

**Table 8.8. Kendall's tau correlation coefficients calculated between measures of utility (YHRQL, 10-year valuations and 50-year valuations; EQ5D; HUI3) and measures of listening performance.**

| | Localisation | | | Speech perception | | |
|---|---|---|---|---|---|---|
| | 3 alternative (60 degree separation) | 5 alternative (30 degree separation) | 5 alternative (15 degree separation) | One competing talker | Seven competing talkers | Twelve competing talkers |
| **YHRQL (10-year valuations)** | .479** | .457** | .384* | .158 | .302 | .337 |
| **YHRQL (50-year valuations)** | .499** | .456** | .374* | .179 | .323 | .353 |
| **EQ5D** | .107 | .230 | .129 | -.112 | -.013 | -.036 |
| **HUI3** | .265 | .318 | .156 | -.011 | .215 | .081 |

*$p$<.05, **$p$<.01 (Bonferroni corrected)

### *Sensitivity*

#### Monaural Vs. Binaural listening

Differences in utility from monaural to binaural listening derived from the YHRQL, EQ5D and HUI3 were not normally distributed. Median utility values for the three questionnaires for both monaural and binaural listening are displayed in Figure 8.6. Wilcoxon signed ranks tests demonstrated that with the YHRQL, the population mean rank was significantly higher with binaural devices than monaural devices when using both valuations (both Z = -3.622, *p*<.001). No significant difference was found between utility values in binaural and monaural listening with the EQ5D (Z = -1.219, *p*=.223). With the HUI3 the population mean rank was higher in the binaural condition than the monaural condition at the level of significance (Z=-1.963, *p*=.050).

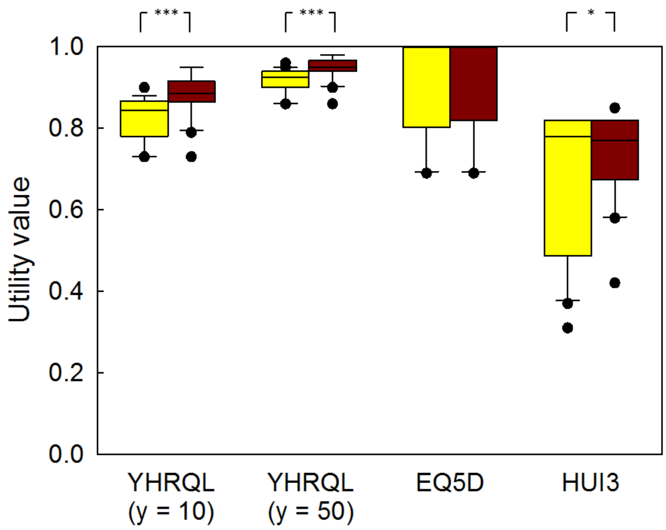


**Figure 8.6. Median utility values for monaural (yellow) and binaural (red) listening measured by the YHRQL, EQ5D, and HUI3. Asterisks indicate significant differences (* p<.05, *** p<.001).**

#### Gain from bimodal and bilateral CI listening

Mann-Whitney U tests showed that the benefit in hearing utility obtained from listening with a second device was significantly higher for the bilateral CI users (10 year: median = .09, IQR = .10, 50 year: median = .05, IQR = .06) than the bimodal listeners (10 year: median = .01, IQR = .03, 50 year: median = .01, IQR = .02) when using the YHRQL for both the 10-year (U = 11.00, Z = -2.932, *p*=.003) and 50-year (U = 12.50, Z =-2.818, *p*=.005) valuations. Benefits in utility using the EQ5D and HUI3 from a contralateral acoustic hearing aid compared to a second CI were compared in Chapter 6 which showed a non-significant difference in the amount of benefit received (see Table 6.8).

#### Cost-effectiveness of bilateral cochlear implantation

Table 8.10 shows that when using the YHRQL and HUI3, the mean gain in utility from bilateral cochlear implantation compared to unilateral cochlear implantation is at or above the threshold of .05 as defined by Bond et al. (2009) as being required in order for bilateral cochlear implantation to be considered cost effective. When compared to bimodal aiding, the gain in utility is below this threshold with all measures.

### Reliability

Correlations were calculated on data from the 25 participants who completed the questionnaire at both time points. Strong positive correlations were found between the utility values measured at the two time points when using both the 50-year ($r = .822$, $p<.001$) and 10-year ($r = .794$, $p<.001$) valuations.

**Table 8.9. Mean gain in utility from bilateral cochlear implantation compared to unilateral cochlear implantation and bimodal aiding. d = Cohen's d**

| Measure of utility | Bilateral CI users listening with one CI (SD) | Bimodal users listening with both devices (SD) | Bilateral CI users listening with both CIs (SD) | Bilateral gain from unilateral CI use (95% CI) | Bilateral gain from bimodal devices (95% CI) |
|---|---|---|---|---|---|
| YHRQL (10 year) | .814 (.052) | .857 (.060) | .903 (.035) | .090 (.054 to .125), d = .43 | .046 (.007 to .091)†, d=.39 |
| YHRQL (50 year) | .910 (.029) | .935 (.034) | .960 (.018) | .050 (.030 to .071), d = .33 | .024 (.002 to.048) †, d= .27 |
| EQ5D | .913 (.106) | .918 (.135) | .920 (.116) | .007 (-.079 to .089), † d = .04 | .003 (-.010 to .107) †, d=.01 |
| HUI3 | .692 (.184) | .708 (.079) | .751 (.127) | .058 (-.056 to .194), † d = .14 | .043 (-.059 to .145), d=.13 |

† Bootstrapped mean and confidence intervals calculated as the assumption of normality was not met.

### 8.3.3 Discussion

***Construct validity***

The YHRQL, containing just three questions, is not as broad in scope as other hearing specific questionnaires (e.g. the SSQ, CCIQ, NCIQ, and the Spatial Listening Questionnaire) yet this study found strong positive correlations between the utility values from the YHRQL and scores on the SSQ. This result demonstrates that the YHRQL measures aspects of hearing that are also measured by the longer SSQ, thus establishing the construct validity of the YHRQL.

Correlations between the SSQ and the HUI3 were less strong. This result was expected as the questions in both the YHRQL and the SSQ are specific to listening, whereas the HUI3 addresses other functional dimensions in addition to hearing. The fact that no correlations were observed between the EQ5D and the SSQ is not surprising, considering that the EQ5D does not contain questions related to hearing and listening.

Unlike the HUI3 and EQ5D, there were strong relationships between localisation performance and hearing utility values from the YHRQL, which offers support on the construct validity of the questionnaire. However, even though the strength of the correlations between utility values and speech perception performance increased as task difficulty increased (from one to twelve competing talkers), the relationships did not survive Bonferroni correction. However significant differences in hearing utility values were found between clinically distinct groups, adding further support for the construct validity of this questionnaire.

***Sensitivity***

Using the YHRQL no differences were found between the three groups when considering life with their first (or only) CI. As utility values were not at ceiling with one CI this measure had the availability to measure improvements from a second device. Using the YHRQL, significant benefits in hearing-related quality of life were observed from binaural listening compared to monaural listening. Furthermore, the YHRQL was able to detect differences between the benefits obtained by two types of binaural listening (bilateral CIs and bimodal devices) with a greater benefit found from a second CI. Consistent with previous research (Barton et al., 2005; Grutters et al., 2007), the EQ5D was found to be insensitive to differences in hearing, with the median utility value being at ceiling for both monaural and binaural listening. This reflects the limitations of this instrument in that it does not have any questions related to hearing, listening, or speech understanding. However, the HUI3, which does contain questions on these domains, was only just able to detect differences between monaural and binaural hearing but as was reported in Chapter 6, it was not able to detect differences between types of binaural hearing. This finding is in line with previous research (Longworth et al., 2014; Yang et al., 2013), which has demonstrated that the HUI3 is somewhat sensitive to detecting differences between groups differing in their hearing ability but isn't always able to detect differences (Summerfield et al., 2006). As one of the more established advantages from bilateral implantation over bimodal aiding is improved spatial listening ability (see Chapters 2 and 5), the fact that the HUI3 does not contain any questions related to spatial listening could account for this limited sensitivity to differences.

### *Reliability*

It was demonstrated that the YHRQL performs well over time, with a strong test re-test reliability.

### *Implications*

This study has demonstrated that the EQ5D is limited in scope and is insensitive for assessing the benefits of binaural over monaural hearing despite the substantial behavioural (Carroll et al., 2011; Kerber & Seeber, 2012; Schafer et al., 2011; Zhang et al., 2010) and self-reported (Flynn & Schmidtke, 2004; Noble & Gatehouse, 2006; Noble et al., 2008b) benefits that can arise as a result of listening with two ears compared to one. When using the YHRQL questionnaire, greater hearing related quality of life was found from binaural listening compared to monaural listening. Furthermore, when comparing bilateral cochlear implantation to unilateral cochlear implantation a small to medium effect size was found, compared to a small effect size with the HUI3. This has important implications for policy makers determining the allocation of funding resources. Currently generic instruments are used to measure the effectiveness component in cost-effective analyses. If they are not able to detect the benefits which binaural devices provide, then the incremental cost-effectiveness ratio of binaural treatments (such as a second CI) is likely to be much higher than current willingness to pay thresholds and therefore treatments are likely to be deemed not cost-effective (see Chapter 4).

This study has developed an instrument that is sensitive to differences between monaural and binaural listening and results in a utility score that can be used in the same manner as current generic quality of life instruments to determine the effectiveness of a treatment. It is recommended that this questionnaire is administered alongside existing instruments such as the HUI3 and EQ5D when assessing treatments for hearing impairment. An effective treatment should result in an increase in utility on the YHRQL but no detriment on the other generic instruments that measure other aspects of health-related quality of life.

### Cost-effectiveness

It was not the primary aim of the current study to assess the cost-effectiveness of a second device for UK adult users of a single CI. However, the present study does suggest that a second device has the potential to be cost-effective. The mean gain in utility of a second CI compared to one CI was .090 (using valuations from the 10-year condition) and .050 (using valuations from the 50-year condition). In a threshold analysis Bond et al. (2009) determined that in order for a second CI to be cost-effective at the current willingness-to-pay threshold of £30,000, the gain in utility would need be at least about .05. Bond et al. made their estimations on the basis of comparing a second CI to individuals already using a single CI. If an individual who currently uses a single CI has sufficient residual hearing remaining it could be argued that the next best alternative to two CIs is bimodal devices. The current study found that the mean gain in utility from a second CI compared to bimodal aiding was .046 (10-year condition) and .024 (50-year condition). Using Bond et al's estimates, this suggests that bilateral cochlear implantation would not be considered cost-effective compared to bimodal aiding.

However, it is important to note that the utility values in this study were obtained from a small self-selecting sample of relatively successful adult CI users (see Chapter 5 for listening performance data). Given how large a sample would be required for a randomised control trial (see Chapter 4), a useful avenue for future research would be to conduct a prospective study in which estimates of the gain in hearing utility from a second device are obtained from a more representative CI sample than that used in the present study. Adults with a unilateral CI who are opting for a second CI or a contralateral acoustic hearing aid, could complete the YHRQL questionnaire before receiving the second device, and then again after they have received the device. If time permitted, the questionnaire could be completed twice before the intervention, separated by three months, to check for any learning effects, and again twice after the intervention to assess if any differences in hearing utility arise only after a prolonged period of use with the second device.

## 8.4 Conclusion

Evident from this study is that although widely used in health economic decisions, the EQ5D is insufficient for detecting differences between types of hearing. The creation of the YHRQL, a questionnaire that is sensitive to different degrees of hearing, will enable differences in hearing-related quality of life to be measured and used in cost-effectiveness analyses. A limitation of the study is the small sample used. However, the results from this study demonstrate the potential for a larger scale study in which a population-representative sample is used to provide the valuations and a larger number of CI users complete the questionnaire.

## 8.5 Summary

- A short questionnaire (the YHRQL), sensitive to the benefits of binaural hearing was developed to assess 'hearing-related' quality of life.
- Adult respondents used two different versions of the time-trade off technique to evaluate 27 health states that varied in their listening ability.
- Participants were willing to trade years of life to relieve hearing difficulties. There was an effect of the time trade off method used, with respondents willing to trade proportionately more in the 10-year time horizon than the 50-year time horizon.
- The YHRQL was administered to a group of 27 CI users to assess the construct validity and sensitivity of the YHRQL.
- Strong correlations between hearing utility measured on the YHRQL and scores on the SSQ established the construct validity of the questionnaire.

# 9 Summary and general discussion

This chapter summarises the findings from the experiments reported in this thesis. Recommendations for clinical practice on the basis of these findings are suggested and options for future research are proposed.

## 9.1 Recap of research aims

The experiments reported in this thesis sought to establish the benefits (and potential drawbacks) to users of a single CI of aiding their non-implanted ear by using either a second CI (bilateral cochlear implantation) or an acoustic hearing aid (bimodal aiding). One aim was to establish the clinical effectiveness of a second device. This was achieved by assessing the performance of patients on a range of listening tasks. Performance with a unilateral CI was compared to performance with bimodal aiding and with bilateral CIs. Self-reported listening ability and quality of life with a second device were also compared with ratings obtained when participants used a unilateral CI. Another aim was to compare the clinical effectiveness between bilateral cochlear implantation and bimodal aiding to determine which option offers profoundly-deafened UK CI users the greater clinical benefit. These two aims were addressed in experiments reported in Chapters 5 and 6.

A second series of experiments focused on head movements as an example of a behaviour that could be employed by CI users, potentially, to gain more benefit from their devices. The aim was to investigate whether head movements could help listeners to improve localisation accuracy and reduce listening effort. A speech-in-noise task was also used to ascertain whether participants adopt optimal head-orientation strategies in difficult listening environments. These aims were investigated in a series of experiments reported in Chapter 7.

Finally, this thesis reported a preliminary assessment of the cost-effectiveness of providing a second device. The first aim was to compare the cost-effectiveness of a second device (either a contralateral acoustic hearing aid or a second cochlear implant) to unilateral cochlear implantation. The second aim was to compare the cost-effectiveness of bilateral cochlear implantation to bimodal aiding. Noting the insensitivity of existing self-report instruments for valuing hearing difficulties, a new self-report instrument was developed and validated; the new instrument was designed to be sensitive to differences in hearing ability whilst being short enough to be completed alongside existing instruments. These aims were investigated in an experiment reported in Chapter 8 and an analysis reported in Appendix C.

## 9.2 Summary of findings

### 9.2.1 Main findings from the study reported in chapter 5

- Compared to unilateral cochlear implantation, listening with bilateral CIs resulted in significantly better sound localisation, and some advantage for speech in noise and speech in speech tasks. However, no significant benefit was found for pitch-related tasks.
- Compared to unilateral cochlear implantation, limited benefit in listening ability was obtained from bimodal aiding. Listeners were able to localise more accurately with bimodal aiding, but no benefit on speech tasks or pitch-related tasks was found.
- Bilateral cochlear implantation was more clinically effective than bimodal aiding, with greater benefit in localising sound sources and perceiving speech in the presence of spatially separated noise.

### 9.2.2 Main findings from the study reported in chapter 6

- Self-reported listening ability was significantly greater with a second device than a single cochlear implant. Bilateral CI users reported a greater benefit in self-reported listening ability than bimodal users.
- Generic health-related quality of life instruments (EQ5D and HUI3) showed no differences between unilateral cochlear implantation and a second device. Furthermore, no differences in health-related quality of life were found between types of binaural hearing: bimodal aiding and bilateral cochlear implantation. As has been demonstrated in Chapters 5 and 6, users of unilateral, bimodal, and bilateral CI users perform differently on listening tasks and self-rated listening ability. These results highlight the limited sensitivity of existing generic health-related quality of life instruments to differences in hearing ability.
- When overall quality of life was assessed with the YorQol, significantly greater quality of life was obtained from a second device compared to unilateral cochlear implantation. However, no difference was found between bimodal aiding and bilateral cochlear implantation.

### 9.2.3 Main findings from the experiments reported in chapter 7

- When orienting to a sound source in the frontal horizontal plane, bilateral CI users were less accurate than NH listeners when the stimulus duration was limited to 1.3s. However, when a continuous stimulus was used, bilateral CI users were as accurate as NH listeners. Despite similar accuracy, bilateral CI users made more complex head movements than NH listeners. Unilateral CI users made more complex head movements when a continuous stimulus was presented but this did not improve their performance.

- When locating sources in the front and rear horizontal planes, bilateral CI users benefited from head movements when the stimulus was greater than five seconds in duration as front-back confusions were reduced. Both bilateral CI users and unilateral CI users made complex head trajectories compared to NH listeners, however unilateral performance remained poor even when head movements were permitted.
- When listening to speech in the presence of background noise, listeners oriented their heads differently depending upon the location of the speech. They did not orient differently depending upon the location of the noise. Individuals who optimized their head position did not perform better than those who did not.

### 9.2.4 Main findings from the study reported in chapter 8

- The time-trade-off technique was used to elicit valuations from NH adults to descriptions of 27 health states that varied in the extent of listening difficulties described. Participants were willing to trade years of life to relieve hearing difficulties. Two time-trade-off methods were used and the study found that the proportion of years respondents were willing to trade differed by method, with respondents willing to trade proportionally more years when a shorter time horizon (10 years) was used compared to when a longer time horizon (50 years) was used.
- A new questionnaire (the YHRQL questionnaire) was developed to measure hearing-related quality of life. Questions related to speech perception, localisation, and effort and fatigue. The questionnaire was completed by a group of CI users. Strong correlations were found between utility values measured with the YHRQL questionnaire and self-rated listening ability using the SSQ, establishing the construct validity of the questionnaire.
- The EQ5D was found to be insensitive to differences in hearing ability and using this instrument a second device would not be deemed cost-effective. The HUI3 is somewhat sensitive to differences in hearing difficulty and using this instrument the gain in utility was just large enough to mean that bilateral cochlear implantation could be considered cost effective. The YHRQL is sensitive to differences between types of hearing and when using this instrument both bimodal aiding and bilateral cochlear implantation would be deemed cost-effective interventions.

## 9.3 General discussion

### 9.3.1 Clinical-effectiveness of a second device

#### *9.3.1.1 Bimodal aiding versus unilateral cochlear implantation*

Previous research has shown mixed results on the clinical effectiveness of bimodal aiding (see Chapter 2). The experiment reported in Chapter 5 compared bimodal aiding to unilateral cochlear implantation on a wide range of listening skills to assess if bimodal aiding is a clinically effective intervention. No previous study had compared bimodal aiding to unilateral cochlear implantation within the same adult participants on as many varied listening measures. Some benefits of bimodal aiding were found. Listening with bimodal devices resulted in significantly better spatial listening performance than listening with a single CI alone. This effect arose despite a conservative Bonferroni correction for multiple comparisons. However, at least for the profoundly-hearing impaired adults tested, bimodal aiding did not improve speech perception ability or performance on pitch-related tasks. However, it is important to note that bimodal aiding did not hinder performance either, despite listeners using two different devices with different processing times and different mappings of frequency to place in the cochleae.

Despite no benefit in listening ability for speech perception and pitch-related tasks measured in the laboratory, listeners did report that they experienced better speech perception, spatial listening and qualities of listening abilities in a self-completed questionnaire. These results demonstrate that listeners may obtain benefits from their contralateral hearing aid that were not measured (or not able to be measured) in the listening tests administered in the study reported in Chapter 5.

#### *9.3.1.2 Bilateral cochlear implantation versus unilateral cochlear implantation*

Consistent with previous research discussed in Chapter 2, greater spatial listening ability with bilateral CIs than a unilateral CI was found (see Chapters 5 and 7). Unlike bimodal aiding, bilateral cochlear implantation provided significant gains to speech perception in the presence of spatially separated noise, and spatially separated talkers compared to a single CI. However, listeners did not benefit from a second CI on pitch-related tasks, highlighting the limitations of CIs in conveying pitch cues. Nevertheless, significantly greater self-reported listening ability in speech perception, spatial listening, and qualities of listening was found for bilateral cochlear implantation compared to unilateral cochlear implantation.

Localisation ability was assessed in Chapters 5 and 7. To enable comparisons between studies, RMS error was calculated and is presented in Table 9.1. Higher RMS errors were found in the experiment reported in Section 7.2 than the other experiments for both bilateral CI and unilateral CI groups. This is likely due to the experiment reported in Section 7.2 having more possible locations (11 compared to 5) over a wider range in azimuth (±75° compared to ±30°). For instance if a participant knows that a sound is being presented from their left hand side but not where on the left they have a one-in-two chance of getting it right in experiment 1 (as they will indicate that the sound was presented from -30° or -15°). Thus if they are wrong they will have an error of 15° for that trial. However, with 11 possible locations (as in experiment 3), if the participant knows that the sound is on the left but not where on the left they have a one-in-five chance of identifying the location correctly. In this experiment the error can be as large as 60° for a trial when the participant indicates the sound came from -75° when in fact it was presented from -15°. This could account for the higher RMS error in experiment 3.

Results from unilateral CI users were consistent across the experiments using 5 locations, with a mean RMS error of around 26°. Whereas bilateral CI users demonstrated better localisation ability in experiment 4 than experiment 1. The RMS error from experiment 1 for the subset of listeners who participated in experiments 3 and 4 was similar to the group mean (mean = 12.30°, SD = 7.13). Therefore it was not simply that the participants who took part in the later experiments were better localisers. Although, both experiments 1 and 4 contained a similar number of trials, this difference could be due to practice and familiarity with the task. In experiment 1 the localisation task was one of several types of listening tasks completed. Furthermore, the task was always completed near the start of the session. Experiment 4 on the other hand was localisation-specific and had 12 conditions lasting a total of about 2 hours (with breaks). Thus performance could have improved over time resulting in lower RMS errors in this experiment.

**Table 9.1. Mean RMS error (°) for sources in the frontal horizontal plane separated by 15°. SD in parentheses.**

| | Number of locations (azimuth range) | Mean length of stimulus | Bilateral | | Unilateral | |
|---|---|---|---|---|---|---|
| Experiment 1 (reported in Chapter 5) | 5 (-30° to +30°) | 1.7 seconds | 13.30 (6.02) | | 27.31 (4.88) | |
| Experiment 3 (reported in Section 7.2) | 11 5 (-75° to +75°) | 1.3 seconds | 25.17 (11.37) | | 56.24 (14.62) | |
| | 11 5 (-75° to +75°) | Continuous | 20.63 (11.25) | | 47.88 (17.41) | |
| Experiment 4 (reported in Section 7.3) | | | Head movement not permitted | Head movement permitted | Head movement not permitted | Head movement permitted |
| | 5 5 (-30° to +30°) | 0.8 seconds | 6.23 (3.50) | 8.02 (3.79) | 27.38 (3.86) | 25.01 (5.20) |
| | | 2.5 seconds | 8.55 (4.90) | 7.43 (4.21) | 25.11 (6.04) | 24.71 (3.87) |
| | | Continuous | 7.85 (3.29) | 8.76 (2.39) | 25.92 (5.36) | 26.25 (4.41) |

#### *9.3.1.3 Bilateral cochlear implantation versus bimodal aiding*

It is important to ascertain which option, bilateral cochlear implantation or bimodal aiding, provides the greater benefit in order for patients using a unilateral CI to make an informed decision when opting to aid their non-implanted ear. No difference in the amount of benefit obtained from either a contralateral acoustic hearing aid or second CI was found for pitch-related tasks of emotion perception and melody recognition. This result is consistent with a previous study (Cullington & Zeng, 2011) which compared a similar number of bimodal and bilateral participants on pitch-related tasks. However, the experiment reported in Chapter 5, demonstrated that a second CI provided a greater benefit than a contralateral hearing aid for listening to speech in the presence of spatially separated noise and an even greater benefit was found for spatial localisation tasks. Both groups demonstrated improved self-reported ratings of listening ability however the bilateral CI users reported a greater benefit than bimodal users for spatial listening and qualities of listening. These findings suggest that bilateral cochlear implantation offers more clinically effective benefits than bimodal aiding.

### 9.3.2 Head movements

#### *9.3.2.1 Accuracy of localisation*

It is a common assumption that listeners make head movements to resolve front-back confusions (Plack, 2014). However, head movements did not improve overall localisation accuracy for NH adults. For bilateral CI users, permitting head movements improved performance when sounds could be presented in either the front or rear horizontal plane if the stimulus was long enough. With a short (0.8s) sound, head movements hindered performance. As was discussed in Section 7.3, there may have been insufficient time to make and complete an informative head movement with a short stimulus. Bilateral CI users made fewer front-back errors when head movements were permitted if the stimulus was 5 seconds or longer in duration. Thus, head movements can improve localisation performance of CI users by helping to reduce the number of front-back confusions.

#### *9.3.2.2 Duration of stimulus*

The orientation experiment reported in Section 7.2 demonstrated that the duration of the stimulus was important for orientation accuracy but only for bilateral CI users. NH listeners were able to accurately orient to a short stimulus (1.3 seconds) and therefore received no additional benefit from a longer continuous stimulus. On the other hand, unilateral CI users were unable to orient accurately to a stimulus even when it was continuously repeated. With a 1.3 second stimulus bilateral CI users had a better orientation accuracy than unilateral CI users but performed significantly worse than NH listeners. However, when the stimulus duration increased to a continuous stimulus, performance by bilateral CI users was as good as performance by NH listeners.

The sound localisation experiment reported in Section 7.3 also demonstrated that NH listeners did not benefit from additional time in localising a sound stimulus. However, the effect of duration was mixed for bilateral CI users. When locating sources in the frontal horizontal plane and head movements were not permitted, bilateral CI users had a significantly higher overall accuracy for a short 0.8 second stimulus than a 5.4 second, or continuous stimulus. However, when locating sources in the front and rear horizontal plane and head movements were permitted overall accuracy was significantly higher for a long stimulus than medium and short stimuli. Nevertheless, increasing the duration of the stimulus reduced the number of front-back confusions made by bilateral CI users. Thus bilateral CI users can benefit from longer stimulus durations when orienting to sounds on the frontal horizontal plane and a stimulus of at least 5 seconds can improve sound localisation performance by reducing the number of front-back confusions made.

#### *9.3.2.3 Complexity of head movement*

In the orientation experiment reported in Section 7.2, despite similar levels of accuracy to NH listeners when a continuous stimulus was presented, bilateral CI users made more complex head movements when orienting to a sound source. They made more reversals in head direction, had longer durations of movement, and also fixated at their final orientation for longer before reporting that they had finished orienting. More complex head movements by bilateral CI users were also observed in the sound localisation experiment reported in Section 7.3. However, in this latter experiment they did not perform as well as NH listeners. Possible reasons for increased head movement complexity include uncertainty about where the stimulus was presented from or a learned behavioural response. These alternatives were discussed in detail in Sections 7.2 and 7.3 and an experiment to attempt to tease apart these two explanations was proposed in Section 7.3 in which participants would rate the certainty of their responses.

### 9.3.3 Cost-effectiveness of a second device

The experiments reported in Chapters 6 and 8 have highlighted the inadequacy of existing generic health-related quality of life instruments for detecting benefits in hearing ability from a second device. It is inarguably a challenge for any generic quality of life instrument to be sensitive to changes that affect a very specific area of life, whilst being short enough to complete, yet broad in coverage. Chapter 4 highlighted that different health-related quality of life measures (and different methodologies) can impact the gain in utility measured from interventions intended to improve hearing, which in turn impact judgements of the cost-effectiveness of the intervention. An advantage of generic health-related quality of life instruments for policy makers is that they can be used to compare the cost effectiveness of multiple treatments across a range of health states – essential for an organization making resource allocations on a finite budget.

However, an undesirable consequence of using insensitive generic self-report instruments is that interventions that result in increased patient quality of life are not funded because the generic instruments do not detect the benefits obtained. This was demonstrated using the EQ5D, where bimodal and bilateral CI users considering their lives with just unilateral CI listening resulted in scores at ceiling (see Chapter 6), which left no room to measure any potential benefit from different additional hearing interventions. The HUI3 is somewhat sensitive to differences between 'no hearing' and 'some hearing' but is less sensitive to differences between 'some hearing' and 'more than some hearing'. In light of these limitations, a new self-report instrument (the YHRQL) was developed that was designed to be sensitive to differences in hearing ability. The new instrument was shown to be valid and reliable and is short enough that it can be administered alongside existing questionnaires.

#### *9.3.3.1 Bimodal aiding Vs. Unilateral cochlear implantation*

The cost of providing a contralateral acoustic hearing aid was estimated in order to inform a preliminary analysis of the cost-effectiveness of bimodal aiding compared with unilateral cochlear implantation. Using the most recent cost-data from the Department of Health (2013), even in the most conservative analysis (in which a hearing aid was replaced every 5 years and all recipients required aftercare), bimodal aiding was found to be a potentially cost-effective intervention compared to unilateral cochlear implantation when the YHRQL was used to elicit utility valuations (see Appendix C). Despite a lifetime cost of just £1,736 per recipient (see Appendix C), the lack of benefit found by the EQ5D and HUI3 mean that bimodal aiding would not be deemed cost effective. This again highlights the need for a measure sensitive to the benefits of binaural hearing compared to monaural listening. This analysis was preliminary using a small number of patients. The results indicate that bimodal aiding has the potential to be cost-effective but this needs to be investigated further with a larger more representative sample of respondents.

#### *9.3.3.2 Bilateral cochlear implantation Vs. Unilateral cochlear implantation*

The utility gain required for bilateral cochlear implantation to be a cost-effective intervention compared to unilateral cochlear implantation had been estimated previously by Bond et al. (2009) to be about .05. Previous research (see Chapter 4) had found that the gain in utility measured using either the HUI3 (Chen et al., 2014; Summerfield et al., 2006) or EQ5D (Summerfield et al., 2006) was lower than this and therefore insufficient for bilateral cochlear implantation to be judged cost-effective. Using the EQ5D, the experiment reported in Chapter 8 found results consistent with previous research in that the gain in utility was insufficient for bilateral cochlear implantation to be considered cost-effective. However, with the HUI3 the gain was large enough (mean = .058) to mean that bilateral cochlear implantation has the potential to be cost-effective at a willingness-to-pay threshold of £30,000 per QALY.

Table 9.2 is an updated version of Table 4.1 with the results from this thesis included. This table demonstrates the mean gain in utility obtained from bilateral cochlear implantation compared to unilateral cochlear implantation as measured with the HUI3. The gain found in the experiment reported in Chapter 6 is higher than that reported by Summerfield et al. (2006) for bilateral CI users at three and nine months post-implantation. The users who completed the HUI3 in the experiment reported in this thesis had had their second CI for a mean of 6.3 years (see Chapter 5). One possibility is that the increase in gain between 3 and 9 months post implantation found in the study reported by Summerfield et al. (2006) could continue to increase as the duration of using a second CI increases. However, this possibility would not explain why Chen et al. (2014) found no gain in utility despite users having their second CI for at least one year. Chen et al. gave bilateral CI users short descriptions of outcomes from unilateral and bilateral cochlear implantation and asked respondents to complete the HUI3 based on their readings of these descriptions, whereas Summerfield et al. (2006) and the experiment reported in Chapter 8 asked patients to complete the HUI3 considering their life in the past two weeks. It is possible, therefore, that differences in methodology may account for the different findings.

**Table 9.2. Mean gain in utility of bilateral cochlear implantation compared to unilateral cochlear implantation as measured by the HUI3 in previously reported studies and in an experiment reported in this thesis.**

| Study | Method | Participants | Mean gain in utility |
|---|---|---|---|
| Summerfield et al. (2002) | Time-trade-off technique | Professional informants | .031 |
| Summerfield et al. (2006) | HUI3 at 3 months post implantation | CI users | .021 |
| | HUI3 at 9 months post implantation | | .030 |
| Chen et al. (2014) | HUI3 completed considering description of clinical scenarios. | Professional informants | .080 |
| | | CI candidates | .030 |
| | | Unilateral CI users | .030 |
| | | Bilateral CI users | .000 |
| | | All | .035 |
| Experiment reported in Chapter 6. | HUI3 | Bilateral CI users | .059 |

When using the YHRQL, a mean gain in utility of .050 (50-year valuations) and .090 (10 year valuations) for bilateral cochlear implantation compared to unilateral cochlear implantation were found. These results also demonstrate that bilateral cochlear implantation has the potential to be a cost-effective intervention. As with the bimodal gain discussed in section 9.3.3.1, the analysis is preliminary using a small number of bilateral CI users. Future research should administer the questionnaire to a larger, more representative sample of bilateral CI users.

#### 9.3.3.3 Bilateral cochlear implantation Vs. Bimodal aiding

No previous study has directly assessed the cost-effectiveness of bilateral cochlear implantation compared to bimodal aiding in adults. This in an important analysis to conduct because current guidelines (NICE, 2013) suggest that cost-effectiveness analyses should compare an intervention to the ‘next best alternative’. Although previous studies (e.g. Bond et al., 2009; Chen et al., 2014; Summerfield et al., 2006) have compared the cost-effectiveness of bilateral cochlear implantation to unilateral cochlear implantation, it is arguable that, at least for patients who have some contralateral residual acoustic hearing, bimodal aiding is the ‘next best alternative’ to bilateral cochlear implantation. None of the measures used found a large enough gain in utility for bilateral cochlear implantation to be judged to be a cost-effective use of resources compared with bimodal aiding.

#### 9.3.3.4 Summary

The experiments reported in this thesis have demonstrated that when using a measure sensitive to differences in hearing ability both bimodal aiding and bilateral cochlear implantation have the potential to be cost-effective interventions compared to unilateral cochlear implantation. When using generic health related quality of life measures the results are mixed: The EQ5D is insensitive to difficulties with hearing with scores at ceiling with only one CI and it is unable to discriminate between clinically distinct groups. The HUI3 is somewhat sensitive to difficulties with hearing (as shown by the gain in utility with bilateral CIs compared to unilateral cochlear implantation) but the gain was not great enough for bilateral cochlear implantation to be considered cost-effective when compared to bimodal aiding (see Table 9.3).

**Table 9.3. Cost-effectiveness of bimodal aiding and bilateral cochlear implantation as measured by three measures. Ticks indicate the intervention would be deemed cost-effective at a willingness-to-pay threshold of £30,000/QALY.**

| Measure | Bimodal aiding Vs. Unilateral cochlear implantation | Bilateral cochlear implantation Vs. Unilateral cochlear implantation | Bilateral cochlear implantation Vs. Bimodal aiding |
|---|---|---|---|
| EQ5D | X | X | X |
| HUI3 | X | √ | X |
| YHRQL | √ | √ | X |

### 9.3.4 Recommendations for clinical practice

This thesis found advantages from a second device over unilateral cochlear implantation and therefore recommends that users of a single CI aid their non-implanted ear. This research suggests that a contralateral hearing aid should be used for four reasons: Some listening benefit is obtained, no detriment to hearing ability is observed, self-reported listening ability is improved, and overall quality of life is rated as greater. As patients can obtain a hearing aid at no charge from the NHS, it is recommended that individuals who currently have one CI aid their non-implanted ear with an acoustic hearing aid. However, this research suggests that a second CI offers three advantages over bimodal aiding: greater spatial listening ability, greater benefit for speech perception in the presence of spatially separated noise, and greater self-reported listening benefit. Overall the results reported suggest that bilateral cochlear implantation offers greater clinical benefits than bimodal aiding.

### 9.3.5 Recommendations for measuring the cost-effectiveness of a second device

Existing self-report measures are limited in their sensitivity to hearing difficulties and the benefits obtained from different interventions for hearing loss. The YHRQL questionnaire (see Chapter 8) is sensitive to differences in hearing ability. It is recommended that this new questionnaire be administered alongside existing generic health-related quality of life instruments. The generic instruments can detect changes in a patient's health state that are not hearing-specific and therefore are not detected by the YHRQL questionnaire. Initial results with the YHRQL questionnaire (Chapter 8) suggest that bilateral cochlear implantation has the potential to be cost-effective compared to unilateral cochlear implantation. This idea should be explored further in a comparison with a larger sample of patients (see section 9.4.2).

## 9.4 Future research

### 9.4.1 Behaviours leading to gain

The experiments reported in Chapter 7 focused on a behaviour that had the potential to improve listening performance: head movements. The experiment reported in Chapter 5 demonstrated some improvement in spatial listening ability from bimodal aiding compared to unilateral cochlear implantation. This was also reflected in self-report measures reported in Chapter 6. It is unclear why participants benefitted on spatial listening. One possibility is that they used head movements to help them by either maximising the signal level at one ear or by maximising the SNR. In Chapter 7 the question of whether head movements improved performance for bilateral CI users was addressed. Future research could address whether head movements improve the localisation performance of bimodal users.

### 9.4.2 A randomised control trial to assess the cost-effectiveness of a second device

The experiment reported in Chapter 8 demonstrated that with the YHRQL questionnaire the gain in utility from a second device can be large enough (greater than .05) to be considered a cost-effective intervention. This gain in hearing related quality of life was found in the absence of any detriment to generic health related quality of life (as measured with the EQ5D and HUI3).

The first step for future research assessing the cost effectiveness of a second device would be to gather valuations from a larger, more representative sample of the UK general public. This is outlined in NICE (2013) guidelines as the appropriate method for gathering valuations. The second step would be, using the new valuations, to check that variability estimates are similar with a new set of patients. For instance, the experiment reported in chapter 8 found lower estimates of variability in the gain of bilateral implantation compared to unilateral implantation with the HUI3 than previous research (United Kingdom Cochlear Implant Study Group, 2004b) with an SD of .08. As variability estimates are used to estimate the sample size required for a well-powered randomised control trial, it is important to establish accurate estimates.

The third step would be to conduct a randomised control trial. Previous estimates of variability using the HUI3 are around .20 (United Kingdom Cochlear Implant Study Group, 2004b), therefore with a gain of .05 required a trial would be looking for a gain in utility of around a quarter of a SD (.05/.2 = .25). To detect an effect of this size with 80% power would require 126 participants overall (for a within subjects comparison) or 126 participants in each group for a between-subjects comparison. As discussed in Chapter 4, this size of a trial would be very expensive to conduct.

However, variability estimates from the YHRQL as found in the experiment reported in Chapter 8 are much smaller. Using the 10-year valuations resulted in a larger SD than using the 50-year valuations. Using the SD estimates with the 10-year valuations, the gain in bilateral implantation from unilateral implantation had an SD of .06. Thus the required gain of .05 is a much larger proportion of the standard deviation of the YHRQL (.05/.06 = .83). Using these estimates, a trial with 80% power would require 11 participants for a within subjects comparison or 22 participants (11 in each group) for a between-subjects comparison. This would be a much more affordable trial. Even with a more conservative sample size estimate to achieve 90% power would require 15 participants for a within subjects comparison or 30 participants (15 in each group) for a between-subjects comparison. Estimates of the variability in the gain in utility from bilateral cochlear implantation compared to bimodal aiding were estimated from bootstrapping. With 10 year valuations the SD was estimated to be .022 (the SD with 50 year valuations was .012). Using the SD with the 10-year valuations a trial with 90% power would require 6 participants (3 in each group).

The minimum gain in utility required for bimodal aiding to be considered cost-effective compared to unilateral implantation was estimated to be between .002 and .011 depending upon the cost data used (see Appendix C). Sample size estimates to achieve 80% power were estimated in Appendix C to be 15 participants (within-subjects comparison with 50-year valuations) and 44 participants (within-subjects comparison with 10-year valuations). To achieve 90% power would require 20 participants for a within-subjects comparison (50-year valuations) or 59 participants (10-year valuations).

Thus an affordable and well powered trial could be conducted in which participants with a unilateral CI are randomly assigned to receive either a second cochlear implant or a contralateral acoustic hearing aid. The primary outcome would be the gain in utility as measured with the YHRQL. However, the EQ5D and HUI3 could also be administered to check that there was no detriment to other aspects of health that are not detected by the YHRQL. Furthermore, secondary outcome measures such as performance on listening tasks could be obtained which can be correlated with the gain in utility. It would be informative to test listeners at four time points, two prior to receiving the intervention (separated by three months) and two post receiving the intervention (6 months post-intervention and 12 months post-intervention). As discussed in Chapter 4, a previous randomised control trial investigating self-reported listening ability and quality of life from bilateral cochlear implantation found that the time in which measurements were made influenced the results (Summerfield et al., 2006). By testing listeners twice before the intervention, it would be possible to ascertain if there were any learning effects. Testing listeners six months after receiving the intervention would allow sufficient time for listeners to become accustomed to listening with their two devices. By testing one year post-intervention, it would be possible to see if any benefits found at six months continue after listeners have used their devices for a prolonged period of time. It will also be possible to ascertain if any benefits (or drawbacks) arise only after a prolonged period of use. With a large enough sample it may be possible to identify variables that predict successful performance with the intervention such as pre-intervention performance scores, levels of residual hearing, or musical training.

However, the questionnaire could also be applied to new technology. Non-traditional bimodal candidates have electro-acoustic stimulation within the same ear through the use of a short electrode array about 10mm in length compared to a length of about 25mm for traditional CIs (Turner, Reiss, & Gantz, 2008). Potentially, these devices offer a middle ground between bilateral cochlear implantation and bimodal aiding. As an emerging technology at the time, the latest NICE guidelines (NICE, 2009) on cochlear implantation did not comment on the candidacy requirements for hybrid devices. However, the Food and Drug Administration in the United States of America recently approved the use of Hybrid devices in one ear for individuals with severe-to-profound high-frequency hearing loss who also have good unaided low-frequency hearing (FDA, 2014). In determining the cost-effectiveness of an intervention NICE (2013) guidelines recommend that the intervention is compared to the next best alternative. It is therefore important to establish if a hybrid electrode array is 'the next best alternative' to bilateral cochlear implantation or bimodal aiding (or indeed whether bimodal aiding is the next best alternative to hybrid devices). Nevertheless the YHRQL could be used to assess the effectiveness of these interventions.

## 9.5 Conclusion

Using a second device, either a contralateral acoustic hearing aid or a second cochlear implant, is more clinically effective than a single CI alone. However, greater benefits in listening ability and self-reported listening ability can be obtained with a second CI. Bilateral CI users can use head movements to improve sound orientation accuracy and reduce front-back confusions provided that the stimulus is at least five seconds in duration. The EQ5D is insensitive to hearing difficulties. The gain in utility from a second CI compared to a unilateral CI measured with the HUI3 is large enough for bilateral implantation, potentially, to be cost-effective. However, bilateral implantation would not be considered cost-effective when compared to bimodal aiding. When using the EQ5D neither a contralateral acoustic hearing aid nor a second CI would be considered to be cost-effective. A short questionnaire was developed which is sensitive to the benefits of binaural hearing and using this instrument the gain in utility from both bimodal aiding and bilateral cochlear implantation compared to unilateral cochlear implantation was large enough to be considered cost-effective at current willingness-to-pay thresholds. In conclusion, the experiments reported in this thesis demonstrate that both bimodal aiding and bilateral implantation have the potential to be clinically-effective and cost-effective alternatives to unilateral cochlear implantation, although greater clinical benefits can be obtained from a second cochlear implant.

# Appendix A

**Table A1. Summary of papers included in the literature review discussed in Chapter 2.**

| Study | Participants | Comparison | Task | Stimuli | Result |
|---|---|---|---|---|---|
| Sasaki, Yamamoto, Iwaki, & Kubo (2009) | 4 CICI<br>11 CIHA | Between-subjects | Speech perception in quiet | Monosyllabic words at 65dB SPL | Overall performance was higher for bimodal users:<br>• CICI = 53% correct<br>• CIHA = 79% correct<br><br>But benefit from second device compared to a single implant was greater from a second CI.<br>• CICI: 17 percentage points<br>• CIHA: 12 percentage points<br><br>Statistical analyses on these comparisons were not conducted |
| Cullington & Zeng (2010b)/ Cullington & Zeng (2011) | 13 CICI<br>13 CIHA | Between-subjects | 1. Speech perception in noise<br>2. Music perception<br>3. Affective prosody discrimination<br>4. Talker identification | Presented at RMS level of 60dB (A)<br>Stimuli by task:<br>1) Target sentences were HINT sentences spoken by a male in the presence of another talker. The maskers were IEEE sentences spoken by either one male, one female, or one child talker.<br>2) Montreal Battery of Evaluation of Amusia<br>3) Comprehension part of the Aprosodia Battery<br>4) Speakers from the Hillenbrand vowel stimuli. | No significant difference between the groups was found on any test:<br><br>1) Mean SRT for speech perception in noise was similar for both groups.<br>2) Numerically bimodal users performed better than bilateral CI users on 4 out of 6 subtests of the test battery.<br>3) Numerically bimodal users performed better than bilateral CI users on 4 out of 5 subtests of the test battery.<br>4) Numerically the bimodal users performed better than the bilateral CI users. |

| | | | | | |
|---|---|---|---|---|---|
| Yoon, Shin, & Fu (2012) | 12 CICI<br>13 CIHA (divided into two groups; Poor group (n=5) had aided PTA thresholds of 55dB HL at all frequencies, Good group had aided PTA thresholds<55 dB HL). | Between-subjects | 1) Speech perception in quiet<br>2) Speech perception in noise at +5 and +10 dB SNR | Consonant, vowel and sentence (HINT sentences) recognition | Overall performance:<br>• No significant difference in performance between bimodal and bilateral groups.<br><br>Benefit from a second device:<br>• Bilateral CI users had significantly greater benefit than bimodal (poor group) for consonant, vowel and sentence perception in noise and sentence perception in quiet.<br>• Bilateral CI users had significantly greater benefit than bimodal (good group) at sentence perception in quiet.<br>• Bimodal users (good group) had significantly greater benefit than bimodal (poor group) at vowel perception (in noise and in quiet) and sentence perception (in noise). |
| Kong, Mullangi, & Marozeau (2012) | 5 CICI (aged 17-66, two were also members of the bimodal group prior to receiving their second CI)<br>7 CIHA (aged 16 – 65) | Between-subjects and Within-subjects | Speech perception in quiet. | Consonants and vowels presented at a comfortable listening level. | *Mean benefit from a contralateral hearing aid (inferred from figures):*<br>• Consonant perception: 5 percentage points. (7 participants tested).<br>• Vowel: 8 percentage points. (6 participants tested)<br><br>*Mean benefit from a second CI (3 participants tested):*<br>• Consonant perception: 4 percentage points<br>• Vowel: 6 percentage points<br><br>Significant differences between the groups was not assessed. |

| | | | | | |
|---|---|---|---|---|---|
| Gifford, Dorman, Sheffield, Teece, & Olund (2014) | 30 CICI<br>35 CIHA | Between-subjects | Speech perception in quiet.<br>Speech perception in noise. | Speech perception in quiet:<br>Monosyllabic words.<br><br>Speech perception in noise:<br>1. Bamford-Kowal-Bench (BKB) sentences in noise (adaptive)<br>2. Azbio sentences at +5dB SNR | *Speech perception in quiet:*<br>Overall scores were not significantly different:<br>• Bilateral: Mean = 83.1% correct (SD = 12.4)<br>• Bimodal: Mean = 80.5% correct (SD = 11.2)<br><br>Benefit from a second device was not significantly different.<br>• Bilateral: Mean = 9.6 percentage points (SD = 11.51)<br>• Bimodal: 4.23 percentage points (SD = 11.13).<br><br>*Speech perception in noise:*<br>No significant difference between the groups.<br>• Bilateral: Mean threshold = 5.8dB (BKB), mean percent correct = 65.5% (Azbio)<br>• Bimodal: Mean threshold = 6.3dB (BKB), mean percent correct = 58.6% (Azbio). |

| | | | | | |
|---|---|---|---|---|---|
| Potts & Litovsky (2014) | 4 CIHA who then became 4 CICI | Within-subjects | Speech perception in quiet.<br>Sound localisation<br>Self-reported listening ability | Speech perception and localisation:<br>• Monosyllabic words presented at 60 dB SPL (±3dB SPL) from one of 15 loudspeakers in the frontal horizontal plane (±70°). Location selected randomly on each trial.<br><br>Self-reported listening ability: SSQ. | *Speech perception:*<br>• 2/4 participants significantly better with CICI than CIHA (about 18 and 25 percentage points better inferred from graph)<br>• The other two participants were about 5 and 8 percentage points better (inferred from graph) with CICI than CIHA but this benefit was not significant.<br><br>*Localisation:*<br>• Significantly better with CICI than CIHA. RMS error is about 14° better with CICI (inferred from graph).<br><br>*Self-reported listening ability:*<br>• Significantly higher overall SSQ scores with CICI than CIHA. |

| | | | | | |
|---|---|---|---|---|---|
| Kokkinakis & Pak (2014) | 7 CICI<br>7CIHA (with CI in right ear and HA in left ear) | Between-subjects | Speech perception in the presence of noise | BKB sentences presented in 4-talker babble noise (level varied to measure SNR where performance is 50% correct).<br><br>Three conditions:<br>• Speech and noise presented concurrently at 0° azimuth.<br>• Speech presented at 0° and noise presented at +90°.<br>• Speech presented at 0° and noise presented at -90°. | *Mean speech reception thresholds:*<br>Noise front:<br>• Bilateral (5.79dB, SD = 3.00)<br>• Bimodal (4.07dB, SD = 2.47)<br><br>Noise left:<br>• Bilateral (1.79dB, SD = 2.55)<br>• Bimodal (-0.21dB, SD = 2.00)<br><br>Noise right:<br>• Bilateral (3.71dB, SD = 5.77)<br>• Bimodal (8.57dB, SD = 2.62)<br><br>*Head shadow (inferred from graph):*<br>• Bilateral: 8dB<br>• Bimodal: 6.7dB<br>• Not significantly different<br><br>*Binaural squelch (inferred from graph):*<br>• Bilateral: 0.9dB<br>• Bimodal:3.1dB<br>• Not significantly different<br><br>Binaural summation (inferred from graph):<br>• Bilateral:2.5dB<br>• Bimodal:7.7dB<br>• Significantly different |

| | | | | | |
|---|---|---|---|---|---|
| Perreau, Ou, Tyler, & Dunn (2014) | 49 CICI<br>32 CIHA | Between-subjects | Self-reported spatial listening ability | Spatial hearing questionnaire | *Overall score:*<br>• Significantly higher score (better ability) with CICI than CIHA.<br><br>*Sub-scales:*<br>• Significantly higher scores (better ability) with CICI than CIHA on 5 out of 8 sub-scales (understanding male voices, understanding female voices, understanding children's voices, music, and localisation). |

# Appendix B

**Table B1. Summary of studies investigating the role of head movements for sound localisation by normally-hearing adults.**

| Study | Participants | Apparatus | Stimuli | Conditions | Results |
|---|---|---|---|---|---|
| Perrett & Noble (1997a) | 12 normally-hearing listeners. | 25 loudspeakers separated by 15°. Loudspeakers were positioned in the left horizontal plane from 0° azimuth to 180° azimuth. | Low-pass white noise bursts (3 second and 0.5 second samples). Mean presentation level was 55dB A (roved between ±3dB across trials). | Three movement conditions:<br>1) Natural movement<br>2) Rotation: Turning the head 45° horizontally to the left after onset then stopping.<br>3) Motionless<br><br>Two duration conditions:<br>1) 3 second<br>2) 0.5 second | *Absolute accuracy:*<br>In the 3 second duration condition performance was significantly better in both movement conditions compared to the motionless condition<br><br>In the 0.5 second condition performance was significantly better in the rotation condition than the natural movement or motionless conditions.<br><br>*Front-back errors:*<br>With the 3 second stimulus the natural and rotation conditions had significantly fewer confusions (about 1% and 2% of trials respectively) than the motionless condition (about 30% of trials).<br><br>With the 0.5 second stimulus the rotation condition had significantly fewer confusions (about 4% of trials) than the motionless (about 24% trials) and natural conditions (about 17% trials). |
| Perrett & Noble (1997b) | Experiment 1: 10 normally-hearing listeners. | 7 loudspeakers separated by 30° in the vertical plane from 0° in front of the listener to 180° | 7 different white noise signals. Mean presentation level was 60dB A (ranged between ±3dB). Stimulus was 3 seconds long. | Conditions: 7 noise x 4 listening conditions.<br>Listening conditions:<br>1) Normal motionless listening<br>2) Normal rotation listening – oscillated head between | *Front-back discrimination*<br>In the rotation listening conditions errors were minimal (none in the normal listening condition and only 0.6% of trials in the distorted listening condition). |

**Table B1. Summary of studies investigating the role of head movements for sound localisation by normally-hearing adults.**

| Study | Participants | Apparatus | Stimuli | Conditions | Results |
|---|---|---|---|---|---|
| | | behind. | | ±30° azimuth<br>3) 3 Distorted normal listening (short tubes inserted in ear)<br>4) Distorted rotation listening | In motionless listening there were errors in 27% of trials (normal listening) and 35% of trials (distorted listening).<br>*Apparent elevation:*<br>Averaged across all noise types the mean absolute elevation error was 16.2° (normal listening with rotation), 27.0° (normal listening, motionless), 24.1° (distorted rotation), and 35.3° (distorted and motionless). |
| | Experiment 2: 22 normally-hearing listeners. | 17 loudspeakers separated by 30° in the 360° vertical plane. | 2khz low-pass noise. | Two listening conditions:<br>1) Motionless<br>2) Rotation | *Front-back errors:*<br>Motionless: 35% of trials<br>Rotation: 0.4% trials<br>*Apparent elevation:*<br>Rotation improved performance for upper elevated sources but not lower elevated sources. |
| Wightman & Kistler (1999) | 7 normally-hearing listeners. | 15 loudspeakers separated by 10°. Loudspeakers were positioned from directly overhead to -50 degrees below the horizontal plane. | White Gaussian noise (2.5 seconds or 1 second) presented around 70dB SPL. | Three listening conditions:<br>1) Restricted (blindfolded and motionless)<br>2) Freestyle (head movements encouraged)<br>3) Compulsory movement (orient towards source) | *Front-back errors:*<br>When head movements were encouraged few listeners made confusions. Confusions were almost non-existent in the compulsory movement condition (one listener continued to make some errors).<br><br>*Head movement trajectories:* Visual examination revealed the following:<br>1) Head movements were varied<br>2) Most participants oriented towards the target.<br>3) Those who made front-back confusions moved more when they were permitted to do so.<br>4) Those who did not make front-back |

**Table B1. Summary of studies investigating the role of head movements for sound localisation by normally-hearing adults.**

| Study | Participants | Apparatus | Stimuli | Conditions | Results |
|---|---|---|---|---|---|
| | | | | | confusions did not move when permitted to do so |
| Thurlow et al. (1967) | 23 normally-hearing listeners were included in the analyses. | 10 loudspeakers in the horizontal and vertical planes. | High and low frequency filtered noise presented at 48dB SPL. 5 second stimulus. | Participants were instructed to move their head as much as they liked (but not their bodies) after the onset of the stimulus. | *Magnitude of movement:*<br>Mean maximal rotation movements were greater than pitch or roll movements.<br><br>*Direction:*<br>Majority of participants turned towards the target.<br><br>*Reversals:*<br>A number of head movement reversals occurred. |
| Pollack & Rose (1967) | Experiment one: 3 normally-hearing listeners in stationary conditions and one normally-hearing listener in moving conditions. | 19 loudspeakers in horizontal plane positioned 9.6° apart. | Click of about 15ms presented at 86dB SPL. | Three head stationary conditions with the head oriented straight ahead and body oriented:<br>1) Straight-ahead<br>2) +90°<br>3) - 90°<br><br>Two moving head conditions:<br>Moving head left to right in a sweeping motion at<br>1) 120°/s<br>2) 40°/s | *Accuracy*<br>Largely unaffected by body position.<br><br>Significant effect of rate of head movement: More errors in fast condition. |
| | Experiment 2: 3 normally-hearing listeners. | Loudspeakers in the horizontal plane positioned 3.2° apart. | Click of about 15ms presented at 86dB SPL. | Same as experiment 1 but this time a light was used to pace head movements and participants were told not to reverse head movement sharply. | *Accuracy:*<br>More errors when moving than when not moving. |

**Table B1. Summary of studies investigating the role of head movements for sound localisation by normally-hearing adults.**

| Study | Participants | Apparatus | Stimuli | Conditions | Results |
|---|---|---|---|---|---|
| | Experiment 3: 3 normally-hearing listeners | Loudspeakers in the horizontal plane positioned 3.2° apart. | Click of about 15ms presented at 86dB SPL and white noise of 1 second. | Same as experiment 1 but this time a light was used to pace head movements and participants were told not to reverse head movement sharply.<br><br>Also included an unconstrained head movement condition where participants were instructed that they can move head as if searching for an auditory target. | *Accuracy:*<br>Main effect of duration: More accurate with longer duration<br><br>Main effect of head movement: More accurate with head movement |
| | Experiment 4: 2 normally-hearing listeners | Loudspeakers in the horizontal plane positioned 3.2° apart. | Click of about 15ms presented at 86dB SPL and white noise. The duration of the white noise varied between .03 seconds and 3 seconds and was presented at 58dB SPL. | Same as experiment 3. | *Accuracy:*<br>Main effect of movement: More accurate when head is not moving.<br><br>Main effect of duration: More accurate with longer stimuli |
| | Experiment 5: 2 normally-hearing listeners | Loudspeakers in the horizontal plane positioned 3.2° apart. | Click of about 15ms presented at 86dB SPL and white noise lasting 3 seconds presented at 54 dB SPL. | Two listening conditions:<br>1) Unconstrained head movement condition where participants were instructed that they can move head as if searching for an auditory target<br>2) Non-moving<br>5 starting positions facing:<br>1) 0°<br>2) -45°<br>3) +45°<br>4) 90°<br>5) +90° | *Accuracy:*<br>Main effect of movement: More accurate with head movement |

**Table B1. Summary of studies investigating the role of head movements for sound localisation by normally-hearing adults.**

| Study | Participants | Apparatus | Stimuli | Conditions | Results |
|---|---|---|---|---|---|
| Brimijoin et al. (2010) | 17 normally-hearing adults | 11 loudspeakers separated by 15° from -75° to +75° | *Acoustic stimuli:*<br>110 short (1.3 second) sentences. Presented between 65-75dB.<br><br>*Visual stimuli:*<br>Red light emitting diodes. | Three conditions:<br>1. Visual condition<br>2. Auditory (eyes-open)<br>3. Auditory (eyes-closed) | *Orientation accuracy:*<br>Undershot both visual and auditory targets.<br>No difference between eyes-open and eyes-closed conditions.<br><br>*Peak velocity:*<br>Small jumps: 50°/s<br>Large jumps: 150°/s<br><br>*Initial latency:*<br>Average initial latency was 0.4s for auditory targets and 0.3s for visual targets.<br><br>*Fixation latency:*<br>Average fixation latency was 0.9s for auditory targets and 0.8s for visual targets.<br><br>*Head movement trajectory:*<br>Varied between listeners but typically sigmoidal in shape. |

**Table B1. Summary of studies investigating the role of head movements for sound localisation by normally-hearing adults.**

| Study | Participants | Apparatus | Stimuli | Conditions | Results |
|---|---|---|---|---|---|
| Mueller, Meisenbacher, Lai, & Dillier (2014) | 11 normally-hearing listeners | 12 loudspeakers separated by 30° in the horizontal plane. | Target stimuli: Speech spoken by a male talker. Presented at the same intensity as the noise stimuli (±2dB).<br><br>Noise: Background cafeteria noise presented from 12 loudspeakers at 60dB SPL. | Two movement conditions:<br>1. Head movement permitted<br>2. Head movement not permitted<br><br>Three stimulus duration conditions:<br>1. Short (503ms)<br>2. Medium (2.18s)<br>3. Long (4.45s) | *Accuracy:*<br>• Significantly less RMS error with medium and long stimuli compared to short stimuli.<br>• RMS error was significantly reduced when head movements were allowed (for medium and long stimuli).<br><br>*Front-back confusion:*<br>• When head movement was not permitted, as duration increased, confusions reduced. Significantly fewer confusions with long stimulus than medium stimulus.<br>• When head movement was permitted, there were no front-back confusions in the medium and long conditions.<br><br>*Head movement trajectory*<br>• Moved head in direction of target location. |

**Table B2. Summary of studies investigating the role of head movements for sound localisation by hearing-impaired individuals.**

| Study | Participants | Apparatus | Stimuli | Conditions | Results |
|---|---|---|---|---|---|
| Buhagiar et al. (2004) | 18 unilateral CI users. | Semi-circular array of 11 loudspeakers in the horizontal plane separated by 18°. | 7 stimuli:<br>1. Sentence at 60dB<br>2. Sentence + reverberation at 60dB<br>3. Sentence repeated 3 times at 60 dB<br>4. Pink noise at 60dB<br>5. Pink noise at 70dB<br>6. White noise + reverberation at 60 dB<br>7. Tone bursts at 60dB | For stimulus 3: head movements were permitted.<br><br>For all other stimuli head movements were not permitted. | *Accuracy:*<br>• When head movements were not permitted performance was better for sound presented on the side ipsilateral to the implant.<br>• When head movements were permitted there was no difference in accuracy performance between the ipsilateral and contralateral sides. |
| Tyler et al. (2006) | Unspecified number of bilateral and unilateral CI users. | 8 loudspeakers positioned in the horizontal plane. | Everyday sounds. | Two location conditions:<br>1. Loudspeaker array in front of listener<br>2. Loudspeaker array to side of listener<br><br>Two listening conditions:<br>1. Bilateral CIs<br>2. Unilateral CI | *Accuracy:*<br>• When localising sounds in the frontal plane, bilateral performance is near perfect without head movements.<br>• When localising sounds off to the side, bilateral performance is poor without head movements but near perfect when head movements are permitted. Unilateral performance is poor when head movements are permitted. |
| Brimijoin et al. (2010) | 14 hearing-impaired (4FA > 25dB HL, average = | 11 loudspeakers separated by 15° from -75° | *Acoustic stimuli:*<br>• 110 short (1.3 second) sentences. Presented between | Three conditions:<br>1. Visual condition<br>2. Auditory (eyes-open) | *Orientation accuracy:*<br>• Undershoot both visual and auditory targets.<br>• Undershot auditory targets less than visual targets. – Correlated with hearing loss. |

**Table B2. Summary of studies investigating the role of head movements for sound localisation by hearing-impaired individuals.**

| Study | Participants | Apparatus | Stimuli | Conditions | Results |
|---|---|---|---|---|---|
| | 43.5dB HL). | to +75°. | 65-75dB (or between 75-80dB for one HI listener with an 82dB average hearing threshold).<br><br>*Visual stimuli:*<br>• Red light emitting diodes. | 3. Auditory (eyes-closed) | *Peak velocity:*<br>• Small jumps: 50°/s<br>• Large jumps: 130°/s<br><br>*Initial latency:*<br>• Positive correlation between degree of hearing loss and initial latency for auditory targets.<br>• Average initial latency was 0.6s for auditory targets and 0.4s for visual targets.<br><br>*Fixation latency:*<br>• Positive correlation between degree of hearing loss and fixation latency.<br>• Average fixation latency was 1.3s for auditory targets and 1.0s for visual targets.<br><br>*Head movement trajectory:*<br>• Positive correlation between degree of hearing loss and trajectory complexity. |
| Brimijoin, McShefferty, & Akeroyd (2012) | 36 asymmetrical hearing-impaired listeners<br>20 listeners with better hearing thresholds in | 24 loudspeakers separated by 15° in the horizontal plane. | Target stimuli: Short sentences (2-3s). Presentation level was adapted based on performance.<br><br>Noise: Speech shaped noise presented at 70dB | Speech in noise task with five target locations:<br>1. 105°<br>2. -45°<br>3. 60°<br>4. -30°<br>5. -90°<br>Five noise | Head yaw orientation:<br>• Left-ear listeners oriented to the right of target (median = +51.2°, IQR = 12.2-79.8°)<br>• Right-ear listeners oriented to the left of the target (median = -48.6°, IQR = -9.5 - -78.8°).<br>• No difference between distracter conditions.<br>• No significant differences between two listener types for pitch and roll. |

**Table B2. Summary of studies investigating the role of head movements for sound localisation by hearing-impaired individuals.**

| Study | Participants | Apparatus | Stimuli | Conditions | Results |
|---|---|---|---|---|---|
| | their left ear (left-ear listeners) and 16 right-ear listeners. | | | separations:<br>1. ±180°<br>2. -90°<br>3. -30°<br>4. +30°<br>5. +90° | Results show listeners sought to maximise the signal level and not the signal-to-noise level. |
| Mueller, Meisenbacher, Lai, & Dillier (2014) | 7 bilateral CI users. | 12 loudspeakers separated by 30° in the horizontal plane. | Target stimuli: Speech spoken by a male talker. Presented at the same intensity as the noise stimuli (±2dB).<br><br>Noise: Background cafeteria noise presented from 12 loudspeakers at 60dB SPL. | Two movement conditions:<br>1. Head movement permitted<br>2. Head movement not permitted<br><br>Three target stimulus duration conditions:<br>1. Short (503ms)<br>2. Medium (2.18s)<br>3. Long (4.45s) | *Accuracy:*<br>• No difference between duration conditions.<br>• No benefit from head movement.<br><br>*Front-back confusion:*<br>• More confusion when head movement was not permitted (23.6% of trials with medium duration, 25% for long duration).<br>• Significantly less confusions when head movement was allowed for medium (10.4% of trials) and long (5.5% of trials) stimuli.<br>• No difference for short stimuli.<br><br>*Head movement trajectory*<br>• Moved head from left to right in a search-like manner.<br>• For the medium and long conditions head movements were significantly longer than normally-hearing listeners (see Table B1).<br>• For medium and long conditions the head movement trajectories were more complex than those made by normal hearing listeners (see Table B1) - quantified by polynomial order. |

# Appendix C

# Cost-effectiveness of a contralateral hearing aid for users of a single cochlear implant

## C.1 Introduction

This appendix reports an analysis of the cost-effectiveness of providing a contralateral acoustic hearing aid for individuals with one cochlear implant. The comparison investigated is the cost of providing a contralateral hearing aid with no intervention. Thus the incremental cost is the cost of providing a hearing aid and the incremental benefit is the gain in QALYs from having a hearing aid compared with not having a hearing aid.

### C.1.1 Costs

Following discussions with audiologists, Summerfield et al. (2002) identified three main costs of providing an acoustic hearing aid to adults: the fitting session (£100[7] incurred every three years), the cost of a new hearing aid (£250[1] incurred every three years), and therapeutic rehabilitation (£300[1] per year which was considered to be incurred by only 10% of patients). The cost of a new hearing aid identified by Summerfield et al. is slightly above the upper cost of a digital signal processing hearing aid in the UK found by Barton et al. (2003) when using cost data from the Department of Health at 2000/2001 cost levels. Barton et al. found the cost of a digital signal processing hearing aid in the UK to range between £164.30 and £241.80. In the early 2000's when these studies were published, hearing services including the provision of hearing aids were in the process of being modernised to improve services and provide modern technology. Indeed, Barton et al. (2003) identified that just 1.3% of hearing aids provided in the UK in 2000/2001 were digital aids. Today, the majority of users in the UK, including 99% of recipients in Northern Ireland, receive a digital hearing aid (Moore, 2012).

The NHS is able to reduce the cost of a hearing aid through bulk buying. Therefore with larger numbers of individuals receiving digital hearing aids compared to analogue aids it is possible that the estimates of the cost of a digital hearing aid provided by Summerfield et al. (2002) and Barton et al. (2003) are higher than would be the case today. In a more recent study, using costs from the NHS supply chain, Bond et al. (2009) identified the cost of a digital hearing aid to the NHS to be

[7] At year 2000 cost levels.

between £62 and £152 (at 2007 cost levels). In their analyses they estimated the average cost of a hearing aid to the NHS to be £100. Following a personal communication with a clinical Director of Audiology they assumed that a hearing aid would be replaced every five years and that the costs of batteries were sufficiently small not to be worth including in their cost model. In a more recent publication, Summerfield, Lovett, Bellenger, and Batten (2010) following assumptions by Bond et al. (2009), estimated the cost of a new hearing aid to be £100 and replaced every five years. No other costs related to a hearing aid were included in their model.

In an economic model to estimate the effectiveness of screening older adults for hearing loss, Morris et al. (2012) used the UK NHS 2009/2010 Adult Hearing Services Indicative Tariff. This tariff, produced by the Department of Health, indicated that the cost of a single hearing aid and ear mould was £122, the cost of an audiological assessment was £57, the cost of a hearing aid fitting appointment was £69, the cost of a follow-up appointment was £49, and the cost of hearing aid repair was £26. The most recent UK NHS Adult Hearing Services Tariff (Department of Health, 2013) has combined some of the aforementioned costs into one 'pathway cost'. The costs listed include an audiology hearing aid assessment which is £54. The 'pathway for hearing aid assessment' includes the cost of fitting, the cost of one hearing aid, and the first follow up. The total cost amounts to £273. Finally, hearing aid aftercare (repairs) costs are estimated to be £26. Thus this analysis suggests that the cost of providing a hearing aid is higher than the value estimated by Bond et al. (2009).

### C.1.2 Current study

The aforementioned studies by Summerfield et al. (2002) and Bond et al. (2009), whilst considering the cost of an acoustic hearing aid, were mainly concerned with estimates of the costs that would be averted by providing unilateral or bilateral cochlear implants to individuals. These studies did not directly investigate the cost-effectiveness of providing a contralateral hearing aid to users who already have one implant. As mentioned above and discussed in detail in Chapter 4, the cost of providing a contralateral acoustic hearing aid to a user of a single implant can be inferred from Bond et al's analyses. However, Bond et al. only considered the cost of a hearing aid (estimated to be £100) upgraded every 5 years in their cost analysis. As outlined above, there are other costs which need to be taken into account (e.g. fitting and repair costs).

The current study had two aims. First, to estimate the incremental cost of providing a contralateral hearing aid to users of a single cochlear implant. Second, to calculate the minimum gain in utility required for a hearing aid to be considered a cost-effective intervention. The first aim was addressed by using the costs outlined by Summerfield et al. (2002) and the costs outlined by the Department of Health (2013). The costs estimated by Summerfield et al. are more expensive and include more regular upgrades. Moreover, they also include rehabilitation costs. The costs outlined by the Department of Health are more recent estimates which are likely to be more representative of the actual costs incurred.

In order to test the sensitivity of conclusions to assumptions about the frequency of replacements and the percentage of patients receiving rehabilitation, four cost models were compared:

- Summerfield et al. (2002) costs with the hearing aid replaced every three years, and 10% of patients receiving rehabilitation
- Summerfield et al. (2002) costs with the hearing aid replaced every five years, and with 10% of patients receiving rehabilitation
- Department of Health (2014) costs with the hearing aid replaced every five years, and with 10% of patients receiving aftercare
- Department of Health (2014) costs with the hearing aid replaced every five years, and with 100% of patients receiving aftercare (i.e. worst case scenario)

The costs estimated by each model were used to infer the minimum gain in utility required for a hearing aid to be considered cost-effective.

## C.2 Methods

### C.2.1 Remaining life years

In a sample of 311 participants, the United Kingdom Cochlear Implant Study Group (UKCISG, 2004) found the mean age of implantation for adults was 50.8 years (95% CI = 49.1-52.5). In their economic analyses, Bond et al. (2009) set the basecase mean age at which an implant was received by a post-lingually deafened adult to be 50 years old. Consistent with this research, the present study used 50 years old as the basecase age at which an adult receives a cochlear implant. Using government produced actuarial life tables for individuals in England and Wales, the average expected life expectancy for someone aged 50 today is 31 years for a man and 34 years for a woman, with an average of 33 years (Office for National Statistics, 2014). These were the number of remaining life years used in the analyses.

### C.2.2 Gender distribution

The proportion of males and females who received an implant at NHS centres in England between 2008 and 2013 was calculated using Hospital Episode Statistics (2009-2014).

### C.2.3 Costs

Two sets of costs of providing a hearing aid were used: costs identified by Summerfield et al. (2002) and costs outlined by the Department of Health (2013). Summerfield et al. costs were inflated to 2013 cost levels using the June 2014 update of the UK Gross Domestic Product deflator (HM Treasury, 2014). The costs outlined by the Department of Health were already at 2013-2014 cost levels and were therefore not adjusted. Summerfield et al. identified that a hearing aid would be updated every three years, whereas Bond et al. (2009) state that a hearing aid would be expected to be updated every 5 years. Summerfield et al. identified that therapeutic rehabilitation would be given to 10% of patients. The Department of Health (2014) did not include rehabilitation costs but did include a cost of hearing aid aftercare (such as repairs). As such four sets of costs were calculated, descriptions for which are shown in Table C1.

**Table C1. Four cost models were used.**

| Costs from: | Years that hearing aid is upgraded | Percentage receiving rehabilitation/aftercare |
|---|---|---|
| Summerfield et al. (2002) | 3 | 10% |
| Summerfield et al. (2002) | 5 | 10% |
| Department of Health (2013) | 5 | 10% |
| Department of Health (2013) | 5 | 100% |

The cost of not providing a hearing aid (no intervention) was set at zero. Therefore costs reported are the incremental costs.

### C.2.4 Discounting

Costs and benefits were discounted at a rate of 3.5% (consistent with NICE, 2013 guidelines). Costs were assumed to be incurred at the start of the year, while benefits were assumed to be incurred at the end of the year. As such, costs were discounted from year zero and benefits were discounted from year one.

### C.2.5 Cost-effectiveness

The incremental benefit was expressed as the number of QALYs gained. The number of QALYs was calculated by summing together the discounted utility gain across the remaining life years. The incremental cost-effectiveness ratio (ICER) was calculated as:

$$ICER = \frac{Incremental\ cost}{Incremental\ benefit}$$

### C.2.6 Benefit required

The four cost models were used to assess the minimum gain in utility required for a contralateral acoustic hearing aid to be deemed cost-effective at a willingness to pay threshold of £30,000/QALY and at a willingness to pay threshold of £20,000/QALY. ICERs at these thresholds are requested by NICE (2013).

### C.2.7 Benefit obtained

The gain in utility from a contralateral acoustic hearing aid compared to a unilateral cochlear implant was reported in experiments in Chapters 6 and 8. These values were used to assess if the minimum benefit required for a contralateral hearing aid to be cost-effective was met. The four measures used were the Health Utilities Index Mark III (HUI3), the EuroQol (EQ5D), the York Quality of life questionnaire (YorQol), and the York hearing-related quality of life questionnaire (YHRQL). Full details of the participants and measures can be found in Chapters 6 and 8.

## C.3 Results

### C.3.1 Gender distribution of cochlear implant recipients

**Table C2. Total number of admissions for cochlear implantation in England between 2008 and 2013. Also shown are the number of male recipients of a cochlear implant and the proportion of male and female recipients of a cochlear implant.**

| Year | Total number of admissions | Number of males | Male:Female |
|---|---|---|---|
| 2012-2013 | 931 | 420 | 45:55 |
| 2011-2012 | 1115 | 503 | 45:55 |
| 2010-2011 | 923 | 445 | 48:52 |
| 2009-2010 | 870 | 428 | 49:51 |
| 2008-2009 | 802 | 391 | 49:51 |
| **Total 2008-2013** | **4641** | **2187** | **47:53** |

### C.3.2 Costs

Table C3 shows the lifetime costs incurred by providing a hearing aid as estimated with the four cost models. The cost per male recipient, female recipient and average recipient are shown. The average costs are calculated using a 47:53 male:female gender distribution.

**Table C3. Incremental cost of providing a hearing aid using the four cost models. Average is for a 47:53 Male:Female ratio.**

| | Years that HA is upgraded | Percentage receiving rehabilitation/aftercare | Cost per male recipient | Cost per female recipient | Average cost per recipient |
|---|---|---|---|---|---|
| Summerfield et al. (2002) | 3 | 10% | £4,070 | £4,260 | £4,171 |
| Summerfield et al. (2002) | 5 | 10% | £2,892 | £2,931 | £2,913 |
| Department of Health (2013) | 5 | 10% | £1,261 | £1,263 | £1,262 |
| Department of Health (2013) | 5 | 100% | £1,722 | £1,748 | £1,736 |

### C.3.3 Benefit required

Table C4 shows the minimum gain in utility required at year zero for a hearing aid to be cost-effective at a willingness to pay threshold of £30,000/QALY and at a willingness to pay threshold of £20,000/QALY.

**Table C4. Minimum gain in utility required at year zero for a hearing aid to be cost-effective at £30,000/QALY and at £20,000/QALY using the four cost models.**

| | Year that HA is upgraded | Percentage receiving rehabilitation/ aftercare | Minimum utility value required in year zero | | |
|---|---|---|---|---|---|
| | | | Male | Female | Average |
| Summerfield et al. (2002) | | | | | |
| £30,000/QALY | 3 | 10% | .0073 | .0073 | .0073 |
| £20,000/QALY | | | .0109 | .0109 | .0109 |
| Summerfield et al. (2002) | | | | | |
| £30,000/QALY | 5 | 10% | .0052 | .0050 | .0051 |
| £20,000/QALY | | | .0078 | .0075 | .0076 |
| Department of Health (2013) | | | | | |
| £30,000/QALY | 5 | 10% | .0023 | .0022 | .0022 |
| £20,000/QALY | | | .0034 | .0033 | .0033 |
| Department of Health (2013) | | | | | |
| £30,000/QALY | 5 | 100% | .0031 | .0030 | .0031 |
| £20,000/QALY | | | .0046 | .0045 | .0046 |

### C.3.4 Benefit obtained

With the exception of the HUI3, utility values were not normally distributed therefore Table C5 summarises the median gain in utility obtained from the four quality of life measures from using a contralateral acoustic hearing aid. The median gain was at floor with the HUI3 and EQ5D. The largest gain in utility was obtained with the YorQol, and the YHRQL showed a median gain of .010 with both sets of valuations. See chapters 6 and 8 for full details, including statistical analyses, of these results.

**Table C5. Median gain in utility from a contralateral hearing aid as measured on the four questionnaires. Also shown are the 25th (25%) and 75th (75%) percentile.**

| Questionnaire used | N | Median gain in utility | 25% | 75% |
|---|---|---|---|---|
| HUI3 | 12 | .000 | -.060 | .137 |
| EQ5D | 12 | .000 | .000 | .000 |
| YorQol | 12 | .036 | .002 | .105 |
| YHRQL (50 year valuations) | 9 | .010 | .000 | .020 |
| YHRQL (50 year valuations) | 9 | .010 | .000 | .030 |

## C.4 Discussion

### C.4.1 Gender distribution

Publically available data showed that slightly more females were receiving a cochlear implant than males consistent with Bond et al. (2009) who found the same overall proportion (47:53 Male:Female) during the period 2003-2006. The current study did not separate gender distribution by age. Bond et al. (2009) separated their proportion into age bands and found that for individuals aged over 15 years of age the ratio of male:female recipients of cochlear implants became 41:59. Nevertheless the use of a five year period gives a recent estimate on the proportion of each gender receiving a cochlear implant and was therefore used as a parameter of the model.

### C.4.2 Costs

Costs were slightly higher for female recipients of a hearing aid due to having a longer life expectancy than males as an extra three years of costs were incurred. Costs were lower when using the tariff provided by the Department of Health (2013). This is likely to be more representative of the costs incurred by the NHS as it was compiled by the UK Government Department of Health for this year whereas the Summerfield et al. (2002) estimations were based on consultations with a small number of audiologists. As outlined in the introduction, the costs estimated by Summerfield et al. were obtained in the early 2000's when digital hearing aids are likely to have been more expensive than today due to the small number of recipients. The costs outlined by the Department of Health are 'Non-mandatory' which means that there is the possibility that average prices are higher (or indeed, lower) than those outlined here.

Nevertheless, in a worst-case scenario in which 100% of hearing aid recipients required aftercare each year, a low cost of under £1750 was found. This cost of providing a contralateral acoustic hearing aid to a user of a single cochlear implant is substantially lower than the cost of providing a second implant (see Chapter 4).

### C.4.3 Benefit required

Minimal differences in the gain in utility required by each gender were found. Using cost data from Summerfield et al. (2002), at a willingness-to-pay threshold of £30,000 a gain in utility of at least .0073 was required for a contralateral hearing aid to be considered cost-effective. This rose to a gain of .0109 at a willingness-to-pay threshold of £20,000. However, these gains were observed with a new hearing aid fit every three years. When a new hearing aid was fit every five years (in line with NHS practice, Bond et al., 2009) the gain reduced to .0051 and .0076 for willingness-to-pay thresholds of £30,000 and £20,000 respectively. When using the most recently available cost data obtained from the Department of Health (2013) the gain in utility required fell to .0022 and .0033 at a willingness-to-pay threshold of £30,000 and £20,000 respectively. At a willingness to pay threshold of £30,000, the gain in utility required in a worse-case scenario where aftercare was used by 100% of recipients was slightly higher at .0031 than if aftercare was required by just 10% of recipients. Similarly, the gain in utility required was slightly higher (at .0046) than if aftercare was required by just 10% of recipients at a willingness-to-pay threshold of £20,000.

### C.4.4 Benefit obtained

Using generic health-related quality of life questionnaires no gain in utility was observed. The EQ5D is insensitive to hearing difficulties, and the HUI3, whilst sensitive to 'some hearing' over 'no hearing', is less sensitive to differences between 'some hearing' and 'a bit more than some hearing'. This point is discussed in more detail in Chapters 4 and 6. The gain in utility as measured using the YorQol is large enough for a contralateral hearing aid to be considered cost-effective using costs obtained from both Summerfield et al. (2002) and the Department of Health (2013). The gain in utility obtained from the two versions of the YHRQL is large enough for a contralateral hearing aid to be considered cost-effective when using costs obtained from the Department of Health (2013) and when using the costs estimated by Summerfield et al. (2002) with a hearing aid updated every five years. However, the median gain in utility just falls short of being considered cost-effective at a willingness to pay threshold of £20,000 when a hearing aid is updated every three years. As an upgrade every three years is not common practice in the NHS (Bond et al, 2009), it can be concluded that these data suggest that providing a contralateral hearing aid to a user of a single implant has the potential to be cost effective.

However, it is important to note that the gains in utility reported come from a small self-selecting sample of bimodal users in the UK. It would be informative to administer the quality of life questionnaires to a larger sample of bimodal users more representative of the UK population. The SD of utility estimates on the HUI3 is about .20 (United Kingdom Cochlear Implant Study Group, 2004b). Therefore the estimated effect size is .011 standard deviations (using a .0022 utility gain) or .055 standard deviations (using a .0109 utility gain). In a within-subjects design, to detect a difference of this size with a two tailed paired-samples t-test at an alpha of .05 and at 80% power would require 64,785 participants (.0022 utility gain) or 2640 participants (.0109 utility gain). The SD of the gain in utility from bimodal devices compared to unilateral cochlear implantation was estimated in Chapter 8 to be .015 (with the 50-year valuations) and .026 (with the 10 year valuations). Thus a gain of .011 is a large proportion of the standard deviation of the 50-year valuations (.011/.015 = .73) and about 40% of the standard deviation of the 10-year valuations (.011/.026 = .42). Using the 50-year valuations would require 15 participants for a within-subjects comparison or 30 (15 in each group with a between-subjects comparison) to achieve 80% power. To achieve 90% power would require 20 participants for a within-subjects comparison or 40 participants for a between-subjects comparison. Using the 10-year valuations would require 44 participants for a within-subjects comparison or 88 participants (44 in each group) for a between-subjects comparison to achieve 80% power.

### C.4.5 Conclusion

In conclusion, this study has demonstrated that there is a low cost incurred to the NHS by providing a contralateral acoustic hearing aid to users of a single cochlear implant. Furthermore, the minimum gain in utility required for a contralateral acoustic hearing aid to be judged cost-effective is also small. Using data from a small sample of bimodal users in the UK, the medium gain in utility as measured using generic health-related quality of life instruments was at floor. However, when using questionnaires that are more sensitive to differences in hearing ability, the gain in utility was large enough for a contralateral hearing aid to be considered cost-effective at a willingness-to-pay threshold of £30,000. Furthermore, using the most up-to-date cost estimates provided by the Department of Health, the gains in utility observed with the more sensitive questionnaires are large enough for a contralateral acoustic hearing aid to be cost-effective at a willingness-to-pay threshold of £20,000. A contralateral acoustic hearing aid has the potential to be cost-effective, but a larger, more representative sample of patients is required to confirm this conclusion.

## C.5 Summary

- Four cost models were created using the costs of providing an acoustic hearing aid obtained from Summerfield et al. (2002) and the Department of Health (2014).
- The average incremental cost of providing a contralateral hearing aid ranged between £1,262 and £4,171 depending on the cost model used.
- The minimum gain in utility required for a contralateral hearing aid to be considered cost effective at a willingness-to-pay threshold of £20,000 ranged between .0033 and .0109 depending on the cost model used.
- The minimum gain in utility required for a contralateral hearing aid to be considered cost effective at a willingness-to-pay threshold of £30,000 ranged between .0022 and .0073 depending on the cost model used.
- Median gains in utility from a contralateral hearing aid obtained from four measures were summarised.
- Gains in utility using generic health-related quality of life instruments were not large enough for a contralateral hearing aid to be considered a cost-effective intervention.
- Gains in utility from questionnaires sensitive to differences in hearing were large enough for a contralateral hearing aid to be considered a cost-effective intervention.

# Appendix D

The 10 familiar tunes used in the experiment reported in Chapter 5 were:

- Auld Lang Syne
- Baa Baa black sheep
- Chimes of Big Ben
- Frere Jacque
- Good King Wenceslas
- God rest ye merry gentlemen
- Jingle bells
- Old MacDonald
- This old man
- Twinkle twinkle little star

# Appendix E

**Table E1. Individual participant mean results for the eight measures reported in Section 7.2 for the visual condition.**

| PID | Number of CIs | RMSE (°) | Latency to respond (s) | Maximum velocity (°/s) | Reversals (count) | Length of movement (°) | Initial latency (s) | Duration of movement (s) | Latency at fixation (s) |
|---|---|---|---|---|---|---|---|---|---|
| 201 | 2 | 14.61 | 1.34 | 81.41 | 2.04 | 41.46 | 0.25 | 0.59 | 0.50 |
| 214 | 2 | 9.88 | 1.06 | 107.19 | 1.72 | 46.33 | 0.13 | 0.49 | 0.43 |
| 216 | 2 | 6.71 | 1.36 | 145.21 | 2.66 | 68.41 | 0.18 | 0.76 | 0.42 |
| 480 | 2 | 27.08 | 0.77 | 170.6 | 1.24 | 43.60 | 0.09 | 0.49 | 0.17 |
| 169 | 1 | 15.20 | 0.93 | 118.89 | 1.77 | 43.75 | 0.13 | 0.39 | 0.39 |
| 111 | 1 | 15.08 | 1.07 | 142.75 | 1.93 | 43.75 | 0.18 | 0.33 | 0.54 |
| 323 | 1 | 13.49 | 0.77 | 118.92 | 0.68 | 42.49 | 0.11 | 0.38 | 0.26 |
| 303 | 1 | 13.15 | 0.85 | 121.85 | 1.59 | 40.39 | 0.08 | 0.39 | 0.38 |

**Table E2. Individual participant mean results for the eight measures reported in Section 7.2 for the auditory short condition.**

| PID | Number of CIs | RMSE | Latency to respond | Maximum velocity | Reversals | Length of movement | Initial latency | Duration of movement | Latency at fixation |
|---|---|---|---|---|---|---|---|---|---|
| 201 | 2 | 31.83 | 3.20 | 79.34 | 9.46 | 54.34 | 0.71 | 1.79 | 0.67 |
| 214 | 2 | 9.55 | 1.88 | 104.71 | 3.76 | 58.14 | 0.46 | 0.75 | 0.65 |
| 216 | 2 | 24.21 | 2.09 | 81.65 | 6.39 | 37.13 | 0.48 | 0.64 | 0.92 |
| 480 | 2 | 35.1 | 3.49 | 186.99 | 8.91 | 55.59 | 0.31 | 1.18 | 0.88 |
| 169 | 1 | 46.72 | 2.39 | 58.88 | 5.19 | 23.81 | 1.56 | 0.34 | 0.41 |
| 111 | 1 | 58.58 | 3.18 | 50.58 | 6.96 | 17.11 | 1.63 | 0.41 | 0.84 |
| 323 | 1 | 43.71 | 3.56 | 167.37 | 6.60 | 120.82 | 0.49 | 2.37 | 0.68 |
| 303 | 1 | 75.95 | 3.77 | 24.98 | 12.84 | 12.9 | 0.82 | 0.26 | 1.25 |

**Table E3. Individual participant mean results for the eight measures reported in Section 7.2 for the auditory long condition.**

| PID | Number of CIs | RMSE | Latency to respond | Maximum velocity | Reversals | Length of movement | Initial latency | Duration of movement | Latency at fixation |
|---|---|---|---|---|---|---|---|---|---|
| 201 | 2 | 16.16 | 4.14 | 86.74 | 9.45 | 76.13 | 0.69 | 2.44 | 0.98 |
| 214 | 2 | 37.45 | 6.56 | 97.44 | 11.43 | 127.03 | 0.89 | 4.58 | 1.00 |
| 216 | 2 | 13.93 | 3.36 | 122.75 | 8.64 | 72.61 | 0.53 | 1.92 | 0.91 |
| 480 | 2 | 14.98 | 4.73 | 141.58 | 13.87 | 89.90 | 0.53 | 3.29 | 0.88 |
| 169 | 1 | 45.20 | 4.69 | 118.47 | 9.14 | 109.67 | 1.00 | 3.23 | 0.44 |
| 111 | 1 | 52.4 | 6.89 | 79.89 | 10.63 | 119.7 | 2.13 | 3.88 | 0.85 |
| 323 | 1 | 25.98 | 12.14 | 169.85 | 16.44 | 438.81 | 0.86 | 10.85 | 0.42 |
| 303 | 1 | 67.93 | 4.99 | 100.98 | 16.69 | 71.51 | 0.48 | 3.65 | 0.85 |

# Appendix F

**TableF1. Number of participants in each group who completed each experimental condition.**

| Target location | Noise separation | NH listeners | Unilateral CI users | Bilateral CI users |
|---|---|---|---|---|
| -90 | 0 | 24 | 3 | 3 |
| | 30 | 24 | 3 | 2 |
| | -30 | 12 | 3 | 2 |
| | 90 | 12 | 2 | 3 |
| | -90 | 24 | 3 | 3 |
| | 180 | 24 | 3 | 3 |
| -45 | 0 | 24 | 4 | 2 |
| | 30 | 24 | 4 | 3 |
| | -30 | 12 | 4 | 2 |
| | 90 | 12 | 4 | 2 |
| | -90 | 24 | 4 | 3 |
| | 180 | 24 | 4 | 3 |
| -30 | 0 | 23 | - | - |
| | 30 | 23 | - | - |
| | -30 | 11 | - | - |
| | 90 | 11 | - | - |
| | -90 | 23 | - | - |
| | 180 | 23 | - | - |
| 60 | 0 | 24 | 3 | 3 |
| | 30 | 24 | 3 | 4 |
| | -30 | 12 | 2 | 4 |
| | 90 | 12 | 2 | 3 |
| | -90 | 23 | 3 | 3 |
| | 180 | 24 | 3 | 4 |
| 105 | 0 | 24 | 1 | 4 |
| | 30 | 24 | 2 | 4 |
| | -30 | 12 | 2 | 3 |
| | 90 | 12 | 2 | 3 |
| | -90 | 24 | 2 | 4 |
| | 180 | 24 | 2 | 3 |

# Appendix G

## Instructions for the 10-year condition

This questionnaire consists of 27 'scenarios'. Each scenario is a description of three aspects of a person's ability to **hear**. We want you to imagine that we are describing **you**.

> First, we describe your ability to understand speech when there is background noise.
> Second, we describe your ability to work out where sounds are coming from; that is, to 'localise' sounds.
> Third, we describe the amount of effort that you have to make in order to hear. Also, we describe how tired this makes you feel by the end of the day.

Please read each scenario carefully and imagine that it is describing your own ability to hear. Now imagine that you are told that you have 10 years left to live. Imagine that you are also told that you can choose *either* to live these 10 years with the hearing abilities that are described in the scenario, *or* that you can choose to give up some years of life to live for a shorter period with no problems with your hearing.

We shall then ask you to indicate the **number of years with no problem with your hearing** that you think is of **equal value to 10 years with the abilities described in the scenario**.

Please look at the examples on the next page. Then work your way through all 27 scenarios, one at a time. When you reach the end of the questionnaire, please check that you have answered all of the scenarios.

**There are no right or wrong answers. We are simply trying to find out how people value different aspects of the ability to hear.**

## Instructions for the 50-year condition

While you are completing this questionnaire, we would like you to imagine that you are 30 years old and that you will live for **50 more years**, until you are 80 years old.

The questionnaire consists of 27 'scenarios'. Each scenario is a description of three aspects of a person's ability to **hear**. We want you to imagine that we are describing **you**.

First, we describe your ability to understand speech when there is background noise.
Second, we describe your ability to work out where sounds are coming from; that is, to 'localise' sounds.
Third, we describe the amount of effort that you have to make in order to hear. Also, we describe how tired this makes you feel by the end of the day.

Please read each scenario carefully and imagine that it is describing your own ability to hear. Any difficulties with your hearing are permanent. They are not life-threatening, but there is no cure. Then imagine that you could give up some of your remaining 50 years of life in order to be free of any difficulties with your hearing. You would hear normally now, and for the rest of your life. The years that you would give up would be taken from the **end** of your life.

Remember: you are 30 years old and you can expect to live for 50 more years. **Please read each scenario carefully. Imagine that it is describing your hearing. Then tell us how many of those 50 years you would be willing to give up in order to hear normally now, and for the rest of your life.**

Please work your way through all 27 scenarios, one at a time. When you reach the end of the questionnaire, please check that you have answered all of the scenarios.

**There are no right or wrong answers. We are simply trying to find out how people value different aspects of the ability to hear.**

# Appendix H

**Table H1. Utility valuations from the experiment reported in Chapter 8. Numbers in the first three columns correspond to the response number on the patient questionnaire.**

| Speech in noise | Localisation | Effort | 50-year values | 10-year values |
|---|---|---|---|---|
| 1 | 1 | 1 | 0.99 | 0.97 |
| 1 | 1 | 2 | 0.98 | 0.93 |
| 1 | 1 | 3 | 0.97 | 0.89 |
| 1 | 1 | 4 | 0.95 | 0.86 |
| 1 | 1 | 5 | 0.93 | 0.83 |
| 1 | 2 | 1 | 0.98 | 0.95 |
| 1 | 2 | 2 | 0.97 | 0.92 |
| 1 | 2 | 3 | 0.95 | 0.88 |
| 1 | 2 | 4 | 0.94 | 0.85 |
| 1 | 2 | 5 | 0.92 | 0.82 |
| 1 | 3 | 1 | 0.98 | 0.93 |
| 1 | 3 | 2 | 0.96 | 0.90 |
| 1 | 3 | 3 | 0.94 | 0.87 |
| 1 | 3 | 4 | 0.93 | 0.84 |
| 1 | 3 | 5 | 0.92 | 0.81 |
| 1 | 4 | 1 | 0.97 | 0.90 |
| 1 | 4 | 2 | 0.95 | 0.87 |
| 1 | 4 | 3 | 0.93 | 0.84 |
| 1 | 4 | 4 | 0.92 | 0.82 |
| 1 | 4 | 5 | 0.91 | 0.79 |
| 1 | 5 | 1 | 0.95 | 0.86 |
| 1 | 5 | 2 | 0.94 | 0.84 |
| 1 | 5 | 3 | 0.92 | 0.82 |
| 1 | 5 | 4 | 0.91 | 0.79 |
| 1 | 5 | 5 | 0.90 | 0.77 |
| 2 | 1 | 1 | 0.98 | 0.94 |
| 2 | 1 | 2 | 0.97 | 0.91 |
| 2 | 1 | 3 | 0.96 | 0.88 |
| 2 | 1 | 4 | 0.94 | 0.85 |
| 2 | 1 | 5 | 0.92 | 0.82 |
| 2 | 2 | 1 | 0.97 | 0.93 |
| 2 | 2 | 2 | 0.96 | 0.90 |
| 2 | 2 | 3 | 0.95 | 0.87 |
| 2 | 2 | 4 | 0.93 | 0.84 |
| 2 | 2 | 5 | 0.92 | 0.81 |
| 2 | 3 | 1 | 0.97 | 0.91 |
| 2 | 3 | 2 | 0.95 | 0.88 |
| 2 | 3 | 3 | 0.94 | 0.85 |
| 2 | 3 | 4 | 0.92 | 0.82 |

| | | | | |
|---|---|---|---|---|
| 2 | 3 | 5 | 0.91 | 0.79 |
| 2 | 4 | 1 | 0.96 | 0.89 |
| 2 | 4 | 2 | 0.94 | 0.86 |
| 2 | 4 | 3 | 0.93 | 0.83 |
| 2 | 4 | 4 | 0.91 | 0.80 |
| 2 | 4 | 5 | 0.90 | 0.78 |
| 2 | 5 | 1 | 0.94 | 0.87 |
| 2 | 5 | 2 | 0.93 | 0.84 |
| 2 | 5 | 3 | 0.92 | 0.81 |
| 2 | 5 | 4 | 0.90 | 0.79 |
| 2 | 5 | 5 | 0.89 | 0.76 |
| 3 | 1 | 1 | 0.97 | 0.92 |
| 3 | 1 | 2 | 0.96 | 0.90 |
| 3 | 1 | 3 | 0.95 | 0.87 |
| 3 | 1 | 4 | 0.93 | 0.84 |
| 3 | 1 | 5 | 0.91 | 0.80 |
| 3 | 2 | 1 | 0.96 | 0.90 |
| 3 | 2 | 2 | 0.95 | 0.88 |
| 3 | 2 | 3 | 0.94 | 0.85 |
| 3 | 2 | 4 | 0.92 | 0.82 |
| 3 | 2 | 5 | 0.91 | 0.79 |
| 3 | 3 | 1 | 0.96 | 0.89 |
| 3 | 3 | 2 | 0.94 | 0.86 |
| 3 | 3 | 3 | 0.93 | 0.84 |
| 3 | 3 | 4 | 0.92 | 0.81 |
| 3 | 3 | 5 | 0.90 | 0.78 |
| 3 | 4 | 1 | 0.95 | 0.88 |
| 3 | 4 | 2 | 0.93 | 0.85 |
| 3 | 4 | 3 | 0.92 | 0.83 |
| 3 | 4 | 4 | 0.91 | 0.79 |
| 3 | 4 | 5 | 0.89 | 0.76 |
| 3 | 5 | 1 | 0.94 | 0.87 |
| 3 | 5 | 2 | 0.92 | 0.84 |
| 3 | 5 | 3 | 0.91 | 0.81 |
| 3 | 5 | 4 | 0.89 | 0.78 |
| 3 | 5 | 5 | 0.88 | 0.75 |
| 4 | 1 | 1 | 0.96 | 0.91 |
| 4 | 1 | 2 | 0.95 | 0.88 |
| 4 | 1 | 3 | 0.94 | 0.86 |
| 4 | 1 | 4 | 0.92 | 0.83 |
| 4 | 1 | 5 | 0.91 | 0.80 |
| 4 | 2 | 1 | 0.96 | 0.90 |
| 4 | 2 | 2 | 0.94 | 0.87 |
| 4 | 2 | 3 | 0.93 | 0.84 |
| 4 | 2 | 4 | 0.92 | 0.82 |
| 4 | 2 | 5 | 0.90 | 0.79 |
| 4 | 3 | 1 | 0.95 | 0.88 |

| | | | | |
|---|---|---|---|---|
| 4 | 3 | 2 | 0.94 | 0.86 |
| 4 | 3 | 3 | 0.92 | 0.83 |
| 4 | 3 | 4 | 0.91 | 0.80 |
| 4 | 3 | 5 | 0.89 | 0.77 |
| 4 | 4 | 1 | 0.94 | 0.87 |
| 4 | 4 | 2 | 0.93 | 0.84 |
| 4 | 4 | 3 | 0.91 | 0.81 |
| 4 | 4 | 4 | 0.90 | 0.78 |
| 4 | 4 | 5 | 0.88 | 0.75 |
| 4 | 5 | 1 | 0.93 | 0.85 |
| 4 | 5 | 2 | 0.92 | 0.82 |
| 4 | 5 | 3 | 0.91 | 0.79 |
| 4 | 5 | 4 | 0.89 | 0.76 |
| 4 | 5 | 5 | 0.87 | 0.74 |
| 5 | 1 | 1 | 0.96 | 0.90 |
| 5 | 1 | 2 | 0.94 | 0.87 |
| 5 | 1 | 3 | 0.93 | 0.84 |
| 5 | 1 | 4 | 0.92 | 0.82 |
| 5 | 1 | 5 | 0.90 | 0.79 |
| 5 | 2 | 1 | 0.95 | 0.89 |
| 5 | 2 | 2 | 0.94 | 0.86 |
| 5 | 2 | 3 | 0.92 | 0.83 |
| 5 | 2 | 4 | 0.91 | 0.81 |
| 5 | 2 | 5 | 0.89 | 0.78 |
| 5 | 3 | 1 | 0.94 | 0.88 |
| 5 | 3 | 2 | 0.93 | 0.85 |
| 5 | 3 | 3 | 0.92 | 0.83 |
| 5 | 3 | 4 | 0.90 | 0.80 |
| 5 | 3 | 5 | 0.89 | 0.77 |
| 5 | 4 | 1 | 0.93 | 0.86 |
| 5 | 4 | 2 | 0.92 | 0.83 |
| 5 | 4 | 3 | 0.91 | 0.80 |
| 5 | 4 | 4 | 0.89 | 0.77 |
| 5 | 4 | 5 | 0.88 | 0.75 |
| 5 | 5 | 1 | 0.92 | 0.83 |
| 5 | 5 | 2 | 0.91 | 0.80 |
| 5 | 5 | 3 | 0.90 | 0.76 |
| 5 | 5 | 4 | 0.88 | 0.75 |
| 5 | 5 | 5 | 0.87 | 0.73 |

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