Comparisons of unilateral and bilateral cochlear implantation for children: spatial listening skills and quality of life

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Abstract

Recently, controversy in the care of severely-profoundly deaf children has centred on whether they should be provided with bilateral cochlear implants (two implants, one in each ear) rather than a unilateral cochlear implant (one implant in one ear). Potentially, implanting both ears rather than one could improve children's spatial listening skills, meaning the ability to localise sources of sound (by comparing the intensity and timing of sounds arriving at the two ears) and to perceive speech in noise (by attending to whichever ear gives the better signal-to-noise ratio). The overall aim of the studies reported in this thesis was to assess whether bilateral implantation for children is more effective than unilateral implantation in improving spatial listening skills and quality of life. The first study measured the relationship between spatial listening skills and age in normally-hearing children. The second study compared the spatial listening skills of unilaterally- and bilaterally-implanted children. Whilst controlling for confounds, the bilateral group performed significantly better than the unilateral group on tests of sound-source localisation. Moreover, the bilateral group, but not the unilateral group, displayed improved speech perception when the source of a masking noise was moved from the front to either side of the head. Neither group of implanted children performed as well as normally-hearing children on tests of the ability to localise sources of sound and to perceive speech in noise. The third study measured the spatial listening skills of normally-hearing adults when listening to simulations of unilateral or bilateral implants. The differences in performance between simulations were similar to the differences in performance between groups of implanted children, which provides further evidence that the children's performance was primarily influenced by the number of implants they used rather than by confounds. The fourth study found that there was no significant difference between bilaterally- and unilaterally-implanted children in parental estimates of quality of life. The fifth study presented informants, who were not the parents of hearing-impaired children, with descriptions of a hypothetical child with unilateral or bilateral implants. The informants judged that the bilaterally-implanted child had a higher quality of life than the unilaterally-implanted child. These studies indicate that bilateral implantation for children is more effective than unilateral implantation in enabling spatial listening skills, but the extent of any gain in quality of life remains uncertain.

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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 supervisor. As part of undergraduate projects that were co-supervised by the candidate, Shan Huang collected the data from adults reported in Chapter 4 and Georgina Batten and Hannah Bellenger collected the data for Experiment 2 in Chapter 7. The remaining testing and all analyses were conducted by the candidate.

Publications & conference presentations

Lovett, R.E.S., Kitterick, P.T., Hewitt, C.E., & Summerfield, A.Q. (2010). Bilateral or unilateral cochlear implantation for deaf children: an observational study. *Archives of Disease in Childhood, 95,* 107-112.

Summerfield, A.Q., Lovett, R.E.S., Batten, G., & Bellenger, H. (in press.) Estimates of the cost-effectiveness of pediatric bilateral cochlear implantation. *Ear and Hearing.*

Lovett, R.E.S., Huang, S., & Summerfield, A.Q. (2009). Spatial listening with bilateral implants or bimodal devices: a simulation study. Poster presented at the Conference on Implantable Auditory Prostheses, Lake Tahoe, CA.

Lovett, R.E.S., & Summerfield, A.Q. (2008). Children with unilateral or bilateral cochlear implants: listening skills and quality of life. Poster presented at the British Society of Audiology Short Papers Meeting on Experimental Studies of Hearing and Deafness, York, UK.

Lovett, R.E.S., & Summerfield, A.Q. (2008). Bilateral versus unilateral cochlear implantation: spatial listening skills. Oral presentation at the British Cochlear Implant Group Conference, Bradford, UK.

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Lovett, R.E.S., & Summerfield, A.Q. (2007). Tests of spatial listening for preschool children. Poster presented at the British Society of Audiology Short Papers Meeting on Experimental Studies of Hearing and Deafness, London, UK.

Chapter 1

Overview of Thesis

This chapter provides a brief introduction to the thesis and an overview of the subsequent chapters.

1.1 Introduction

A cochlear implant is an electronic device which is implanted surgically into the inner ear of patients who are severely-profoundly deaf (Ramsden, 2002). Cochlear implantation for severely-profoundly deaf children became widespread in the early 1990s (Summerfield & Marshall, 1995), and for over 20 years the policy in the UK and elsewhere was to offer a single cochlear implant in one ear (unilateral implantation). Compared to amplification using acoustic hearing aids, unilateral implantation is effective in improving children's speech perception, language skills, and quality of life (Boothroyd & Eran, 1994; Stacey, Fortnum, Barton, & Summerfield, 2006; Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). Although paediatric unilateral implantation is costly (£60,000 per child at 2007 cost levels), the average gain in quality of life is large enough to justify the cost (Barton, Stacey, Fortnum, & Summerfield, 2006b; Bond et al., 2007).

The issue of whether deaf children should be provided with bilateral implants (two cochlear implants, one in each ear) rather than a unilateral implant has generated considerable debate (Balkany et al., 2008; National Institute for Health and Clinical Excellence, 2007, 2008a, 2009). It has been argued that the provision of two implants creates the potential for binaural hearing, which could improve children's ability to localise sources of sound (by comparing the intensity and timing of sounds arriving at the two ears; B. C. J. Moore, 2003) and to perceive speech in noise (by attending to whichever ear gives the better signal-to-noise ratio; Litovsky, 2005). These spatial listening skills may help children to avoid hazards outdoors and to understand speech better in noisy environments at home and at school. Evidence that children realise the potential benefits of bilateral implantation is needed to justify the additional surgery and extra cost of a second implant (£27,000 per child at 2007 cost levels; Bond et al., 2007).

The overall aim of the studies reported in this thesis was to assess whether bilateral implantation for children is more effective than unilateral implantation in improving spatial listening skills and quality of life. The first study measured the spatial listening skills of normally-hearing children, in order to confirm that the test battery was appropriate for young children and to measure the relationship between spatial listening skills and age. The second study compared the spatial listening skills of unilaterally- and bilaterally-implanted children. In order to minimise bias, statistical techniques were used to impute missing data and to control for confounding differences between the groups. The third study measured the spatial listening skills of normally-hearing adults who listened to simulations of unilateral or bilateral implants. The aim was to assess whether the differences in listening skill that had been observed between unilaterally- and bilaterally-implanted children would be replicated in a simulation study. Such a pattern of results would provide further evidence that the children's performance was primarily influenced by the number of implants they used, rather than by confounds. The fourth study used questionnaires to obtain parental estimates of the quality of life of unilaterally- and bilaterally-implanted children. In the fifth study, informants who were not the parents of hearing-impaired children read descriptions of a hypothetical profoundly-deaf child with no implant, a unilateral implant, or bilateral implants. The informants estimated the quality of life of the child in each scenario.

1.2 Overview of the following chapters

Chapter 2: Hearing and Deafness

This chapter describes the structure and function of the normal ear, and provides an overview of the prevalence and aetiology of impaired hearing. A section on binaural hearing describes the differences in the level and timing of signals at the two ears that arise from the location of sources of sound in space. The sensitivity of normally-hearing adults to these interaural differences is summarised. The main benefits of binaural hearing are an improved ability to understand speech in noise and to localise sources of sound (collectively known as spatial listening skills). The chapter concludes with a review of the spatial listening skills of normally-hearing adults and children.

Chapter 3: Cochlear Implants

This chapter provides an overview of how a cochlear implant works and the benefits of unilateral implantation for children. The main part of the chapter reviews the evidence regarding the effectiveness of bilateral implantation for children in improving spatial listening skills, language skills, and quality of life. The chapter includes a critical assessment of the risk of bias in published studies. The chapter concludes with a summary of the variables that predict performance with either bilateral implants or bimodal devices (meaning a unilateral implant and a contralateral acoustic hearing aid).

Chapter 4: Spatial Listening Skills of Children and Adults with Normal Hearing

This chapter reports an experiment that measured the performance of normally-hearing children and adults on a battery of tests of spatial listening. The tests measured the ability to: 1) discriminate a source of sound on the left from a source of sound on the right; 2) identify the location of a source of sound when presented with an array of three or more possible locations; 3) track moving sources of sound; 4) perceive speech in noise; and 5) benefit from the spatial separation of a source of target speech and a source of masking noise (spatial release from masking). The test-retest reliability was assessed.

Chapter 5: Spatial Listening Skills of Children with Unilateral or Bilateral Cochlear Implants

This chapter reports a study that compared the spatial listening skills of children with unilateral or bilateral cochlear implants. Variables which predict success with a unilateral implant were measured and confounding differences between the bilateral and unilateral groups were controlled statistically. The study also compared the spatial listening skills of children who received bilateral implants in a single surgery and children who received bilateral implants in sequential surgeries.

Chapter 6: Spatial Listening with Simulated Unilateral or Bilateral Cochlear Implants

This chapter reports a study in which normally-hearing adults attempted tests of spatial listening whilst listening to simulations of cochlear implants presented over headphones. Five conditions simulated bilateral implants, a unilateral implant with no contralateral acoustic hearing, and bimodal devices with an increasing bandwidth of contralateral acoustic hearing. The first aim was to assess whether the differences in performance between conditions were similar to the differences in performance between the groups of implanted children in Chapter 5. The second aim was to measure whether simulations of bimodal devices resulted in higher levels of performance than a simulation of bilateral implants. The third aim was to compare absolute levels of performance between adults listening to simulations of implant(s) and children who used implant(s).

Chapter 7: Quality of Life of Children with Unilateral or Bilateral Cochlear Implants

Measurements of quality of life contribute to the effectiveness component of cost-effectiveness analysis, which is used by policy-makers in the UK and elsewhere to prioritise spending within the healthcare system. This chapter reports two studies that assessed the quality of life of children with unilateral or bilateral cochlear implants. In the first study, the parents of unilaterally- and bilaterally-implanted children used questionnaires to estimate their child's general quality of life, health-related quality of life, and listening skills. In the second study, informants who were not the parents of hearing-impaired children read descriptions of a hypothetical profoundly-deaf child with no implant, a unilateral implant, a unilateral implant and an acoustic hearing aid, or bilateral implants. The informants used a visual-analogue scale and the time trade-off technique to estimate the general and health-related quality of life of the child in each scenario.

Chapter 8: Summary and General Discussion

This chapter summarises the results of the studies reported in this thesis and discusses the implications of those results. Ideas for further research are suggested.

Chapter 2

Hearing and Deafness

The aim of this chapter is to provide a context for the remainder of the thesis, which examines the consequences of providing deaf children with either one or two cochlear implants. The chapter begins with a summary of the structure and function of the normal ear. The prevalence and aetiology of impaired hearing are summarised, along with the consequences of deafness for an individual and for society. A section on binaural hearing describes the differences in the level and timing of signals at the two ears that arise from the location of sources of sound in space. The sensitivity of normally-hearing adults to interaural differences is reviewed. The main benefits of binaural hearing are an improved ability to localise sources of sound and to understand speech in noise. Collectively, these are known as spatial listening skills. The chapter concludes with a review of the spatial listening skills of normally-hearing adults and children.

2.1 Normal hearing

The peripheral auditory system converts changes in air pressure into neural impulses that represent the frequency, amplitude, and timing of sounds in the environment. The first stage of this process takes place in the outer ear, which is composed of the pinna, concha, and auditory canal (Figure 2.1). The pinna filters sound and funnels it towards the auditory canal (Yost, 2000). The concha and the auditory canal have resonant frequencies of approximately 2.5 and 5 kHz, respectively. Consequently, these parts of the outer ear amplify sounds that are between 1.5 and 7 kHz by 10 to 15 dB (Shaw, 1974). This range of frequencies is important for speech perception (ANSI, 1997). The tympanic membrane, located at the end of the auditory canal, vibrates in response to changes in air pressure. This movement is transmitted by the ossicles in the middle ear (the malleus, incus, and stapes) to the oval window, which is a membrane-covered opening in the outer wall of the fluid-filled cochlea.

The cochlea is a bony structure that can be thought of as a cylinder curved into the shape of a snail's shell. If it could be unwound, the 'cylinder' would be approximately

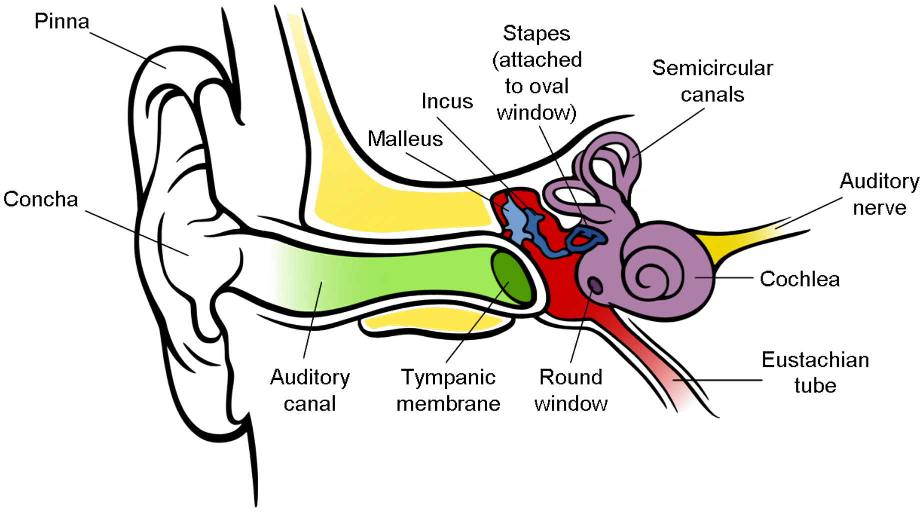

Figure 2.1. A schematic diagram of the peripheral auditory system. Image adapted from Brockmann (2009).

35 mm long and wider at the base (where it connects to the stapes) than at the apex (the top of the spiral). Three channels run for most of the length of the cochlea: scala vestibuli, scala tympani, and scala media (Figure 2.2). At the basal end of the cochlea, the oval window leads to scala vestibuli and the round window (another membrane-covered opening in the outer wall) leads to scala tympani. Scala vestibuli and scala tympani join at the apex. Scala media forms a sealed chamber that contains the organ of corti, which is attached to the basilar membrane. The tectorial membrane runs roughly parallel to the basilar membrane.

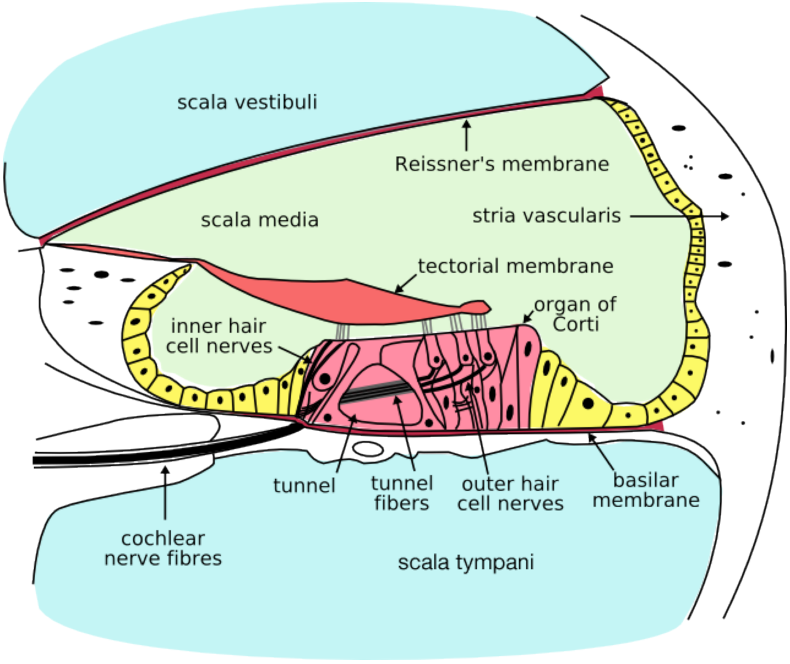

Figure 2.2. A schematic cross-section of the cochlea. Image from Ropshkow (2009).

When the stapes depresses the oval window, the fluid within the cochlea is displaced towards the round window. This displacement sets up a travelling wave moving apically along the basilar membrane (Pickles, 1988). The basilar membrane is narrower and stiffer at the basal end of the cochlea than at the apical end (Gummer, Johnstone, & Armstrong, 1981), meaning that the resonant frequency changes along its length. Consequently, the basal end of the basilar membrane oscillates maximally in response to high-frequency sounds and the apical end oscillates maximally in response to low-frequency sounds. For any location on the basilar membrane, the frequency that causes maximum displacement is known as the characteristic frequency. If a signal is complex (meaning it contains several frequencies) there will be multiple peaks in the displacement of the basilar membrane. This means that the cochlea acts as a frequency analyser by decomposing signals into their constituent frequencies. The amount of displacement of the basilar membrane increases with the level of the stimulus (B. C. J. Moore, 2003).

The conversion of movement into neural impulses is achieved in the organ of corti by the inner hair cells, each of which contains approximately 40 stereocilia (tiny hairs, see Figure 2.2). Displacement of the basilar membrane relative to the tectorial membrane creates a shearing force, which moves the stereocilia, causing 'channels' in the membrane of the hair cell to open or close. Subsequently, the flow of ions into the cell is altered, changing the electrical potential between the inside and outside of the hair cell (B. C. J. Moore, 2003; Yost, 2000). The change in potential causes the release of neurotransmitters into the synapse, leading to activation of the spiral ganglion cells in the auditory nerve (also known as the cochlear nerve). The organ of corti also contains outer hair cells, which are connected to the tectorial membrane. The outer hair cells expand and contract in response to vibration within the cochlea (Brownell, Bader, Bertrand, & Ribaupierre, 1985). This movement amplifies the signal and enhances frequency selectivity, meaning that locations on the basilar membrane are sharply tuned to displace more in response to sounds at their characteristic frequency than in response to sounds at other frequencies (Ashmore, 2008).

Different spiral ganglion cells are innervated by different locations on the organ of corti, so the location of active fibres conveys information about the frequency of the sound (Yost, 2000). In mammals, responses of the auditory nerve to signals below 4 to 5 kHz are 'phase locked,' meaning that the nerve is more likely to fire at a particular phase of the signal (B. C. J. Moore, 2003; Rose, Hind, Anderson, & Brugge, 1971). Thus, the interval between neural responses is approximately an integer multiple of the period of the signal. Consequently, information about the frequency of sound is conveyed by both the location and the timing of neural firing. The overall rate of neural firing, which increases in a nonlinear way with increasing stimulus level, conveys information about the level of sound.

The frequency tuning of the basilar membrane means that the normal cochlea acts like an array of overlapping bandpass filters. When presented with a broadband sound, such as speech, the output of each filter can be thought of as a slowly-varying amplitude envelope superimposed onto a rapidly-varying carrier (the temporal fine structure) whose frequency is close to the centre frequency of the filter (Hopkins, Moore, & Stone, 2008; B. C. J. Moore, 2008). For normally-hearing individuals, the rate of pulses in the auditory nerve represents the amplitude envelope while the timing of pulses represents the temporal fine structure (although the representation of fine structure depends on phase locking, which breaks down for high-frequency signals).

Interim Summary

The peripheral auditory system converts changes in air pressure into movement within the middle ear and cochlea, and then transforms movement into neural impulses. The signals in the auditory nerve are transmitted to several structures in the brainstem and thence to the auditory cortex. The frequency and level of sound are represented by the location, timing, and rate of neural firing.

2.2 Hearing impairment

Hearing impairment can be divided into two categories: conductive impairment, caused by a malfunctioning outer or middle ear, and sensorineural impairment, caused by a malfunctioning cochlea or cochlear nerve (Pickles, 1988). Conductive impairment is often caused by an obstruction within the middle ear, such as fluid or bone growth. The effects of conductive impairment can be ameliorated by using acoustic hearing aids, and the impairment can sometimes be remedied using antibiotics or surgery. Sensorineural impairment can be caused by a tumour surrounding the auditory nerve, or damage to the stereocilia or other parts of the organ of corti. Sensorineural impairment generally cannot be remedied by medication or surgery, but the effects can be ameliorated using acoustic hearing aids or cochlear implants (see the following chapter for further details).

The degree of hearing impairment can be quantified using pure-tone audiometry, the results of which are expressed as a hearing level (HL): the lowest level at which a person can detect a tone on at least 50% of presentations (British Society of Audiology, 1981). HLs are measured across a range of frequencies and are calibrated relative to normally-hearing young adults, who have an average HL of zero. Greater HLs indicate greater hearing impairment. The five-frequency average is the mean of HLs measured at octave frequencies between 0.25 and 4 kHz. A five-frequency average greater than 95 dB is referred to as a profound impairment, 71–95 dB a severe impairment, 41–70 dB a moderate impairment, and 20–40 dB a mild impairment (British Society of Audiology, 1988). The results of pure-tone audiometry reflect difficulties in detecting sound. In addition, people with hearing impairment of cochlear origin display difficulties in frequency resolution and in encoding temporal fine structure (B. C. J. Moore, 2008; Pickles, 1988).

2.2.1 Consequences of hearing impairment

Severe to profound hearing impairment limits people's ability to communicate using spoken language. Consequently, adult-onset severe-profound hearing impairment is associated with isolation, restricted career options, and impaired quality of life (Barton, Bankart, & Davis, 2005; Chorost, 2005; Heath, 1991; Mohr et al., 2000). Moreover, in childhood, severe-profound hearing impairment can significantly impair the acquisition of spoken, signed, and written language (Svirsky et al., 2000). Prior to the widespread provision of cochlear implants, it was reported that profoundly-deaf 16-year-olds had language skills similar to those of normally-hearing 9-year-olds, on average (Moeller, Osberger, & Eccarius, 1986; Osberger, Moeller, Eccarius, Robbins, & Johnson, 1986). The cost to society of caring for a congenitally severely-profoundly deaf child, including provision of special education and lost productivity due to poor vocational prospects, may exceed $1 million (Mohr et al., 2000).

2.2.2 Prevalence and aetiology of hearing impairment in children

The most common cause of mild to moderate hearing impairment in children is otitis media with effusion ('glue ear'), which generates fluid in the middle ear. The condition affects between 10 and 30% of children under the age of 3 years, and the impairment is usually temporary (Lous et al., 2005). Permanent childhood hearing impairment is comparatively rare, and is predominantly sensorineural rather than conductive (Fortnum & Davis, 1997). For every 1000 live births in the UK, on average, one child is diagnosed with a permanent impairment (>40 dB HL in the better-hearing ear) by the age of 3 years, and an additional one child is diagnosed by the age of 10 years (Fortnum, Summerfield, Marshall, Davis, & Bamford, 2001). About half of these children have a moderate impairment, a quarter a severe impairment, and a quarter a profound impairment. Hearing impairment is, however, more common in older adults than in children: 18% of adults over the age of 70 have at least a moderate impairment (A. C. Davis, 1989).

Over 50% of all cases of congenital hearing impairment have a genetic aetiology (Tranebaerg, 2008). Other cases may be caused by ototoxic medication, infections such as cytomegalovirus and rubella, and complications during birth (Cristobal & Oghalai, 2008; Fortnum & Davis, 1997). Hearing impairment that is diagnosed after birth can be caused by many of the same factors and, additionally, by meningitis or head trauma (Hutt, 2008). The cause of hearing impairment is unknown for a large number of children (Fortnum and Davis).

Interim Summary

Conductive hearing impairment caused by fluid in the middle ear is common in early childhood, and the impairment is usually temporary. Permanent hearing impairment is comparatively rare, is often sensorineural in nature, and has a range of causes. Permanent severe-profound hearing impairment affects one child in a thousand, and impairs the acquisition of language, educational achievements, and quality of life.

2.3 Binaural hearing

The following paragraphs describe the differences between sounds at the two ears that arise from the location of sources of sound in space, and the acuity with which normally-hearing adults can detect those differences. The perception of interaural differences underlies spatial listening, meaning the ability to use both ears together to perceive speech in noise and to localise sources of sound on the horizontal plane. The importance of binaural hearing is illustrated by studies of unilaterally-deaf individuals, who show impaired performance on these tasks relative to normally-hearing listeners (Bess, Tharpe, & Gibler, 1986; Humes, Allen, & Bess, 1980).

It is useful to define a method for specifying the location of sound sources, relative to the centre of the listener's head. Azimuth is the angle by which a source is displaced from straight ahead of the listener, on a horizontal plane passing through the top of both ear canals (B. C. J. Moore, 2003). The convention of positive angles denoting sounds to the right of the listener will be used throughout this thesis, and angular locations will refer to positions on the horizontal plane unless specified otherwise.

2.3.1 Interaural differences in timing and level

Consider a sound source to the right of a listener's head: the signal arrives sooner, and is more intense, at the right ear than the left ear. Interaural time difference (ITD) is the disparity in the time of arrival of a sound at the two ears, and it arises when there is a shorter distance between the source of sound and one ear than between the source and the other ear. Measurements using microphones placed in the auditory canals of participants show that ITD is zero for a source at 0°. ITD increases systematically up to 700 microseconds (μs) for a source at 90°, then decreases to almost zero for sources at 180° (directly behind the listener; Fedderson, Sandel, Teas, & Jeffress, 1957; Grantham, 1995). The rate of change in ITD with increasing azimuth slows at around 80–100°, meaning that a 10° change in location at the side results in a smaller ITD change than a 10° change in location straight ahead of the listener. An increase in the rate of firing of the spiral ganglion cells in each auditory nerve reflects the arrival of the signal at that ear, which provides a basis for sensitivity to ITD. In addition to the difference in time of arrival at the ears, a sound located to one side can cause an ongoing difference in phase at the two ears. For example, a 1000 Hz tone has a wavelength of 1000 μs. An ITD of 500 μs would therefore result in an interaural phase difference of 180°. Phase locking in the auditory nerve provides the basis for sensitivity to interaural phase differences. For stimuli above about 700 Hz, interaural phase difference can be an ambiguous cue to source location because it may be difficult to determine which waveform peak at the left ear corresponds to a certain waveform peak at the right ear (B. C. J. Moore, 2003). For example, the maximum ITD for an average human head, 700 μs, is equivalent to the wavelength of a 1.4 kHz tone. At this frequency, a sound from straight ahead and a sound from +90° (giving an ITD of 700 μs) both result in an interaural phase difference of zero.

When sound sources are located to the side of the listener, sounds with a short wavelength (relative to the size of the head) reflect off the head rather than diffracting around it. Thus, the head casts an acoustic shadow and less high-frequency energy arrives at the far ear, creating an interaural level difference (ILD). Measured values of ILD vary with frequency: for a source located at +90°, ILD ranges from under 5 dB (for frequencies lower than 500 Hz) to 35 dB (for a 10 kHz tone; Fedderson et al., 1957; Middlebrooks, Makous, & Green, 1989). The rate of change in ILD with increasing azimuth is slower between 70° and 110° than at locations directly in front of, or behind, the listener. For narrowband stimuli, ILD is a simple difference in level between the two ears. For broadband stimuli, there is also a difference in spectrum at the two ears, with the ear further from the source containing less high-frequency energy. The firing rate of cells in the auditory nerve increases with amplitude: combined with frequency selectivity, this forms the basis of sensitivity to ILDs.

The first structure in the ascending auditory pathway after the cochlea is the cochlear nucleus. Above this level, brainstem structures and the cortex receive signals from both ears (Yost, 2000). The mechanisms by which the brain detects interaural differences in timing, phase, and level are the subject of ongoing research and are beyond the scope of this review (for further details, see Colburn, Shinn-Cunningham, Kidd, & Durlach, 2006 or McAlpine, 2005).

2.3.2 The sensitivity of normally-hearing listeners to interaural differences

The ability to discriminate differences in ITD and ILD can be measured by presenting stimuli over headphones. For pure-tone stimuli, listeners are most sensitive to ITDs at frequencies between 0.5 and 1.3 kHz (Klumpp & Eady, 1956). The smallest ITD which listeners can discriminate from an ITD of zero (referred to as the just-noticeable difference or JND) is just 11 μs for a 1 kHz tone (Klumpp and Eady). Listeners cannot detect ITDs of pure tones whose frequency is greater than 1.5 kHz, perhaps because of ambiguous interaural phase differences. In contrast, listeners can detect ITDs of noise stimuli that only contain energy above 2.4 kHz (Klumpp and Eady), and of high-frequency pure tones whose amplitude is modulated at a lower frequency (Henning, 1974). Listeners' sensitivity to ITDs in complex high-frequency stimuli is probably based on a comparison of the amplitude envelope at each ear, rather than a comparison of the temporal fine structure (Colburn et al., 2006).

Listeners can discriminate ILDs across a range of frequencies: the JND is 0.5 to 1 dB for pure tones between 0.2 and 10 kHz (Mills, 1960). However, low-frequency ILDs are not likely to be useful for localising sources of sound, because ILDs that vary systematically with azimuth are only generated by sounds whose frequency is above about 500 Hz (Fedderson et al., 1957; B. C. J. Moore, 2003).

2.4 Spatial listening skills of normally-hearing adults

2.4.1 Identifying the location of sources of sound

The ability to localise sources of sound can be assessed using the minimum audible angle (MAA): the smallest angular separation between two sources on the horizontal plane that a participant can reliably discriminate (Figure 2.3). The task for the listener can be thought of as left-right discrimination. Using pure-tone stimuli, the MAA for 75% correct is lowest for tones whose frequency is under 1 kHz, and is only 1° when the reference location is straight ahead (Mills, 1958). The change in ITD resulting from a 1° change in location directly in front of a listener is approximately 10 μs, so Mills' sound-field measurements correspond well with studies of sensitivity to ITD when stimuli are presented over headphones (B. C. J. Moore, 2003).

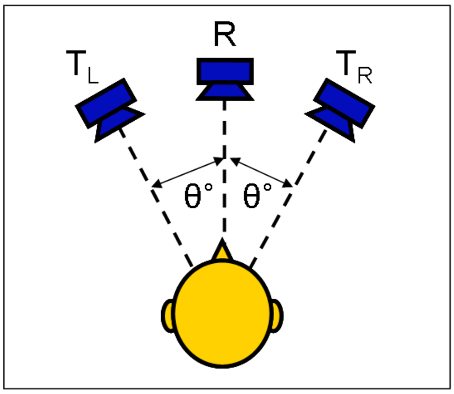

Figure 2.3. The standard technique for measuring minimum audible angle (MAA). A stimulus is presented from a reference location (R) followed by a stimulus from a 'test' location to the left (T_L) or the right (T_R) of the reference. The angle between the reference and test locations, θ, is varied. The participant's MAA is the smallest value of θ at which they can report whether the test stimulus came from the left or right of the reference with a certain accuracy (such as 75% correct). Figure adapted from Mills (1958).

An alternative to measuring the MAA is to assess participants' accuracy in identifying the location of a source of sound when they are presented with several possible locations (henceforth, these will be referred to as localisation tasks). Accuracy can be measured as the percentage of correct responses or as the root mean square (RMS) error (calculated by taking the angular distance between the participant's response and the source location, squaring it, and taking the square root of the average for all trials). An experiment by Stevens and Newman (1936) measured localisation in an anechoic environment created by seating the listener on top of a ventilator shaft. Localisation errors were highest for pure tones between 2 and 4 kHz. Other studies have used broadband stimuli, which means that listeners could potentially use ITDs, ILDs, and unambiguous interaural phase differences. The performance of normally-hearing adults on localisation tasks with broadband stimuli depends on the number of loudspeakers and the separation between loudspeakers (Bess et al., 1986; Van Deun et al., 2009). With nine loudspeakers separated by 13°, for example, the median RMS error is zero (Van Deun et al., 2009).

The Duplex theory of sound-source localisation was based on measurements of the ability to detect ITDs and ILDs, and to localise sources of sound, using pure-tone stimuli (Rayleigh, 1907). It was proposed that ITDs were used to localise stimuli below approximately 1.5 kHz and ILDs were used to localise higher-frequency stimuli. Demonstrations that listeners are sensitive to ITDs in the envelope of complex high-frequency stimuli (see section 2.3.2) indicate that the Duplex theory is an oversimplification. Studies using contradictory ITDs and ILDs indicate that ITDs dominate the localisation of stimuli containing low frequencies and ILDs dominate the localisation of stimuli containing only high frequencies (Wightman & Kistler, 1992), but listeners can use either cue in challenging listening situations (Akeroyd, 2006; Lorenzi, Gatehouse, & Lever, 1999).

It should be noted that some cues to source location are available to a monaural listener (i.e. a listener with only one ear). The filtering effect of the pinna creates cues to the elevation of a sound source. Consequently, the localisation of sources of sound on the median plane (a vertical plane going through the nose and dividing the body in half) is almost as accurate when listening monaurally as when listening binaurally (Middlebrooks & Green, 1991; Oldfield & Parker, 1986). Pinna cues also help to resolve front-back confusions. Regarding localisation on the frontal horizontal plane, monaural listeners can learn the level and spectral cues associated with a certain location if the same stimulus is presented repeatedly (Van Wanrooij & Van Opstal, 2004). In addition, with sounds of long duration, monaural listeners may be able to move their head and use the resulting level and spectral changes to localise the source (Perrott, Ambarsoom, & Tucker, 1987). Nonetheless, on the horizontal plane, binaural hearing gives more accurate sound-source localisation than monaural hearing, particularly for stimuli that are unfamiliar, changeable, or of short duration

(Oldfield & Parker, 1986; Van Wanrooij & Van Opstal, 2004).

2.4.1.1 Movement tracking

A further potential benefit of binaural hearing is the ability to track moving sources of sound (Middlebrooks & Green, 1991). Perrott and Musicant (1977) used loudspeakers on rotating booms. The speed of rotation was fixed and the duration of the stimulus was varied to estimate the minimum audible movement angle: the minimum arc of movement required for a participant to detect that the source was moving rather than stationary. The minimum audible movement angle was 8.3° at a rotation speed of 90 degrees per second, and larger for higher rotation speeds.

2.4.2 Speech perception in noise

People are often faced with a situation in which they are trying to understand one voice in the presence of several competing voices—the 'cocktail-party problem' (Cherry, 1953). The benefit of binaural rather than monaural listening in such situations can be demonstrated using four effects that are described in the following paragraphs. To measure the first three effects in normally-hearing listeners, stimuli are recorded using microphones placed in the auditory canals of a manikin. The stimuli are then presented to participants via headphones. This protocol simulates the experience of listening to speech and noise in the sound field, whilst allowing the experimenter to temporarily deprive normally-hearing listeners of one ear.

Several of the following studies used variations of an experimental design in which target speech was presented in the presence of noise. Participants were asked to repeat the target speech and the signal-to-noise ratio was varied adaptively (Levitt, 1971). The results are reported as a speech-reception threshold (SRT): the minimum signal-to-noise ratio at which the participant could correctly report a certain proportion of the target words (such as 50% or 70.9%). Lower SRTs reflect an ability to tolerate more noise.

Binaural summation When listeners are presented with speech and noise from the same location, their SRTs are 1 to 3 dB lower when listening binaurally than when listening monaurally (see Figure 2.4; Bronkhorst & Plomp, 1988; Ching, van Wanrooy, Hill, & Dillon, 2005; Hawley, Litovsky, & Culling, 2004). This effect is known as binaural summation. It probably arises because the auditory system receives two versions of the signal and, by comparing the two versions, can minimise the internal noise (noise introduced by the auditory system itself).

Binaural squelch If speech and noise are presented from spatially-separated sources, the ITD and ILD of the speech differ from the ITD and ILD of the noise. Binaural

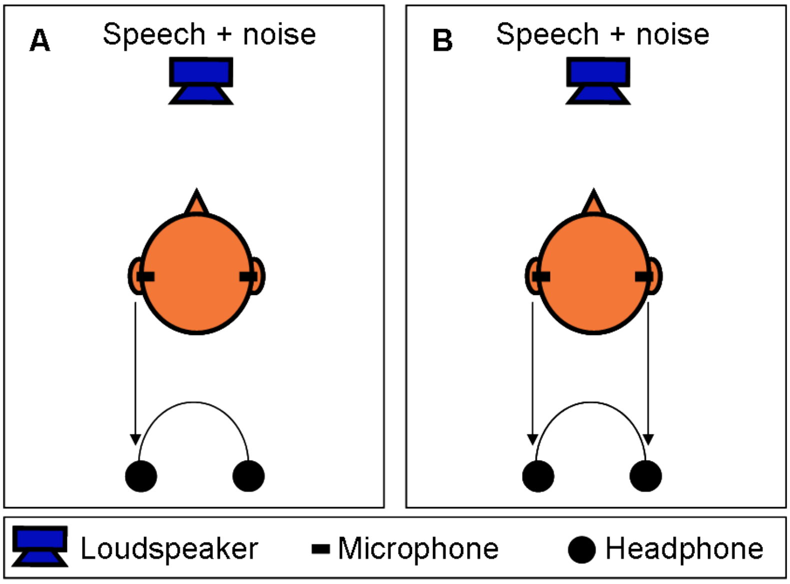

Figure 2.4. Measuring binaural summation in normally-hearing listeners. The orange figures depict a manikin with a microphone in each auditory canal. Stimuli are recorded from the microphones whilst speech and noise are presented from a single loudspeaker. A) Monaural condition: the recording from one microphone is presented to one ear using headphones. B) Binaural condition: the recording from each microphone is presented to each ear using headphones. SRTs are normally lower in the binaural condition, an effect known as binaural summation.

listeners can use these differences to aid their perception of speech. One measure of binaural benefit is binaural squelch (Figure 2.5). Normally-hearing adults show 1 to 6 dB of binaural squelch (Bronkhorst & Plomp, 1988, 1992; Hawley et al., 2004). Durlach (1963) proposed an Equalization-Cancellation model to explain how the auditory system uses a difference between the ITD of a tone and a noise to improve the perception of the tone. He suggested that the auditory system equalises the level and timing of the signal at each ear, and then subtracts the signal at one ear from the signal at the other ear. If there is a difference in ITD between the tone and the noise, this process should cancel much of the noise and improve the tone-to-noise ratio. Culling and Summerfield (1995) presented an updated model based on the perception of speech, in which the Equalization-Cancellation process was applied within, rather than across, frequency channels.

Head-shadow effect A further measure of binaural benefit is the head-shadow effect (Figure 2.6). SRTs are usually 10 to 13 dB lower in the binaural condition than in the monaural condition (Bronkhorst & Plomp, 1988, 1992). This difference arises because, in the binaural condition, the listener can attend to the ear that is shielded from the noise and therefore has a beneficial signal-to-noise ratio at frequencies above 0.5 to 1 kHz (i.e. the frequencies at which the head casts an acoustic shadow—see section 2.3.1). Furthermore, the speech and noise have different ITDs so listeners can potentially 'cancel' some of the noise.

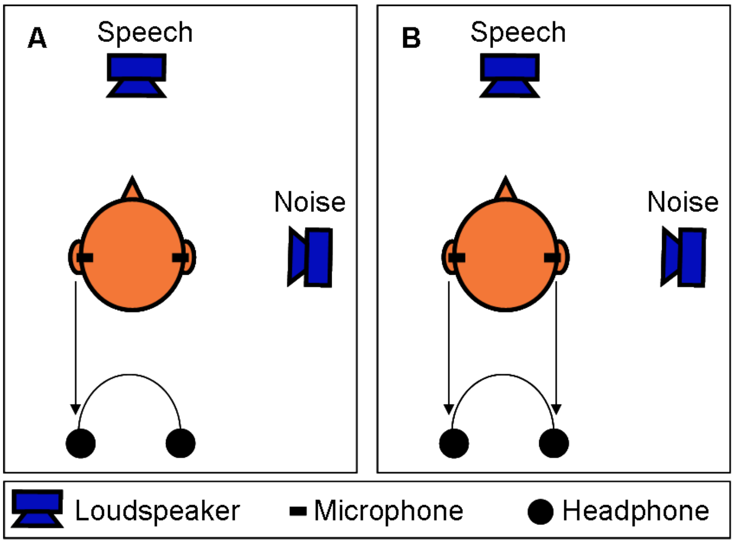

Figure 2.5. Measuring binaural squelch in normally-hearing listeners. The orange figures depict a manikin with a microphone in each auditory canal. Stimuli are recorded from the microphones whilst speech is presented from the front and noise from 90° to one side. A) Monaural condition: the recording from the microphone furthest from the noise is presented to one ear using headphones. B) Binaural condition: the recording from each microphone is presented to each ear using headphones. SRTs are normally lower in the binaural condition, an effect known as binaural squelch.

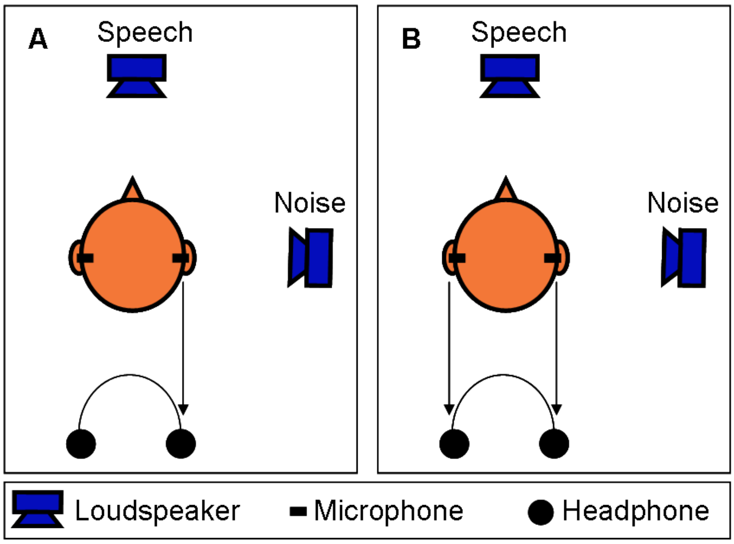

Figure 2.6. Measuring the head-shadow effect in normally-hearing listeners. The orange figures depict a manikin with a microphone in each auditory canal. Stimuli are recorded from the microphones whilst speech is presented from the front and noise from 90° to one side. A) Monaural condition: the recording from the microphone closest to the noise is presented to one ear using headphones. B) Binaural condition: the recording from each microphone is presented to each ear using headphones. SRTs are normally lower in the binaural condition—this improvement in performance is known as the head-shadow effect.

Spatial release from masking An alternative measure of the binaural benefit for speech perception is spatial release from masking (SRM), which is assessed by comparing *binaural* listening in two conditions (Figure 2.7). SRTs are typically lower in the condition with noise from the side than in the condition with noise from the front. This difference arises because, with noise from the side, one ear is shielded from the noise and therefore has a beneficial signal-to-noise ratio at frequencies above 0.5 to 1 kHz. Also, in the condition with noise from the side, the speech and noise have different ITDs so listeners can potentially 'cancel' some of the noise. SRM is typically between 5 and 11 dB and varies according to the number and type of maskers (Bronkhorst & Plomp, 1988, 1992; Hawley et al., 2004). Spatial release from masking is a useful measure when working with children because the stimuli are presented from loudspeakers rather than headphones—often, young children are reluctant to wear headphones.

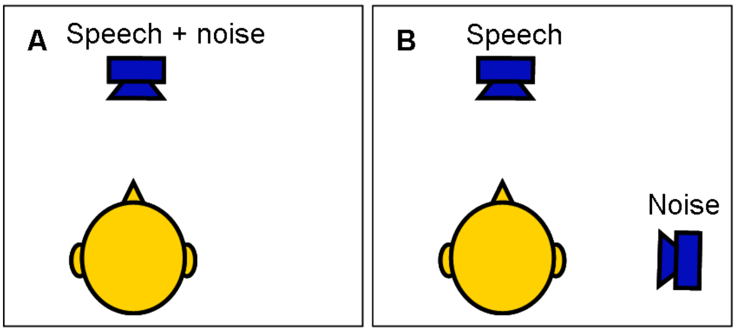

Figure 2.7. Listening conditions used to measure SRM in normally-hearing listeners. The yellow figures depict a listener sat in a testing booth containing two loudspeakers (shown in blue). A) Speech and noise are presented from the front. B) Speech is presented from the front and noise is presented from 90° to one side (illustrated here on the listener's right). SRM is calculated as the SRT in condition A minus the SRT in condition B. Positive values of SRM indicate that SRTs are lower in condition B.

Interim summary

The normal auditory system is remarkably sensitive to differences in the level and timing of sounds at the two ears. Listeners derive two main benefits from binaural hearing: the ability to localise the spatial position of a source of sound on the horizontal plane, and an enhanced ability to understand speech in the presence of noise. When listening binaurally, adults can distinguish two sound sources separated by as little as 1°. The benefits of binaural hearing for speech perception are demonstrated by binaural summation, binaural squelch, the head-shadow effect, and SRM.

2.5 Spatial listening skills of normally-hearing children

2.5.1 Identifying the location of sources of sound

2.5.1.1 Left-right discrimination tasks

To measure the MAA of preschool children, an observer judges whether the child made a head turn in response to the auditory stimulus and, if so, in what direction. With older children, the participant is asked to respond verbally or to point towards the location of the source of sound. The following summary refers to the MAA for 70.7% correct, unless stated otherwise. On average, the MAA for 4-month-old children is 20° (Ashmead, Davis, Whalen, & Odom, 1991), and performance improves to around 6° by the age of 18 months (Litovsky, 1997; Morrongiello, 1988). The MAA decreases further between 18 months and adulthood, but the trajectory of this improvement is not clear. Litovsky (1997) found that 5-year-olds had a mean MAA of 1.6°, which was not significantly different to the adult mean of 0.8°. In contrast, Ashmead et al. (1998) found that 12- to 15-year-olds had a mean MAA of 3.0°, significantly larger than the adult mean of 1.7°. It is likely that the difference in the results of Litovsky (1997) and Ashmead et al. (1998) is due to a difference in methods. Although both studies used noise-burst stimuli that were presented at a fixed level, the participants were blindfolded in the study by Ashmead et al. (to allow for comparison with visually-impaired children). Possibly, the removal of a visual referent for ‘straight ahead’ made the task more challenging, revealing differences in listening skill between children and adults. It is also possible that the estimates of MAA would be greater for both children and adults if the stimuli were roved in level. Grieco-Calub, Litovsky, and Werner (2008) used stimuli that were roved in level in order to reduce monaural cues to source location, and found that the mean MAA for 80.0% correct was 14° for children aged 26 to 36 months. This MAA is larger than the estimate of 6° for 18-month-olds using a fixed stimulus level (Litovsky, 1997). However, the two estimates are not directly comparable because Litovsky (1997) measured the MAA for 70.7% correct whereas Grieco-Calub et al. (2008) measured the MAA for 80.0% correct.

2.5.1.2 Localisation tasks

A handful of studies have assessed children’s ability to identify the location of a source of sound when they are presented with an array of possible locations. Van Deun et al. (2009) used a test with nine possible source locations ranging from −60° to +60°. They found that 4-year-olds had larger error scores than adults, whereas 5- and 6-year-olds performed at a similar level to adults. Bess et al. (1986) measured the performance of children aged 6 to 13 years, using a test with 13 possible source locations ranging from −90° to +90°. The children’s average error score was not significantly different to that of adults. Thus, performance on localisation tests appears to be adult-like by the age of 5 or 6 years, at least for tests with up to 13 alternative locations.

2.5.1.2.1 Tracking moving sounds A search of the literature did not reveal any studies that assessed the ability of normally-hearing children to track moving sources of sound. However, one relevant study used a procedure in which two loudspeakers (located at −45° and +45°) presented pairs of click stimuli (Cranford, Morgan, Scudder, & Moore, 1993). When the stimuli were presented concurrently, adults and children reported that the sound came from a source located straight ahead. When one of the clicks was delayed, the sound appeared to come from a source on the side of the leading loudspeaker: this is known as the precedence effect (Litovsky, 1997). Cranford et al. presented a series of pairs of clicks and varied the delay systematically, to create an illusion of a moving source of sound. Normally-hearing children used a laser pointer to track the apparent source. The responses of a group of children aged 10 or 11 years correlated with the delay between clicks to a greater degree than did the responses of children aged 6 to 9 years. Thus, those aged 10 or 11 years were better able to track the apparently-moving source. This oldest group of children performed similarly to a group of adults tested in a previous study (C. A. Moore, Cranford, & Rahn, 1990).

2.5.2 Speech perception in noise

2.5.2.1 Binaural summation, binaural squelch, and the head-shadow effect

Ching, van Wanrooy, et al. (2005) found that children aged between 7 and 16 years showed 1 dB of binaural summation; the same value was shown by adults. A search of the literature did not reveal any studies that measured binaural squelch or the head-shadow effect in normally-hearing children. However, Ching, van Wanrooy, et al. (2005) did assess whether children could use ITDs to aid the perception of speech in noise, using a paradigm called the binaural intelligibility level difference. The task was to report the words in sentences in steady-state noise. In the delayed condition, the speech was presented at the same time to both ears and the noise had an ITD of 700 μs. Children's SRTs in the delayed condition were 2.7 dB lower than in a condition where both speech and noise had an ITD of zero. The adults showed a difference of 3.7 dB between conditions. These results suggest that children are able to use ITDs to aid the perception of speech in noise. It follows that children may also benefit from binaural squelch, but this has not been demonstrated.

2.5.2.2 Spatial release from masking

The results of three studies that measured SRM in normally-hearing children are shown in Table 2.1; all of the studies used the Children's Realistic Index of Speech

Perception (CRISP; Garadat & Litovsky, 2007; Johnstone & Litovsky, 2006; Litovsky, 2005). CRISP is a closed-set single-word perception test in which the target voice is male. Different maskers can be used—Table 2.1 displays conditions in which the masker was a female voice reading sentences. The level of the target was varied adaptively, to estimate the signal-to-noise ratio at which the child performed at a level of 79.4% correct. Table 2.1 indicates that children as young as 3 years show SRM. The estimates of SRM are variable across studies and also within studies (the standard deviation was often as large as the observed SRM). A further relevant study tested 10 children aged between 7 and 12 years on a speech-detection task (rather than a speech-identification task). The average amount of SRM was 6 dB (Mok, Galvin, Dowell, & McKay, 2007).

It is not clear if the benefit from SRM increases as children get older. Garadat and Litovsky (2007) reported that 5-year-old children showed more SRM with a speech masker than 3-year-old children, but the difference was not significant. Two of the studies in Table 2.1 compared the performance of children with that of adults. Litovsky (2005) found that children and adults showed a similar amount of SRM with a noise masker. Conversely, Johnstone and Litovsky (2006) found that 5- to 7-year-old children showed less SRM than adults with a noise masker, and more SRM than adults with a reversed-speech masker. In the latter study, adults completed a 25-alternative task without feedback whereas children completed a 4-alternative task with feedback. Different results may be obtained if adults and children complete the same task.

Table 2.1. SRM in normally-hearing children. The age range of participants (in years), the number of participants (*N*), the set size, and the amount of SRM (in dB with standard deviation in parentheses) are listed. Set size refers to the number of different target words that were used. Only one target word was presented per trial.

Age range	*N*	Set size	SRM (*SD*)	Study
3.3 to 3.8	10	16	7.7 (7.2)	Garadat & Litovsky, 2007
4.2 to 5.5	10	16	11.0 (7.1)	Garadat & Litovsky, 2007
4.2 to 5.5	10	25	9.0[a]	Garadat & Litovsky, 2007
4.5 to 7.5	9	25	5.2 (4.0)	Litovsky, 2005
5.0 to 6.9	10	25	5.0 (8.0)	Johnstone & Litovsky, 2006

[a] Standard deviation was not reported.

2.6 Conclusion

Binaural hearing allows normally-hearing adults and children to localise sources of sound and improves the ability to perceive speech in noise. Some details regarding the development of skills in spatial listening are unclear because only a few studies have used a single set of tests to compare the listening skills of normally-hearing children of different ages.

2.7 Summary

- In the normal ear, changes in air pressure are converted into movement within the middle ear and cochlea, and then transformed into neural impulses by the inner hair cells.

- In the normal auditory nerve, the frequency of sound is represented by the location and timing of neural firing. The level of sound is represented by the rate of neural firing.

- Permanent severe-profound hearing impairment affects one child in a thousand, and can impair the acquisition of language, educational achievements, and quality of life.

- Sound sources located to the side of a listener create differences in the timing and level of sounds on arrival at each ear.

- Normally-hearing adults can detect ITDs of 11 μs and ILDs of 1 dB.

- Normally-hearing adults have a MAA of 1°. Adults typically show 1–3 dB of binaural summation, 1–6 dB of binaural squelch, a head-shadow effect of 10–13 dB, and 5–11 dB of SRM.

- The MAA of normally-hearing children decreases with age, from approximately 20° at 4 months to approximately 2° at 5 years.

- The performance of normally-hearing children on localisation tasks improves between the ages of 4 and 6 years, at which point performance is similar to that of adults.

- Children over 7 years old show adult levels of binaural summation, and can use ITDs to improve their perception of speech in noise.

- Children as young as 3 years show SRM, but it is not clear if SRM increases with age.

Chapter 3

Cochlear Implants

Worldwide, approximately 188,000 individuals with severe-profound deafness use a cochlear implant to help them to hear (National Institute on Deafness and Other Communication Disorders, 2010). This chapter provides an overview of how a cochlear implant works and the benefits of unilateral implantation (a single cochlear implant in one ear) for adults and children. Recently, controversy in the care of deaf children has centred on whether they should be provided with bilateral implants (two cochlear implants, one in each ear) rather than a unilateral implant. In this chapter, the evidence regarding the effectiveness of bilateral implantation for children is reviewed. Evidence from studies using similar research designs is grouped together to form three main sections: between-subjects comparisons, within-subjects comparisons, and longitudinal studies. For the most part, measurements of listening skill have been used as the measure of outcome, with only a couple of studies assessing language skills or quality of life. The review of the evidence concludes with a discussion of the ways in which these studies may be biased. At the end of the chapter there is an overview of the emerging evidence regarding variables that predict performance with either bilateral implants or bimodal devices (meaning a unilateral implant and a contralateral acoustic hearing aid).

3.1 Introduction to cochlear implantation

A cochlear implant is an electronic device which is implanted surgically into the inner ear of patients who are severely-profoundly deaf (Ramsden, 2002). Typically, individuals with sensorineural hearing impairment have damaged or missing hair cells but at least some surviving spiral ganglion cells (Wilson, 2004). Cochlear implants work by electrically stimulating the spiral ganglion cells.[1]

The internal parts of a cochlear implant consist of a receiver-stimulator coil,

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[1] There are other implantable electronic devices that help people to hear, such as an auditory brainstem implant (Rauschecker & Shannon, 2002). However, in this thesis, the term 'implant' is used to refer to a cochlear implant.

placed in a depression drilled into the mastoid bone behind the ear, and an electrode array, placed in scala tympani in the first one, or one and a half, turns of the cochlea (Figure 3.1). Externally, there is a transmitter coil, placed over the skin next to the receiver-stimulator coil, and a sound processor and microphone that are usually worn behind the ear. Sounds in the environment are detected via the microphone, then processed and converted to a digital signal by the sound processor. The transmitter coil sends the signal through the skin to the receiver-stimulator, which decodes the signal and converts it to electrical pulses. The electrode array delivers the pulses, which stimulate nearby spiral ganglion cells.

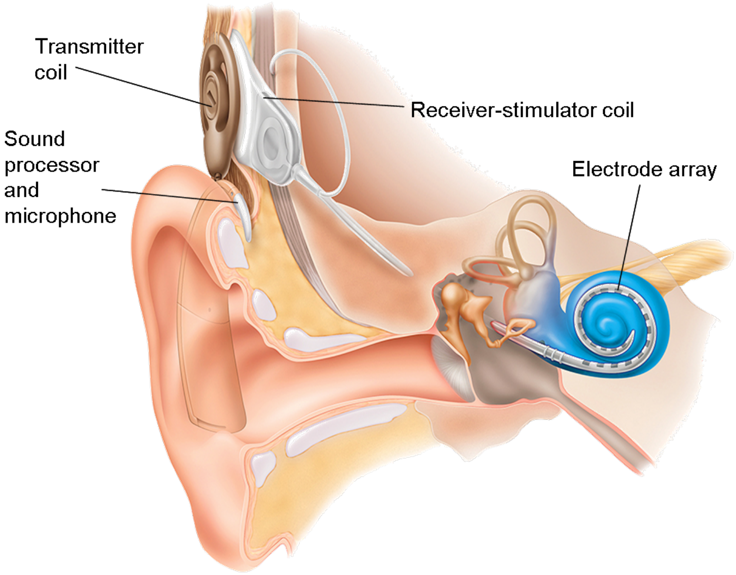

Figure 3.1. A schematic diagram of a cochlear implant. Image adapted from Seslami (2008).

The signal-processing strategy converts the signal from the microphone into a signal that can be delivered by the electrode array. Although strategies vary between cochlear-implant systems, many share the characteristics of continuous interleaved sampling (Figure 3.2; Wilson et al., 2005). Briefly, the signal is filtered into several frequency channels and then, within each channel, the amplitude envelope is extracted, compressed, and used to modulate a train of electrical pulses.[2] Consequently, the amplitude of the pulses represents the amplitude envelope of that channel. The signal from each channel is delivered to a single electrode: signals derived from high-frequency bandpass filters are delivered to electrodes near the base of the cochlea, signals derived from low-frequency bandpass filters are delivered to electrodes nearer the apex. Thus, the frequency-to-place mapping in the normal cochlea is approximated by a cochlear implant. However, because electrodes are not inserted all the way to the apex, the frequency-to-place mapping is not a replica of

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[2] In this thesis, ‘channel’ is used to refer to a frequency band that is extracted by a cochlear-implant processor. The term does not imply that the listener is able to distinguish each channel from adjacent channels (Friesen, Shannon, Baskent, & Wang, 2001; Shannon, 1995).

the normal auditory system. Signals derived from low-frequency sounds are often delivered to places in the cochlea that would normally be stimulated by higher-frequency sounds (Skinner et al., 2002).

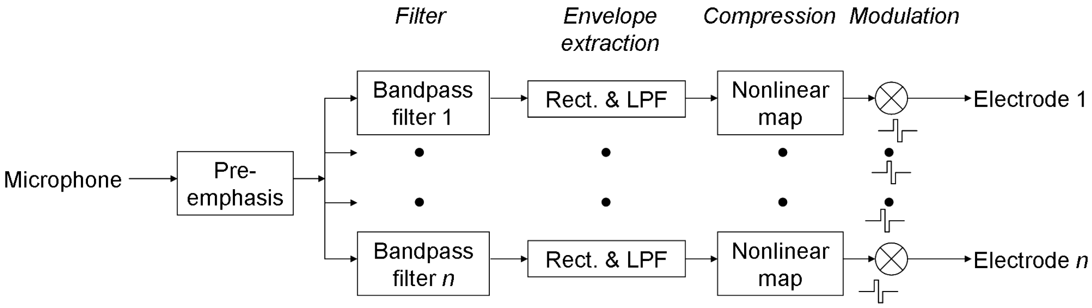

Figure 3.2. The continuous interleaved sampling sound-processing strategy for a cochlear implant with n electrodes. There are n channels of processing (only two channels are shown). The input from the microphone is pre-emphasised to boost medium- and high-frequency sounds (over 1.2 kHz), and then processed by n contiguous bandpass filters. The amplitude envelope is extracted using half-wave rectification and low-pass filtering (Rect. & LPF). The signal is compressed, to reduce the wide dynamic range of acoustical speech to the limited dynamic range of electrical hearing, and then used to modulate a pulse train. The pulse trains in different channels are interleaved so that the electrodes are not stimulated simultaneously. Image adapted from Wilson et al. (2005).

3.1.1 Outcomes following cochlear implantation

Approximately 400 adults and 270 children receive a cochlear implant every year in England and Wales (Bond et al., 2007). Although cochlear implantation does not restore normal hearing, it does lead to substantial improvements in the ability to detect sounds and to understand speech (Rauschecker & Shannon, 2002). There is considerable variation in outcomes following implantation, but the majority of adult patients understand more than 50% of the words in sentences presented in quiet, compared to fewer than 20% prior to implantation (UK Cochlear Implant Study Group, 2004c). Unilateral implantation in adults improves health-related quality of life (UK Cochlear Implant Study Group, 2004c) and may improve people's career prospects (Harris, Anderson, & Novak, 1995; Hogan, Stewart, & Giles, 2002).

Compared to amplification using acoustic hearing aids, unilateral implantation in severely-profoundly deaf children is associated with improved skills in speech perception, a faster acquisition of language, an increased likelihood of attending mainstream school, and higher health-related quality of life (Barton, Stacey, Fortnum, & Summerfield, 2006a; Boothroyd & Eran, 1994; Cheng et al., 2000; Stacey et al., 2006; Svirsky et al., 2000). Indeed, for children who are born deaf and who receive an implant before the age of two years, the average rate of language acquisition is similar to that of normally-hearing children (Holt & Svirsky, 2008). Children with an implant show higher educational achievements than children with a similar hearing impairment who do not use an implant, yet the cost to society of special education is reduced (Barton et al., 2006a). Although paediatric unilateral cochlear implantation is costly (the incremental discounted lifetime cost is £60,000 per child at 2007 cost levels), the average gain in quality of life is large enough to justify the cost (Barton et al., 2006b; Bond et al., 2007). Consequently, this is viewed as a cost-effective intervention (National Institute for Health and Clinical Excellence, 2009).

As a group, hearing-impaired children consistently benefit from unilateral implantation, yet the outcomes vary widely from child to child. Some of the variability can be explained by factors to do with the implant, the child, the family, and the educational setting (Geers, Brenner, & Davidson, 2003). Better speech perception following implantation is associated with a fully-implanted and fully-functioning electrode array, a younger age at implantation, a longer time since implantation, higher nonverbal intelligence, fewer additional disabilities, a smaller family, and an educational setting that is focussed on oral (rather than signed) language (Geers et al., 2003; O'Donoghue, Nikolopoulos, & Archbold, 2000; Stacey et al., 2006). In addition, better performance on more advanced measures of outcome, such as language and reading skills, is associated with female gender, higher socioeconomic status, better pre-operative hearing, and later onset of deafness (Moog & Geers, 2003; Nicholas & Geers, 2006).

3.1.2 Bilateral cochlear implantation

Until 2009, the policy of the National Health Service in the UK was to provide severely-profoundly deaf children with a unilateral cochlear implant (CI-only), with the option of an acoustic hearing aid in the nonimplanted ear (CI-HA, also referred to as bimodal stimulation). A few children received bilateral cochlear implants (CI-CI) because they had private funding, or because the child had additional sensory disabilities such as impaired vision. There were calls from parents, clinicians, and scientists for more widespread provision of bilateral implants for children (British Cochlear Implant Group, 2007; Broekhuizen & Byrne, 2009; Mueller, Schoen, & Helms, 2000; Vermeire, Brokx, Heyning, Cochet, & Carpentier, 2003; Wilson, Lawson, Muller, Tyler, & Kiefer, 2003).

There are three main arguments for bilateral implantation. First, the provision of two implants may give children the potential to develop binaural hearing, which could improve their ability to localise sources of sound and to perceive speech in noise (see section 2.3). These spatial listening skills may help children to avoid hazards outdoors and to understand speech better in noisy environments at home and at school. Second, bilateral implantation provides children with a back-up device in case they have low batteries, a faulty sound processor, or a malfunctioning electrode array. Third, implanting both ears ensures that the physiologically more-responsive ear will be stimulated (Papsin & Gordon, 2008).[3] On the other hand, bilateral implantation requires additional surgery, which entails additional risk. Furthermore, the ensuing damage to the cochlea may mean that the child cannot benefit from future interventions to improve hearing (Papsin and Gordon). The additional cost is considerable: compared to unilateral implantation, bilateral implantation in a single surgical session incurs an incremental discounted lifetime cost of £27,000 per child at 2007 cost levels (Bond et al., 2007). Evidence that children realise the potential benefits of bilateral implantation (in other words, evidence of clinical effectiveness) is needed to justify the additional surgery and extra cost. The evidence regarding clinical effectiveness is reviewed in section 3.1.3.

3.1.2.1 Cues to spatial listening from bilateral implants

There are limitations to the accuracy with which ITDs and ILDs are represented in the signals delivered by bilateral implants. Normally-hearing listeners are able to encode the temporal fine structure of signals below about 5 kHz, which provides a cue to ITD. Current cochlear-implant systems use a fixed pulse rate (van Hoesel et al., 2008), so the original temporal fine structure is not conveyed to the listener. Moreover, patients with bilateral implants use two independent sound processors, meaning that the timing of the moments at which pulses are generated is independent at the two ears. Consequently, the stimulation from bilateral implants does not precisely represent ITDs (Tyler, Dunn, Witt, & Preece, 2003). More positively, the signals delivered by cochlear-implant systems do represent ITDs in the amplitude envelope. Nonetheless, the ability of bilaterally-implanted adults to detect ITDs is poorer than that of normally-hearing listeners. Grantham, Ashmead, Ricketts, Haynes, and Labadie (2008) presented stimuli using headphones that were placed over patients' sound processors, and reported that only 4 out of 11 bilaterally-implanted adults could detect ITDs smaller than 700 μs. Thus, the majority of participants could not detect the largest ITD that occurs for humans. The ability of implanted adults to detect ITDs is typically better when stimuli are presented directly to electrodes rather than via their sound processors (Poon, Eddington, Noel, & Colburn, 2009), which suggests that future improvements in sound processors could lead to an improved perception of ITDs.

Bilateral implants provide listeners with a relatively accurate cue to ILDs, because the amplitude of the electrical pulses represents the amplitude envelope of the

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[3] There are two reasons why, with a policy of unilateral implantation for children, the more-responsive ear is not always implanted. 1) Identifying the more-responsive ear prior to surgery is not always straightforward, particularly in young children. 2) In the UK, many surgeons choose to implant the poorer-hearing ear in children, to increase the chance of benefit from a contralateral acoustic hearing aid. However, in adults, better hearing in the to-be-implanted ear is associated with better outcomes (Rubinstein, Parkinson, Tyler, & Gantz, 1999; UK Cochlear Implant Study Group, 2004b).

signal. Bilaterally-implanted listeners appear to rely more on ILDs than ITDs to localise sources of sound (Grantham et al., 2008; van Hoesel et al., 2008), and some implanted listeners can detect ILDs as small as 1–2 dB (Grantham et al.). However, the independence of the two processors may limit the accuracy with which ILDs are represented. Cochlear-implant processors apply automatic gain control (AGC) so that, above a certain sound pressure level, the signal is compressed more than at lower levels. This system prevents high-level sounds causing uncomfortably high levels of stimulation. If the signal at one ear is below the AGC activation threshold and the signal at the other ear is above the AGC activation threshold, the ILD could be reduced. Indeed, Grantham et al. demonstrated that the ILD thresholds of bilaterally-implanted adults were poorer when the AGC circuitry was active (mean 3.8 dB) than when the AGC was switched off (mean 1.9 dB). On the other hand, Noel and Eddington (2007) showed that patients' sound-source localisation performance was similar when the AGC circuitry was active and when the AGC was disabled. The patients' ability to localise despite the AGC was attributed to ILD cues that were present at the beginning of the stimulus, before the gain was fully reduced.

In summary, the accuracy with which ITDs and ILDs are represented in the signals delivered by bilateral implants is limited by the signal-processing strategy and the independence of the two sound processors. Moreover, even if interaural differences in timing and level are represented in the signals, patients may have an impaired ability to detect those differences. Individuals who use cochlear implants may have uneven neural survival across the two ears, or abnormal pathways in the auditory brainstem and cortex (Tyler et al., 2003). Interaural differences in the depth to which electrode arrays are inserted may mean that ITDs and ILDs in a certain frequency channel are delivered to noncorresponding places in the two cochleae (Long, Eddington, Colburn, & Rabinowitz, 2003). This may impair the ability to detect interaural differences—data from normally-hearing listeners indicate that the detection of ITDs and ILDs is impaired when the signals at each ear differ in frequency (Colburn et al., 2006; Francart & Wouters, 2007; Nuetzel & Hafter, 1981). Long-term experience with bilateral implants could overcome some of these limitations, particularly in young children whose brains are highly plastic (Tyler et al.).

3.1.2.2 Cues to spatial listening from bimodal stimulation

Three of the factors that affect the cues to spatial listening delivered by bilateral implants also affect the cues delivered by bimodal devices. First, the signal from the implant does not convey temporal fine structure, which will impair the accuracy with which ITDs are represented. Second, the devices at each ear apply independent AGC, which may impair the accuracy with which ILDs are represented. Third, interaural differences in timing and level will be delivered to noncorresponding places in the two cochleae, which may limit listeners' ability to detect those differences. There are also limitations that are specific to bimodal stimulation. At the implanted ear, signals are processed by the external parts of the implant and then transmitted to the electrode array. At the nonimplanted ear, signals are processed by the acoustic hearing aid and propagated through the outer and middle ear before reaching the cochlea. The latter process is slower, which means that ITDs are distorted by bimodal devices (Francart, Brokx, & Wouters, 2009). The majority of bimodally-aided patients have severe-profound hearing impairment in the nonimplanted ear, often with a greater impairment at high frequencies than at low frequencies. Consequently, patients may be limited in their ability to use ILD as a cue to sound-source location because ILDs are small for low frequencies (less than 5 dB for signals below 500 Hz; Fedderson et al., 1957; Middlebrooks et al., 1989).

A search of the literature did not reveal assessments of the sensitivity of bimodally-aided patients to ITDs and ILDs when listening with their usual devices. Francart, Brokx, and Wouters (2009) presented stimuli directly to one electrode in the implanted ear and an insert earphone in the nonimplanted ear, and found that four bimodal listeners had a JND for ITD smaller than 700 μs. An additional four patients were unable to perform the task, even after training. An earlier study by Francart (2008) also presented stimuli directly to an electrode and an insert earphone, and reported that 10 bimodally-aided patients had a median JND for ILD of 1.7 dB (range 1–3 dB). Thus, under optimal conditions, a subset of bimodally-aided patients displayed sensitivity to ITDs and all patients displayed sensitivity to ILDs.

Some authors have argued that the signals delivered by cochlear implants and acoustic hearing aids complement each other successfully precisely because they are different (Ching et al., 2009; Mok, Galvin, Dowell, & McKay, 2009). Potentially, listeners could perceive medium- to high-frequency signals via their implant and low-frequency signals via their hearing aid. Furthermore, the hearing aid delivers a relatively accurate representation of temporal fine structure, which could improve the ability of implanted listeners to perceive pitch. Pitch is important for the enjoyment of music and can be used as a cue to segregate concurrent talkers (Assmann & Summerfield, 1990). In support of this theory, adults perform better on tests of music perception and speech perception in noise when they use an implant and an hearing aid rather than an implant alone (Kong, Stickney, & Zeng, 2005). The acoustic and phonetic cues that may underlie this benefit are discussed in section 6.1.2.2.2.

3.1.3 Assessing the effectiveness of bilateral implantation: research design

To assess clinical effectiveness, it is necessary to compare outcomes between patients who received the intervention of interest and patients who received the standard intervention: in this case, bilateral and unilateral implantation, respectively. The most rigorous assessment of the effectiveness of bilateral implantation would be a randomised controlled trial in which children were randomly allocated to receive either unilateral or bilateral implantation. Randomisation is the only method by which all confounding variables (including those that are not yet known to affect outcome) are controlled, allowing one to be confident that any observed effects of the intervention were not due to pre-existing differences between the groups (Kunz & Oxman, 1998). No randomised trials of bilateral implantation for children have been reported. The original intention was to report such a trial in this thesis. However, before the trial began, the healthcare policy in the UK was changed to recommend bilateral implantation (National Institute for Health and Clinical Excellence, 2007, 2009), thus making a trial unethical and impractical.

Nonrandomised research designs can nonetheless provide evidence about the effectiveness of bilateral implantation. Studies in which outcomes are compared between a group of bilaterally-implanted children and a separate group of unilaterally-implanted children (between-subjects comparisons) are valuable. However, the results can be biased if the groups differ on variables other than the number of implants, especially if those variables are known to affect outcome. Most attempts to assess the effectiveness of bilateral implantation for children have compared the listening skills of bilaterally-implanted patients in two conditions: 1) when using both implants; and 2) when only one implant was switched on. A similar within-subjects design has been used to assess the benefits of a contralateral acoustic hearing aid for unilaterally-implanted children. Each participant acts as their own control, which increases statistical power and avoids the problem of confounding differences between groups. On the other hand, within-subjects designs may overestimate the benefit of a second device because the unilateral condition is unfamiliar to the child. A single study has used a longitudinal design with no control group, meaning that unilaterally-implanted children were assessed before and after receiving a second implant (Zeitler et al., 2008). The disadvantage is that the bilateral condition is confounded with maturation and experience of performance tests.

The following sections review evidence from between-subjects studies, within-subjects studies, and a longitudinal study. Within each section, the evidence regarding skills in sound-source localisation and speech perception will be considered in turn. Bilateral implantation can be provided in a single surgical session, known as simultaneous implantation, or in successive surgeries, known as sequential implantation. Studies of these two groups of children are reported together. Studies were identified using searches of PubMed (http://www.ncbi.nlm.nih.gov/pubmed) and PsycINFO (http://www.apa.org/psycinfo/). The searches were carried out in October 2007 and repeated in November 2009, using the terms in Table 3.1. In addition, the reference lists of published articles were checked and searches were carried out for articles that cited key papers.

Tables are used to summarise the methods and results of published studies. For most studies, it was necessary to estimate the results from a graph. Every table lists a number for each study, to make it easier to compare the tables and the accompanying text. Where studies appear in multiple tables, their number may not be consistent. Outcomes following unilateral implantation are influenced by numerous variables (see section 3.1.1), and it is likely that outcomes following bilateral implantation are influenced by at least some of the same variables. Nonetheless, few studies describe participants in terms of these variables. The tables show the two biographical variables that are reported most frequently: the participants' age and the amount of time for which they have used their device(s). Further relevant biographical information is stated in the text.

Table 3.1. Search terms used to identify relevant studies. The listed words were searched for in any part of a citation. An asterisk denotes the wildcard operator.

Search term
bilateral cochlear implant* AND child*
cochlear implant* AND hearing aid* AND child*
bilateral cochlear implant* AND quality of life
bilateral cochlear implant* AND utility
sound localization child*
spatial release from masking child*
spatial release from masking cochlear implant*

3.2 Between-subjects comparisons of unilaterally- and bilaterally-implanted children

3.2.1 Identifying the location of sources of sound

The four studies that used a left-right discrimination test (see section 2.4.1) to compare unilaterally- and bilaterally-implanted children are summarised in Table 3.2. Accurate performance is represented by a high proportion of correct responses or a low MAA. Study 1 in Table 3.2 found that CI-CI children performed significantly better than CI-only children. Study 2 in Table 3.2 attempted to measure the MAA for 80% correct, but none of the CI-only children could perform with this accuracy at the widest loudspeaker separation of 70°, so data were not reported for CI-only children. Study 3 in Table 3.2 found that CI-CI children had significantly lower MAAs than CI-HA children. Four CI-CI children and one CI-HA child were excluded from this analysis, on the basis that they found the task difficult and had MAAs greater than 60°. However, three of these CI-CI children did have a measurable MAA when both implants were switched on, and arguably their data should have been included.

To assess the effect of the exclusion of these children on the statistical analysis, data for all children with a measurable MAA were extracted from published graphs. The difference in MAA between the CI-HA children ($N = 5$) and CI-CI children ($N = 12$) was not statistically significant (CI-HA group mean 44°, CI-CI group mean 30°, 95% confidence interval for the difference -44 to $+16$).

Study 4 in Table 3.2 used the same methods as study 3, and included some of the same children, and did not find a significant difference between the groups. The discrepancy between the published results of studies 3 and 4 does not appear to be due to the exclusion of children in study 3, as the published level of performance of the CI-CI group was similar in both studies. The discrepancy may have arisen because the CI-HA group in study 3 performed worse than the CI-HA group in study 4: the mean MAAs were 44° and 27°, respectively. It is not clear why this difference in performance arose, as the CI-HA children in both studies were of a similar age with comparable levels of residual hearing and experience of using their devices. A simple explanation is that observing small samples of a population that shows variable outcomes leads to inconsistent results.

To summarise, two studies that analysed results from a total of 24 participants found that bilaterally-implanted children performed significantly better than unilaterally-implanted children on a test of left-right discrimination. One of these studies excluded data from some children. An analysis of the complete set of data, estimated from published graphs, indicated there was no significant difference between the groups. Two further studies, with results from a total of 32 participants, either found no significant difference between unilaterally- and bilaterally-implanted children or did not report statistical tests. A search of the literature did not reveal any studies that used a localisation test (meaning a test with at least three possible source locations—see section 2.4.1) to compare unilaterally- and bilaterally-implanted children.

Table 3.2. Between-subjects comparisons of unilaterally- and bilaterally-implanted children using a left-right discrimination task. Ages and durations are in years. DV refers to the dependent variable. 5FA refers to the average of HLs in the nonimplanted ear, measured at octave frequencies between 0.25 and 4 kHz.

Study	Unilaterally-implanted participants	Bilaterally-implanted participants	Task	Results	Reference
1	*N* = 5. Mean age 5.3. Mean experience of CI-only 3.9. Did not report HL.	*N* = 5. Mean age 3.6. Mean experience of CI-CI 1.8. All but one simultaneous.	Loudspeakers at ±90° and ±30°. DV: % correct head turns.	Loudspeakers at ±90°: CI-only group mean 37%, CI-CI group mean 96%.[a] Loudspeakers at ±30°: CI-only group mean 41%, CI-CI group mean 92%.[a]	Beijen, Snik, & Mylanus, 2007
2	*N* = 8. Mean age 2.8. Mean experience of CI-only 1.5. Did not report HL.	*N* = 10. Mean age 2.5. Mean experience of CI-CI 0.8. All but one sequential.	MAA for 80% correct.	None of the CI-only children, and 5 of the CI-CI children, performed with an accuracy >80% correct at the widest loudspeaker separation.[c]	Grieco-Calub et al., 2008
3	*N* = 6. Mean age 8.6. Mean experience of CI-HA 3.1. Aided 5FA of 47 dB.[d]	*N* = 13. Mean age 7.8. Mean experience of CI-CI 0.6. All sequential.	MAA for 70.9% correct.	CI-HA group mean 44° ($N = 5$), CI-CI group mean 16° ($N = 9$).[a]	Litovsky, Johnstone, Godar, Agrawal, et al., 2006

Table 3.2. (Continued). Between-subjects comparisons of unilaterally- and bilaterally-implanted children using a left-right discrimination task. Ages and durations are in years. DV refers to the dependent variable. 5FA refers to the average of HLs in the nonimplanted ear, measured at octave frequencies between 0.25 and 4 kHz.

Study	Unilaterally-implanted participants	Bilaterally-implanted participants	Task	Results	Reference
4	$N = 10$. Mean age 9.0. Mean experience of CI-HA 3.6. Aided 5FA of 55 dB.[d]	$N = 10$. Mean age 7.4. Mean experience of CI-CI 1.2. All sequential.	MAA for 70.9% correct.	CI-HA group mean 27° ($N = 8$), CI-CI group mean 20° ($N = 6$).[b]	Litovsky, Johnstone, & Godar, 2006

[a] Significant difference between groups, $p < .05$. [b] No significant difference between groups. [c] No statistical test was reported.

[d] Exact HLs were not reported for all children.

3.2.2 Speech perception in noise

Between-subjects studies have compared the speech-perception skills of unilaterally- and bilaterally-implanted children in three ways. First, one can compare the SRTs (or percentage of words reported correctly at a fixed signal-to-noise ratio) of unilaterally- and bilaterally-implanted children, when listening with the device(s) they use everyday. Second, one can compare the extent to which the two groups show SRM, when listening with the device(s) they use everyday. Third, one can compare the extent to which the two groups show binaural summation, binaural squelch, and the head-shadow effect. The third comparison involves testing children whilst using both devices and whilst using only one device. For the remainder of this thesis, the 'first' implant refers to a child's only implant (for unilaterally-implanted children) or the implant that was provided earlier in life (for bilaterally-implanted children).

3.2.2.1 Speech-reception thresholds

A search of the literature did not reveal any study that showed a significant difference between the speech-perception skills of unilaterally- and bilaterally-implanted children when listening with the device(s) they use everyday. Litovsky, Johnstone, and Godar (2006) used the CRISP test (see section 2.5.2.2) with two competing talkers, to estimate the signal-to-noise ratio at which the child could report single words with an accuracy of 79.4% correct. The target speech was presented from 0° and the masker was presented from either −90°, 0°, or +90°. In all conditions, the average SRTs of 10 CI-CI children did not differ significantly from those of 10 CI-HA children. Mok et al. (2009) measured the accuracy with which children could report open-set words presented with four competing talkers at a signal-to-noise ratio of +10 dB. The target speech was presented from the front, with the masker either from the front or from 90° on the side of the first implant. In both conditions, the average scores of four CI-CI children were similar to those of nine CI-HA children; a statistical test was not reported. Schafer and Thibodeau (2006) used a test in which the target speech instructed the child to carry out an action on a doll (e.g. 'wipe his mouth'). The speech was presented from 0° and classroom noise was presented from 135° and 225°. The SRT was estimated as the signal-to-noise ratio at which the child carried out the correct action on 50% of trials. There was no significant difference between the average SRTs of 12 CI-CI children and 10 CI-HA children. In summary, three studies with a total of 55 participants found that unilaterally- and bilaterally-implanted children show a similar ability to perceive speech in noise, despite the potential for the latter group to use both ears and to benefit from electrical stimulation to the physiologically more-responsive ear.

3.2.2.2 Spatial release from masking

The conditions used to measure SRM in implanted listeners are shown in Figure 3.3. One would expect children with a unilateral implant to show SRM with noise contralateral to their implant, because the implant is shielded from the noise in the condition with noise from the side. An important question is whether providing a second device enables children to benefit from SRM with noise ipsilateral to their first implant.

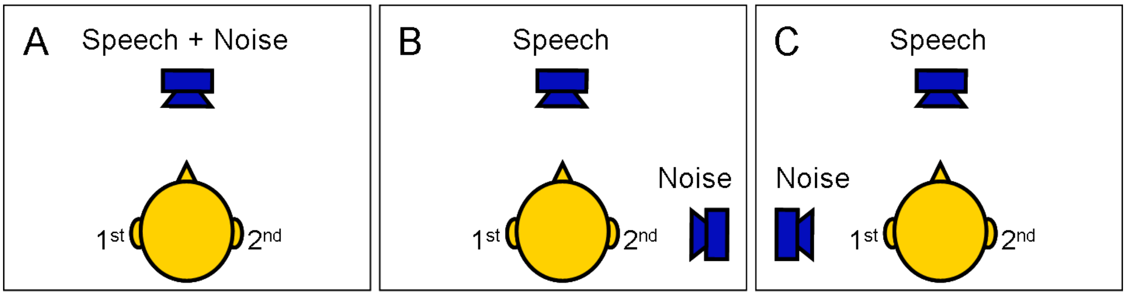


Figure 3.3. Measuring SRM in implanted listeners. The yellow figures depict a participant sat in a testing booth containing loudspeakers (shown in blue). SRM is measured by comparing SRTs in three conditions. In one, speech and noise are presented from the front (Panel A). In the others, speech is presented from the front and noise is presented from the side (Panels B and C). The difference in performance between conditions A and B is the amount of SRM with noise contralateral to the first implant (illustrated in the left ear). The difference in performance between conditions A and C is the amount of SRM with noise ipsilateral to the first implant. The device labelled 2nd is either the implant that was received later in life, an acoustic hearing aid, or no device.

Three studies have compared the amount of SRM shown by unilaterally- and bilaterally-implanted children (Table 3.3). Positive SRM indicates that children could tolerate a less favourable signal-to-noise ratio when noise was presented from the side than when noise was presented from the front (this is the pattern shown by normally-hearing listeners—see section 2.5.2.2). Negative SRM indicates that children required a more favourable signal-to-noise ratio when noise was presented from the side than when noise was presented from the front. The tests used by studies 1 and 3 in Table 3.3 were described in section 3.2.2.1. Study 2 in Table 3.3 used a test in which children were asked to detect a speech token (“baba”) in the presence of broadband noise with the same long-term spectrum as speech. The signal-to-noise ratio was varied to estimate the “detection signal-to-noise ratio”. It is not clear what percentage of correct responses were made at this threshold. Studies 2 and 3 in Table 3.3 reported results from the same group of children, tested at the same age.

Study 1 in Table 3.3 reported a nonsignificant tendency for CI-CI children to show more SRM than CI-HA children, in both noise configurations. Study 2 in Table 3.3 reported that CI-CI children showed significantly more SRM than CI-HA children, with noise ipsilateral to the first implant. However, the difference was small, and it was measured using a test in which children reported the presence, rather than the content, of target speech. The same study reported a nonsignificant tendency for CI-CI children to show more SRM than CI-HA children, with noise contralateral to the first implant. Study 3 in Table 3.3 reported that both CI-HA and CI-CI children showed somewhat poorer performance with noise ipsilateral to the first implant than with noise from the front; a statistical test was not reported. Study 3 in Table 3.3 did not measure SRM with noise contralateral to the first implant.

To summarise, one study of 13 participants reported that bilaterally-implanted children showed significantly greater SRM than unilaterally-implanted children, with noise ipsilateral to the first implant. Two further studies, with results from a total of 33 children, did not report a significant difference between the groups in SRM. The groups of children in the studies by Mok et al. were not well matched: the average age at first implantation was 4 years older for the CI-HA group than for the CI-CI group, and the CI-HA group had 4 years' more experience of using both devices than the CI-CI group.

Table 3.3. Between-subjects comparisons of the SRM shown by unilaterally- and bilaterally-implanted children. Ages and durations are in years. 5FA refers to the average of HLs in the nonimplanted ear, measured at octave frequencies between 0.25 and 4 kHz.

Study	Unilaterally-implanted participants	Bilaterally-implanted participants	Task	Results	Reference
1	*N* = 10. Mean age 9.0. Mean experience of CI-HA 3.6. Mean aided 5FA of 55 dB.[d]	*N* = 10. Mean age 7.4. Mean experience of CI-CI 1.2. All sequential.	CRISP. DV: minimum signal-to-noise ratio for 79.4% correct.	With noise ipsilateral to the first implant: CI-HA group mean −1 dB of SRM, CI-CI group mean +1 dB of SRM.[b] With noise contralateral to the first implant: CI-HA group mean +2 dB of SRM, CI-CI group mean +5 dB of SRM.[b]	Litovsky, Johnstone, & Godar, 2006
2	*N* = 9 CI-HA. Mean age 12.1. Mean experience of CI-HA 5.3. Mean aided 5FA of 57 dB.	*N* = 4 CI-CI. Mean age 10.2. Mean experience of CI-CI 1.3. All sequential.	Speech-detection task. DV: minimum signal-to-noise ratio for detection.	With noise ipsilateral to the first implant: CI-HA group mean −0.4 dB of SRM, CI-CI group mean +0.4 dB of SRM.[a] With noise contralateral to the first implant: CI-HA group mean +3.8 dB of SRM, CI-CI group mean +4.5 dB of SRM.[b]	Mok et al., 2007

Table 3.3. (Continued). Between-subjects comparisons of the SRM shown by unilaterally- and bilaterally-implanted children. Ages and durations are in years. 5FA refers to the average of HLs in the nonimplanted ear, measured at octave frequencies between 0.25 and 4 kHz.

Study	Unilaterally-implanted participants	Bilaterally-implanted participants	Task	Results	Reference
3	*N* = 9 CI-HA. Mean age 12.1. Mean experience of CI-HA 5.3. Mean aided 5FA of 57 dB.	*N* = 4 CI-CI. Mean age 10.2. Mean experience of CI-CI 1.3. All sequential.	Report open-set words presented at a signal-to-noise ratio of +10 dB. DV: % correct.	For CI-HA group, mean accuracy was 6% lower with noise ipsilateral than with noise front. For CI-CI group, mean accuracy was 5% lower with noise ipsilateral than with noise front.[c]	Mok et al., 2009

[a] Significant difference between groups, $p < .05$. [b] No significant difference between groups. [c] No statistical test was reported.
[d] Exact HLs were not reported for all children.

3.2.2.3 Binaural summation

For implanted listeners, binaural summation is measured by presenting speech and noise from straight ahead and comparing SRTs in two conditions: using both devices and using only one device. The device used for the monaural condition is the one that gives the best monaural performance (typically, the first implant). Litovsky, Johnstone, and Godar (2006) found that, on average, CI-CI children showed significantly more binaural summation than CI-HA children. Two studies of a single sample of children found the opposite result: CI-HA children showed significantly more binaural summation than CI-CI children (Mok et al., 2007, 2009). Schafer and Thibodeau (2006) found that neither CI-HA children nor CI-CI children showed significant binaural summation with speech from 0° and noise from 135° and 225° (this configuration creates an approximately equal signal-to-noise ratio at both ears, and can therefore be used to measure binaural summation).

3.2.2.4 Binaural squelch

The conditions used to measure binaural squelch in implanted listeners are shown in Figure 3.4. Only two studies have compared the amount of binaural squelch shown by CI-HA and CI-CI children; both used a configuration with noise contralateral to the first implant. Litovsky, Johnstone, and Godar (2006) found that CI-CI children showed significantly more binaural squelch than CI-HA children; Mok et al. (2007) found no significant difference between the groups.

3.2.2.5 The head-shadow effect

The conditions used to measure the head-shadow effect in implanted listeners are shown in Figure 3.5. Three studies have compared the head-shadow effect shown by CI-HA and CI-CI children; all three used a configuration with noise ipsilateral to the first implant. Two studies found that CI-CI children showed a significantly greater head-shadow effect than CI-HA children (Litovsky, Johnstone, & Godar, 2006; Mok et al., 2007). In contrast, Mok et al. (2009) found no significant difference between the groups.

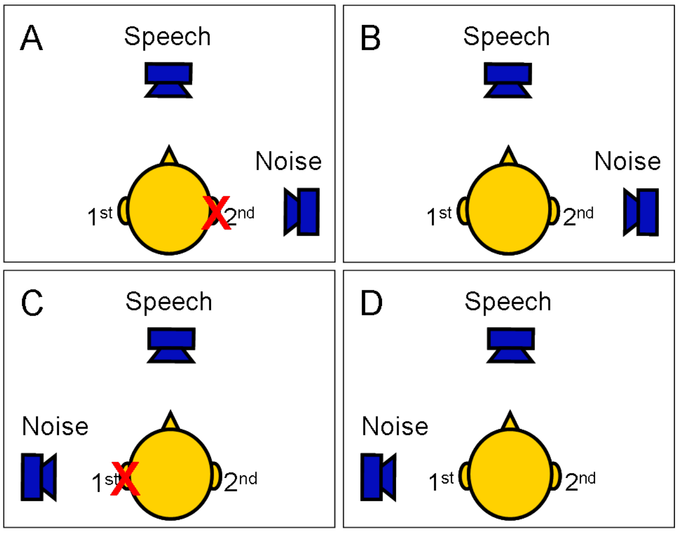


Figure 3.4. Measuring binaural squelch in implanted listeners. The yellow figures depict a participant sat in a testing booth containing loudspeakers (shown in blue). A red cross indicates that a device is turned off. Speech is presented from the front and noise from the side either contralateral (panels A and B) or ipsilateral (panels C and D) to the first implant (illustrated in the left ear). With noise contralateral to the first implant, binaural squelch is the difference in SRTs between the monaural (panel A) and binaural conditions (panel B). With noise ipsilateral to the first implant, binaural squelch is the difference in SRTs between the monaural (panel C) and binaural conditions (panel D).

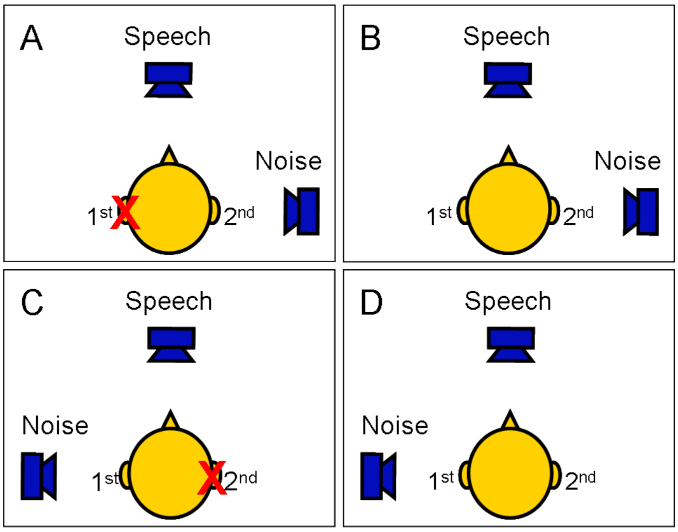


Figure 3.5. Measuring the head-shadow effect in implanted listeners. The yellow figures depict a participant sat in a testing booth containing loudspeakers (shown in blue). A red cross indicates that a device is turned off. Speech is presented from the front and noise from the side either contralateral (panels A and B) or ipsilateral (panels C and D) to the first implant (illustrated in the left ear). With noise contralateral to the first implant, the head-shadow effect is the difference in SRTs between the monaural (panel A) and binaural conditions (panel B). With noise ipsilateral to the first implant, the head-shadow effect is the difference in SRTs between the monaural (panel C) and binaural conditions (panel D).

3.2.3 Language skills and quality of life

One of the motivations for providing implanted children with a second device is to improve their perception of speech, particularly in noisy situations. Potentially, an improved perception of speech could help children to acquire spoken language more rapidly and/or more extensively. A search of the literature revealed only one study that compared the spoken language skills of unilaterally- and bilaterally-implanted children (Nittrouer & Chapman, 2009). Three groups were assessed at the age of 42 months: 1) 15 CI-only children; 2) 17 CI-HA children; and 3) 26 CI-CI children. The groups did not differ significantly on measures of receptive or expressive language. Thus, at the age of 42 months, there was no significant difference between the language skills of unilaterally- and bilaterally-implanted children. The same study reported a separate analysis, for which all of the children were split into two groups: 1) those who had, at some point, used bimodal stimulation; and 2) those who had never used bimodal stimulation. The group with experience of bimodal stimulation had significantly better expressive language skills than the group with no experience of bimodal stimulation. The authors suggested that the acoustic information provided by a hearing aid, specifically an accurate representation of fundamental frequency and voiced formants, helped children to parse running speech into smaller segments and thus aided the acquisition of language. The three groups of children in the main analysis were well-matched on a range of biographical and clinical variables, but corresponding data were not presented for the two groups of children in the subsequent analysis. Thus, it is difficult to assess whether the relationship between bimodal stimulation and language was caused by a confound such as hearing level.

A further study analysed video recordings of 27 CI-only and 26 CI-CI children (Tait et al., 2010). The recordings showed the child interacting with a parent, and they were made prior to implantation (at an average age of 12 months) and one year after implantation. The children's preverbal communication skills were assessed using a video-analysis technique described by Tait, Lutman, and Nikolopoulos (2001). Unilaterally-implanted children who show more vocal than gestural communication, as assessed by this technique, show better skills in speech perception later in life (Tait et al., 2001). One year after implantation, the bilateral group were significantly more likely to show vocal communication than the unilateral group, and the unilateral group were significantly more likely to show gestural communication than the bilateral group. These results suggest that the bilateral group may develop better speech perception skills than the unilateral group. However, the groups were not comparable in their communication style prior to implantation: the unilateral group were significantly more likely to show gestural communication than the bilateral group at the first assessment. Thus, the difference in communication style at the second assessment may not be due to the difference in intervention between the groups. Nine of the bilateral group were implanted sequentially, and it is not clear if the video recording was made one year after the first or second implantation—the latter time period may overestimate the benefits of bilateral implantation.

If bilateral implantation improves listening skills, it could potentially trigger a cascade of benefits including easier social interaction, lower levels of fatigue (because listening is less effortful), and improved acquisition of language (notwithstanding the results of Nittrouer & Chapman, 2009). Having a back-up device could also reduce children's anxiety about device failure. These benefits have been reported by the parents of some bilaterally-implanted children (Scherf et al., 2009a). If bilateral implantation does indeed lead to these benefits, it may improve children's quality of life. Measurements of quality of life contribute to the effectiveness component of the cost-effectiveness calculations that are used by policy-makers in the UK and elsewhere to decide which healthcare interventions to fund. Thus, the question of whether bilateral implantation improves quality of life has implications for healthcare policy. This issue is discussed further in Chapter 7. To date, only one study has compared the quality of life of bilaterally- and unilaterally-implanted children. Beijen et al. (2007) asked the parents of 10 children to complete the parent-proxy version of the Pediatric Quality of Life Inventory, a questionnaire that assesses physical, emotional, and social functioning. There was no significant difference between the groups (bilateral mean 90.2%, unilateral mean 89.4%, 95% confidence interval for the difference -11.0 to $+12.6$).

Summary of between-subjects comparisons

Seven studies have compared the spatial listening skills of unilaterally- and bilaterally-implanted children. Typically, these studies reported a tendency for bilaterally-implanted children to show better performance than unilaterally-implanted children on tests of left-right discrimination, SRM, binaural squelch, and the head-shadow effect. Approximately half of the comparisons showed a significant difference between the groups. The evidence regarding binaural summation is mixed: one study showed significantly more binaural summation in bilaterally-implanted children than bimodally-aided children, whereas two papers reporting data from a single sample of children showed the opposite effect. The latter finding is unique—no other study has reported significantly better listening skills in bimodally-aided children than bilaterally-implanted children. There is no evidence that bilaterally-implanted children have better language skills, or a higher quality of life, than unilaterally-implanted children.

The studies of listening skill compared small, heterogeneous, samples of children, which may explain the inconsistent pattern of results. With the exception of Grieco-Calub et al. (2008) and Schafer and Thibodeau (2006), the studies of listening skill tested a group of unilaterally-implanted children whose duration of deafness prior to implantation was longer than that for the group of bilaterally-implanted children, sometimes by as much as 4 years. A long duration of deafness is associated with poorer outcomes following unilateral implantation, so this confound could lead to an overestimation of the benefits of bilateral implantation. On the other hand, several of the studies tested a group of bimodally-aided children who had more experience of using both devices than the bilaterally-implanted children, which could lead to an underestimation of the benefits of bilateral implantation. The sources of bias that may affect these studies are discussed in more detail in section 3.5.

3.3 Within-subjects comparisons that assessed the benefit of a second device

The following section of the review is structured by outcome measure: for each measure, evaluations of the benefit of a second cochlear implant will be considered first, followed by evaluations of the benefit of a contralateral acoustic hearing aid. Some of the studies that were discussed in the previous section also carried out within-subjects comparisons, and are therefore included here.

3.3.1 Identifying the location of sources of sound

3.3.1.1 Left-right discrimination tasks

The benefit of a second cochlear implant Six studies have compared CI-CI and CI-only performance using a left-right discrimination task (Table 3.4). Three studies found that children performed significantly better using both implants than when using only one implant (studies 1, 4, and 5 in Table 3.4). Study 2 in Table 3.4 found that, for seven out of nine children, performance was significantly above chance in the binaural condition but not in the monaural condition; a statistical comparison of the two conditions was not reported. Study 6 in Table 3.4 reported statistical tests only for a group that contained both children and adults. Study 3 in Table 3.4 found no significant difference between conditions, possibly because the three participants had used bilateral implants for only 3 months. Repeated testing of two of these children up to 2 years after the second implantation showed a tendency for performance in the binaural condition to improve with time (Litovsky, Johnstone, Godar, Agrawal, et al., 2006).

Even when both implants are switched on, bilaterally-implanted children do not perform as well as normally-hearing children on tests of left-right discrimination. For example, studies using a similar protocol reported mean binaural MAAs of 16° for bilaterally-implanted children and 1.5° for normally-hearing children (Litovsky, 1997; Litovsky, Johnstone, Godar, Agrawal, et al., 2006).

The benefit of a contralateral hearing aid Three studies have compared CI-HA and CI-only performance using a left-right discrimination task (Table 3.5). Study 1 in Table 3.5 varied the type of stimuli and found that performance was significantly better in the binaural than the monaural condition, but only for the most challenging task in which the level and spectral content of the stimuli varied from trial to trial. Two smaller studies found a tendency for better performance in the binaural than the monaural condition, but either did not report statistical tests (study 2 in Table 3.5) or found that the difference was not statistically significant (study 3 in Table 3.5).

The performance of bimodally-aided children on tests of left-right discrimination is variable, but generally poorer than that of normally-hearing children. Studies 2 and 3 in Table 3.5 used a similar protocol and reported mean binaural MAAs of 44° and 28°, respectively, whereas the average MAA for normally-hearing children was 1.5° (Litovsky, 1997).

Interim summary Three studies, which reported results from a total of 20 bilaterally-implanted children, reported significantly better left-right discrimination skills when children used both implants than when they used only one. A further three studies, with results from a total of 14 bilaterally-implanted children, did not report a significant benefit of using both devices. One study of 20 bimodally-aided children reported significantly better left-right discrimination skills when using an implant and a hearing aid than when using just an implant. An additional two studies, with results from a total of 13 bimodally-aided children, did not report a significant benefit of using both devices.

Table 3.4. Within-subjects comparisons of bilateral and unilateral performance on left-right discrimination tasks. DV refers to the dependent variable.

Study	Participants	Mean age	Mean time with both devices	Task	Results	Reference
1	*N* = 5, all but one simultaneous.	3.6	1.8	Loudspeakers at ±90°. DV: % correct head turns.	CI-CI mean 96%, mean with first-CI-only or second-CI-only 36%.[a]	Beijen et al., 2007
2	*N* = 9, sequential.	3.3	0.7	Loudspeakers at ±90°. DV: % correct head turns.	CI-CI mean 81%, first-CI-only mean 48%.[c]	Galvin, Mok, Dowell, & Briggs, 2008
3	*N* = 3, sequential.	9.3	0.3	15 loudspeakers between ±70°. DV: % correct head turns.	CI-CI mean 53%, first-CI-only mean 40%.[b]	Litovsky et al., 2004
4	*N* = 13, sequential.	7.8	0.6	MAA for 70.9% correct.	9 children provided data. CI-CI mean 16°, first-CI-only mean 38°.[d]	Litovsky, Johnstone, Godar, Agrawal, et al., 2006
5	*N* = 10, sequential.	7.4	1.2	MAA for 70.9% correct.	6 children provided data. CI-CI mean 20°, first-CI-only mean 50°.[a]	Litovsky, Johnstone, & Godar, 2006

Table 3.4. (Continued). Within-subjects comparisons of bilateral and unilateral performance on left-right discrimination tasks. DV refers to the dependent variable.

Study	Participants	Mean age	Mean time with both devices	Task	Results	Reference
6	$N = 2$, sequential.	14.0	2.0	MAA for 80% correct.	CI-CI mean 6°, first-CI-only mean 15°.[c]	Senn, Kompis, Vischer, & Haeusler, 2005

[a] Significant difference between conditions, $p < .05$. [b] No significant difference between conditions. [c] No statistical test was reported.
[d] The difference was significant ($p < .05$) for a subgroup of 5 children with less than 13 months' experience with both devices.

Table 3.5. Within-subjects comparisons of bimodal and unilateral performance on left-right discrimination tasks. Ages and durations are in years. DV refers to the dependent variable. 3FA refers to the average of HLs measured at 0.5, 1 and 2 kHz; 5FA to the average of HLs measured at octave frequencies between 0.25 and 4 kHz. Both 3FA and 5FA refer to the nonimplanted ear.

Study	Participants	Mean age	Mean time with both devices	Task	Results	Reference
1	$N = 20$. Mean aided 3FA of 51 dB.	11.8	3.5	MAA for 84% correct.	CI-HA mean 76°, CI-only mean 88°.[a]	Beijen, Snik, Straatman, Mylanus, & Mens, 2009
2	$N = 6$. Mean aided 5FA of 47 dB.[d]	8.6	3.1	MAA for 70.9% correct.	5 children provided data. CI-HA mean 44°, CI-only mean 58°.[c]	Litovsky, Johnstone, Godar, Agrawal, et al., 2006
3	$N = 10$. Mean aided 5FA of 55 dB.[d]	9.0	3.6	MAA for 70.9% correct.	8 children provided data. CI-HA mean 27°, CI-only mean 38°.[b]	Litovsky, Johnstone, & Godar, 2006

[a] Significant difference between conditions, $p < .05$. [b] No significant difference between conditions. [c] No statistical test was reported. [d] Exact HLs were not reported for all children.

3.3.1.2 Localisation tasks

The benefit of a second cochlear implant Four studies have compared CI-CI and CI-only performance using a localisation task (Table 3.6). Accurate performance is represented by a high proportion of correct responses or a low RMS error. Study 4 in Table 3.6 found a significant benefit of using both implants rather than just one. The lack of a significant binaural benefit in studies 1, 2, and 3 in Table 3.6 could be due to limited statistical power caused by the small sample sizes, or it could be due to characteristics of the participating children. Steffens et al. (2007) reported that better performance on a localisation task was correlated with a younger age at second implantation and a longer time using both devices. Possibly, the participants of studies 1, 2, and 3 were implanted too late in life, or had insufficient experience of listening with both devices, to show a benefit of using the second implant. It should be noted that study 3 was a follow-up report containing a subset of the participants in study 2.

On average, bilaterally-implanted children cannot localise sources of sound as accurately as normally-hearing children, although a few children perform within the normal range. For example, the mean RMS error of bilaterally-implanted children is 38° when using both devices, compared to under 10° for normally-hearing children tested using the same nine-alternative task (Van Deun et al., 2009, 2010).

The benefit of a contralateral hearing aid Three studies have compared CI-HA and CI-only performance on a localisation task (Table 3.7). All of the studies balanced the loudness and frequency response of the two devices for each child, and found that performance using both devices was significantly better than performance using only the implant. Study 2 in Table 3.7 reported that performance after the two devices were adjusted to complement each other was significantly better than performance prior to adjustment. The participants in study 1 in Table 3.7 were a subset of the participants in study 2. A strength of these three studies is that participants listened monaurally for a week before testing in the monaural condition, which gives a more accurate measure of binaural benefit than studies in which children had around five minutes to adapt to a new listening condition (e.g. Beijen et al., 2007; Litovsky, Johnstone, Godar, Agrawal, et al., 2006; Mok et al., 2007).

Study 2 in Table 3.7 recruited 16 children but only reported results from 11 children. Two children dropped out because the test sessions were inconvenient, and three because they had stopped using their hearing aid. Consequently, study 2 demonstrates that children who choose to use a contralateral hearing aid show a benefit of using that aid in laboratory tests. The benefit of using bimodal devices may be smaller if outcome data are gathered from a more representative sample of unilaterally-implanted children.

A search of the literature did not reveal any studies that compared the performance of bimodally-aided and normally-hearing children using a localisation task. However, the performance of bimodally-aided children on a five-alternative localisation task (median RMS error 49°; study 3 in Table 3.7) was poorer than that of normally-hearing children on a more challenging nine-alternative task (median RMS error 4–10°; Van Deun et al., 2009).

Interim summary One study with results from 16 participants demonstrated that bilaterally-implanted children are significantly better at sound-source localisation when they listen using both implants than when they listen using only one implant. Three other studies, with results from a total of 17 children, did not report a significant benefit. Three studies, with results from a total of 34 unilaterally-implanted children, reported a significant benefit of using a contralateral acoustic hearing aid for sound-source localisation. However, not all children showed this benefit, and it may require the use of expert techniques to fit the hearing aid.

Table 3.6. Within-subjects comparisons of bilateral and unilateral performance on localisation tasks. Ages and durations are in years. DV refers to the dependent variable. *n*AFC refers to an *n*-alternative forced-choice task.

Study	Participants	Mean age	Mean time with both devices	Task	Results	Reference
1	$N = 3$, sequential.	9.3	0.3	15AFC, loudspeakers between ±70° at 10° intervals. DV: RMS error.	CI-CI mean 57°, first-CI-only mean 53°.[b]	Litovsky et al., 2004
2	$N = 10$, sequential.	8.9	0.7	8AFC, loudspeakers between ±90° at 25.7° intervals. DV: RMS error.	8 children provided data. CI-CI mean 70°, first-CI-only mean 68°.[b]	Galvin, Mok, & Dowell, 2007
3	$N = 6$, sequential.	10.3	1.0	8AFC, loudspeakers between ±90° at 25.7° intervals. DV: RMS error.	Mean RMS error was similar in both CI-CI and first-CI-only conditions. Exact results were not reported.[c]	Galvin, Mok, Dowell, & Briggs, 2007
4	$N = 20$, sequential.	7.0	1.4	3AFC, loudspeakers at −90°, 0°, and +90°. DV: % correct.	16 children provided data. CI-CI mean 75%, first-CI only mean 58%.[a]	Steffens et al., 2007

[a] Significant difference between conditions, $p < .05$. [b] No significant difference between conditions. [c] No statistical test was reported.

Table 3.7. Within-subjects comparisons of bimodal and unilateral performance on localisation tasks. Ages and durations are years:months. DV refers to the dependent variable. 5FA refers to the average of HLs in the nonimplanted ear, measured at octave frequencies between 0.25 and 4 kHz. *n*AFC refers to an *n*-alternative forced-choice task.

Study	Participants	Mean age	Mean time with both devices	Task	Results	Reference
1	$N = 5$. Mean unaided 5FA of 105 dB.	13.0	1.0	11AFC, loudspeakers between ±90° at 18° intervals. DV: number of errors.	CI-HA mean 32 errors, CI-only mean 39 errors.[a]	Ching, Psarros, & Hill, 2000
2	$N = 16$. Mean unaided 5FA of 102 dB.	11.4	>6 months[b]	11AFC, loudspeakers between ±90° at 18° intervals. DV: RMS error.	11 children provided data. CI-HA mean 31°, CI-only mean 37°.[a]	Ching, Psarros, Hill, Dillon, & Incerti, 2001
3	$N = 18$. Mean unaided 5FA of 104 dB.	10.1	[c]	5AFC, loudspeakers between ±60° at 30° intervals. DV: RMS error.	CI-HA median 49°, CI-only median 57°.[a]	Ching, Hill, et al., 2005

[a] Significant difference between conditions, $p < .05$. [b] Mean was not stated.

[c] 10 children had used CI-HA for 8 weeks, 8 children for a mean of 3.3 years.

3.3.2 Speech perception in noise

3.3.2.1 Spatial release from masking

Assessments of SRM do not require testing using only one device (Figure 3.3), but they do require a within-subjects comparison and are therefore reviewed in this section. SRM is statistically significant if SRTs (or the proportion of correct responses) differ significantly between the condition with noise from the side and the condition with noise from the front.

The benefit of a second cochlear implant Four studies have assessed SRM in bilaterally-implanted children (Table 3.8), none of which reported significant SRM with noise ipsilateral to the first implant. With noise contralateral to the first implant, study 2 in Table 3.8 reported significant SRM of +4.5 dB, on average. Using the same protocol, normally-hearing children showed significant SRM of +5.6 dB, on average (Mok et al., 2007). Studies 1 and 4 in Table 3.8 appeared to show SRM with noise contralateral to the first implant, but did not report tests of statistical significance.

The benefit of a contralateral hearing aid Three studies have assessed SRM in bimodally-aided children (Table 3.9). In all three studies, children showed a small negative amount of SRM with noise ipsilateral to the implant; the negative SRM was significant in study 2 in Table 3.9. With noise contralateral to the implant, study 2 in Table 3.9 reported significant positive SRM that was 2 dB smaller than the SRM shown by normally-hearing children. With noise contralateral to the implant, study 1 in Table 3.9 showed a tendency for positive SRM but did not report a test of statistical significance.

Interim summary No study has demonstrated that implanted children show significant positive SRM with noise ipsilateral to the first implant. This means that children did not perceive speech more accurately when their second implant or hearing aid was shielded from the noise, compared to the condition with noise from the front. With noise contralateral to the first implant, one study of four bilaterally-implanted children demonstrated significant SRM. Two additional studies, with results from 33 bilaterally-implanted children, did not report statistical tests. With noise contralateral to the first implant, one study of nine unilaterally-implanted children demonstrated significant SRM. An additional study of 10 unilaterally-implanted children did not report a statistical test.

Table 3.8. Estimates of the amount of SRM shown by bilaterally-implanted children. ‘Ipsilateral’ and ‘contralateral’ refer to locations ipsilateral and contralateral to the first implant. Ages and durations are in years. DV refers to the dependent variable.

Study	Participants	Mean age	Mean time with both devices	Task	Results	Reference
1	*N* = 10, sequential.	7.4	1.2	CRISP. DV: minimum signal-to-noise ratio for 79.4% correct.	Mean +1 dB of SRM with noise ipsilateral.[c] Mean +5 dB of SRM with noise contralateral.[c]	Litovsky, Johnstone, & Godar, 2006
2	*N* = 4, sequential.	10.2	1.3	Speech-detection task. DV: minimum signal-to-noise ratio for detection.	Mean +0.4 dB of SRM with noise ipsilateral.[b] Mean +4.5 dB of SRM with noise contralateral.[a]	Mok et al., 2007
3	*N* = 4, sequential.	10.2	1.3	Report open-set words presented at a signal-to-noise ratio of +10 dB. DV: % correct.	Mean accuracy was 5% lower with noise ipsilateral than with noise front.[c]	Mok et al., 2009

Table 3.8. (Continued). Estimates of the amount of SRM shown by bilaterally-implanted children. 'Ipsilateral' and 'contralateral' refer to locations ipsilateral and contralateral to the first implant. Ages and durations are in years. DV refers to the dependent variable.

Study	Participants	Mean age	Mean time with both devices	Task	Results	Reference
4	*N* = 30, sequential.	Not stated. Age range 3–13 years.	0.8	CRISP. Signal-to-noise ratio was varied between children, but fixed for each child. DV: % correct.	23 children provided data. Mean accuracy was 1% lower with noise ipsilateral than with noise front.[c] Mean accuracy was 9% higher with noise contralateral than with noise front.[c]	Peters, Litovsky, Parkinson, & Lake, 2007

[a] Significant difference between conditions, $p < .05$. [b] No significant difference between conditions. [c] No statistical test was reported.

Table 3.9. Estimates of the amount of SRM shown by bimodally-aided children. Ipsilateral’ and ‘contralateral’ refer to locations ipsilateral and contralateral to the implant. Ages and durations are in years. DV refers to the dependent variable. 5FA refers to the average of HLs in the nonimplanted ear, measured at octave frequencies between 0.25 and 4 kHz.

Study	Participants	Mean age	Mean time with both devices	Task	Results	Reference
1	*N* = 10. Mean aided 5FA of 55 dB.[d]	9.0	3.6	CRISP. DV: minimum signal-to-noise ratio for 79.4% correct.	Mean −1 dB of SRM with noise ipsilateral.[c] Mean +2 dB of SRM with noise contralateral.[c]	Litovsky, Johnstone, & Godar, 2006
2	*N* = 9. Mean aided 5FA of 57 dB.	12.1	5.3	Speech-detection task. DV: minimum signal-to-noise ratio for detection.	Mean −0.4 dB of SRM with noise ipsilateral.[a] Mean +3.8 dB of SRM with noise contralateral.[a]	Mok et al., 2007
3	*N* = 9. Mean aided 5FA of 57 dB.	12.1	5.3	Report open-set words presented at a signal-to-noise ratio of +10 dB. DV: % correct.	Mean accuracy was 6% lower with noise ipsilateral than with noise front.[c]	Mok et al., 2009

[a] Significant difference between conditions, $p < .05$. [b] No significant difference between conditions. [c] No statistical test was reported.
[d] Exact HLs were not reported for all children.

3.3.2.2 Binaural summation

The benefit of a second cochlear implant Twelve studies have assessed whether bilaterally-implanted children show binaural summation, of which six studies reported significant summation (Gordon & Papsin, 2009; Kim et al., 2009; Kühn-Inacker, Shehata-Dieler, Müller, & Helms, 2004; Peters et al., 2007; Scherf et al., 2009b; Wolfe et al., 2007). Five of these studies measured the proportion of correct responses at a fixed signal-to-noise ratio, which makes it difficult to compare the results with the published study of binaural summation in normally-hearing children (Ching, van Wanrooy, et al., 2005). Wolfe et al. measured SRTs and reported 6 dB of summation on average, which is greater than the 1 dB of summation shown by normally-hearing children (Ching, van Wanrooy, et al.). However, Wolfe and colleagues presented stimuli using live voice, which may not produce results that are as reliable as those from Ching, van Wanrooy, et al., who used recorded stimuli. Three studies found no statistically-significant binaural summation (Mok et al., 2007, 2009; Schafer & Thibodeau, 2006). Two studies showed a tendency for binaural summation but did not report statistical tests (Litovsky, Johnstone, & Godar, 2006; Mueller et al., 2000). A further study reported that one out of three children showed binaural summation, but did not report a statistical test (Litovsky et al., 2004).

The benefit of a contralateral hearing aid Twelve studies have assessed whether bimodally-aided children show binaural summation. Seven studies reported significant binaural summation (Ching et al., 2000, 2001; Ching, Hill, et al., 2005; Holt, Kirk, Eisenberg, Martinez, & Campbell, 2005; Mok et al., 2007, 2009; Yuen et al., 2009). Again, the majority of studies used a fixed signal-to-noise ratio rather than an adaptive routine. The single study that used an adaptive routine reported 1.3 dB of summation (Mok et al., 2007), which is similar to the amount shown by normally-hearing children (Ching, van Wanrooy, et al., 2005). Two studies found no significant binaural summation (Ching, van Wanrooy, et al., 2005; Schafer & Thibodeau, 2006). Three additional studies either grouped together children and adults (Luntz et al., 2003; Luntz, Shpak, & Weiss, 2005) or did not report statistical tests (Litovsky, Johnstone, & Godar, 2006).

Interim summary Six studies, with results from a total of 148 bilaterally-implanted children, reported significant binaural summation. A further six studies, with results from a total of 35 bilaterally-implanted children, did not report significant binaural summation. Seven studies, with results from a total of 52 bimodally-aided children, reported significant binaural summation. A further five studies, with results from a total of 42 bimodally-aided children, did not report significant binaural summation.

3.3.2.3 Binaural squelch

The benefit of a second cochlear implant Eight studies have assessed whether bilaterally-implanted children show binaural squelch with noise contralateral to the first implant. Peters et al. (2007) found significant binaural squelch, whereas Galvin, Mok, and Dowell (2007) did not. Five studies did not report statistical tests (Galvin, Mok, Dowell, & Briggs, 2007; Galvin et al., 2008; Litovsky et al., 2004; Litovsky, Johnstone, & Godar, 2006; Senn et al., 2005). One study found that children performed significantly *worse* when using both devices than when using only the first implant (Mok et al., 2007). Two studies have assessed whether bilaterally-implanted children show binaural squelch with noise ipsilateral to the first implant. Both showed a very small benefit of binaural squelch and did not report statistical tests (Galvin et al., 2008; Senn et al., 2005).

The benefit of a contralateral hearing aid Two studies have assessed whether bimodally-aided children show binaural squelch with noise contralateral to the first implant. One study found no significant binaural squelch (Mok et al., 2007). The other study reported a tendency for children to perform 1 dB *worse* when using both devices than when using only the implant, but did not report a statistical test (Litovsky, Johnstone, & Godar, 2006).

An important cue to binaural squelch is the difference in ITD between the speech and the noise. Ching, van Wanrooy, et al. (2005) assessed bimodally-aided children's ability to use this cue, by presenting stimuli via the auxiliary input to their devices. In the delayed condition, the speech was delivered at the same time to both devices and the noise was delayed by 700 μs at one ear (see section 2.5.2.1 for further details). Children's SRTs in the delayed condition were similar to their performance in a condition where both speech and noise had an ITD of zero. Thus, these five children were apparently unable to use ITDs to aid the perception of speech in noise.

Interim summary One study of 24 bilaterally-implanted children reported significant binaural squelch with noise contralateral to the first implant, whereas seven studies with data from a total of 36 children did not. Two studies, with results from a total of 19 bimodally-aided children, did not report significant binaural squelch with noise contralateral to the implant.

3.3.2.4 The head-shadow effect

The benefit of a second cochlear implant Ten studies have assessed whether bilaterally-implanted children show the head-shadow effect with noise ipsilateral to the first implant, of which five studies reported a statistically-significant effect (Galvin, Mok, & Dowell, 2007; Mok et al., 2007, 2009; Peters et al., 2007; Steffens et al., 2007). Two studies did not publish analyses of the group as a whole, but reported that a significant head-shadow effect was shown by three out of six children (Galvin, Mok, Dowell, & Briggs, 2007) and five out of six children (Galvin et al., 2008). The size of the head-shadow effect was 3–4 dB, on average (Galvin, Mok, & Dowell, 2007; Galvin et al., 2008; Mok et al., 2007). A search of the literature did not reveal any comparable studies of normally-hearing children, but normally-hearing adults show a head-shadow effect of 10–13 dB (Bronkhorst & Plomp, 1988, 1992). An additional three studies reported a tendency for bilaterally-implanted children to show the head-shadow effect, but did not report statistical tests (Litovsky et al., 2004; Litovsky, Johnstone, & Godar, 2006; Senn et al., 2005).

Only three studies have assessed whether bilaterally-implanted children show the head-shadow effect with noise contralateral to the first implant. Steffens et al. (2007) used an atypical task with speech presented from 45° on the side of the first implant and noise from 45° on the side of the second implant. On average, children correctly reported a higher proportion of target words when using both implants than when using just the second implant. Two further studies showed a head-shadow effect using the conventional loudspeaker arrangement (Figure 3.5), but did not report statistical tests (Galvin et al., 2008; Senn et al., 2005). The average head-shadow effect with noise contralateral to the first implant was 9 dB in the study by Galvin and colleagues, larger than the head-shadow effect of 4 dB with noise ipsilateral to the first implant.

The benefit of a contralateral hearing aid Six studies have assessed whether bimodally-aided children show the head-shadow effect with noise ipsilateral to the implant, of which five studies reported a statistically-significant effect (Beijen, Mylanus, Leeuw, & Snik, 2008; Ching, Hill, et al., 2005; Mok et al., 2007, 2009; Yuen et al., 2009). The size of the head-shadow effect was 2.2 dB in the earlier study by Mok and colleagues. The data from Litovsky, Johnstone, and Godar (2006) do not indicate a head-shadow effect; statistical tests were not reported.

Interim summary Five studies, with results from a total of 59 bilaterally-implanted children, reported a significant head-shadow effect with noise ipsilateral to the first implant. A further five studies, with results from a total of 27 bilaterally-implanted children, did not report a significant head-shadow effect. Five studies, with results from a total of 69 bimodally-aided children, reported a significant head-shadow effect with noise ipsilateral to the first implant. A further study of 10 bimodally-aided children did not report a significant head-shadow effect. Typically, children perform better when using their first implant than when using their second implant or hearing aid. Thus, if children can benefit from the head-shadow effect with noise ipsilateral to the first implant, they are also likely to show a benefit with noise contralateral to the first implant. This argument is supported by Galvin et al. (2008), who found that the head-shadow effect in bilaterally-implanted children was larger with noise contralateral than with noise ipsilateral to the first implant.

Summary of within-subjects comparisons

Several studies of bilaterally-implanted or bimodally-aided children have reported within-subjects comparisons—typically, a comparison of performance using both devices with performance using only the first implant. A substantial proportion of studies reported null results or failed to report statistical tests. Nonetheless, the evidence indicates that, on average, children who use two devices (either two implants or an implant and an acoustic hearing aid) localise sources of sound more accurately when using both devices than when using only the first implant. Despite the benefit of using a second device, the majority of implanted children show impaired sound-source localisation skills relative to normally-hearing children. A few studies reported a tendency for bilaterally-implanted and bimodally-aided children to show SRM with noise contralateral to the first implant, sometimes showing a similar amount of SRM as normally-hearing children. No study has demonstrated that implanted children benefit from SRM with noise ipsilateral to the first implant. The lack of evidence regarding SRM casts doubt on the degree to which a second implant or a contralateral hearing aid will help children to perceive speech in noisy situations at home and at school.

Both bilaterally-implanted and bimodally-aided children have been shown to benefit from binaural summation and the head-shadow effect with noise ipsilateral to the first implant. It is not clear whether bilaterally-implanted children benefit from binaural squelch: although seven out of eight studies reported null results, the largest study found significant binaural squelch (Peters et al., 2007), suggesting that the null results may be due to a lack of statistical power caused by a small sample size. There is no evidence that bimodally-aided children benefit from binaural squelch. The range of outcome measures makes it difficult to compare these studies to establish whether the provision of bilateral implants, or the provision of a unilateral implant and a contralateral acoustic hearing aid, is likely to result in better spatial listening skills for the majority of children.

Within-subjects comparisons may overestimate the benefit of a second device, because the monaural listening condition was unfamiliar to the child (this criticism does not apply to the estimates of SRM, which compared binaural listening in two conditions). The confound of unfamiliarity may be a particular problem for tests of sound-source localisation, because chronic monaural listeners can learn monaural cues to source location (such as changes in level and spectral content that occur as the participant turns their head, Luntz et al., 2002).

3.4 Longitudinal study of implanted children

A search of the literature revealed only one longitudinal study of children who received sequential bilateral implants. Zeitler et al. (2008) assessed the speech-perception skills of 43 unilaterally-implanted children prior to, and three months after, the second implantation. In quiet and in noise, children's performance was significantly better after the second implantation (when they were tested using both implants) than prior to the second implantation (when they were tested using an implant and a hearing aid). The improvements were modest: on average, fewer than 10 percentage points on a test of sentence perception at a signal-to-noise ratio of +10 dB and fewer than 5 percentage points on the same test in quiet. The two assessments were only 5 months apart, so the authors state that the improvement was not likely to be due to maturation. In support of this, performance using only the first implant did not improve between the two testing sessions.

3.5 Sources of bias in nonrandomised studies

Before summarising the results of the literature review, it is important to consider the issue of bias. A study is said to be biased if there is a systematic error in the results. Such an error can lead to an over- or under-estimation of the effectiveness of an intervention (Higgins & Green, 2009). It is difficult to assess whether a study is biased—instead, the design of the study can be examined to determine whether the results are at risk of bias. This section provides an overview of the potential sources of bias that are relevant to this literature review; the following section assesses the risk of bias in the studies included in the review.

Nonrandomised studies can be affected by selection bias, meaning there are systematic differences between the experimental groups in addition to the difference in the intervention they received (Higgins & Green, 2009). Confounding occurs when selection bias creates groups that differ on a variable that is known to affect outcome, and it can lead to a shift in the observed effect as well as an increase in the variability of the observed effect across studies (Deeks et al., 2003). A different type of selection bias refers to the way in which participants are selected for inclusion in a study. If the participants are not representative of the wider population, the results may not generalise to the population (i.e. the external validity is threatened; Deeks et al.). A further potential source of bias is incomplete outcome data, which can be caused by exclusion (data were available but omitted from analyses) or attrition (data were not available). There is evidence that analyses of data after exclusion yield estimates of greater effectiveness than analyses of data from all participants (Tierney & Stewart, 2005). Statistical techniques are available to deal with data that are missing because of attrition; the results may be biased if these techniques are not used (Donders, Heijden, Stijnen, & Moons, 2006). Studies may also be affected by detection bias, meaning that the assessment of outcome was not unbiased and correct, and reporting bias, meaning that the reporting of results was selective both within and across studies.

3.5.1 Risk of bias in studies of implanted children

Several of the between-subjects studies reviewed in this chapter appear to be at risk of selection bias, because the groups of participants differed on variables other than the number of implants. Indeed, there is evidence of confounding in the majority of the between-subjects studies of listening skill: the groups differed on variables that predict outcome (such as age, age at first implantation, or experience of using both devices) in the studies of Beijen et al. (2007), Litovsky, Johnstone, Godar, Agrawal, et al. (2006), Litovsky, Johnstone, and Godar (2006), and Mok et al. (2007, 2009). None of the studies attempted to exercise statistical control over confounds.

The remaining sources of bias can affect between-subjects, within-subjects, and longitudinal designs. Several studies did not report their inclusion and exclusion criteria, or how participants were contacted (e.g. Grieco-Calub et al., 2008; Litovsky, Johnstone, Godar, Agrawal, et al., 2006; Litovsky, Johnstone, & Godar, 2006; Mok et al., 2007, 2009). The lack of reported inclusion and exclusion criteria leaves open the possibility that experimenters (perhaps unknowingly) selected those participants who were likely to reinforce their hypotheses.

Some studies that did report inclusion and exclusion criteria may have limited external validity because they are at risk of selection bias. For example, Galvin, Mok, and Dowell (2007) recruited children who, prior to receiving a second implant, were successful users of the first implant, had no additional disabilities, and had normal cochlear anatomy. Peters et al. (2007) recruited children who, prior to receiving a second implant, could complete the outcome measures, attended an educational setting focussed on oral language, and had normal cochlear anatomy. These criteria probably excluded children who showed poor outcomes with the first implant. It is possible that children with poor outcomes after unilateral implantation will show an above-average benefit from bilateral implantation. For example, if the first electrode array could not be fully inserted into the cochlea, a child may show a great benefit from the second implant. On the other hand, children with poor outcomes after unilateral implantation may show a below-average benefit from bilateral implantation, perhaps because they have abnormal cochlear anatomy or additional disabilities. Thus, the benefits of bilateral implantation demonstrated by Galvin, Mok, and Dowell (2007) and Peters et al. (2007) may be smaller or larger than the benefits to the wider population.

One study was at risk of bias due to excluded outcome data (Litovsky, Johnstone, Godar, Agrawal, et al., 2006). Several studies were at risk of bias due to attrition, either because some children stopped using the second device (Ching et al., 2001; Galvin et al., 2008; Zeitler et al., 2008) or because some children did not complete the outcome measures (Beijen et al., 2009; Galvin, Mok, & Dowell, 2007; Peters et al., 2007; Steffens et al., 2007). A study of unilaterally-implanted adults found that participants with missing data tended to be poorer performers (UK Cochlear Implant Study Group, 2004c). Thus, ignoring data that are missing because of attrition may lead to an overestimation of the benefit of a second device. The studies reviewed in this chapter did not use statistical techniques to deal with missing data.

None of the studies used an assessment of outcome in which the experimenter was blind to the intervention the child had received (or, for within-subject designs, whether the child had one or both devices switched on). Consequently, the studies are at risk of detection bias. Although several papers reported null results, which is evidence against reporting bias within studies, it is difficult to assess whether this area of literature is at particular risk of reporting bias across studies. In general, however, studies that find a statistically-significant effect are more likely to be published than those that do not, particularly for nonrandomised designs (Easterbrook, Berlin, Gopalan, & Matthews, 1991).

Many studies reported results from the same participants (for example, Ching et al., 2000 and Ching et al., 2001; Galvin, Mok, & Dowell, 2007 and Galvin, Mok, Dowell, & Briggs, 2007; Litovsky, Johnstone, & Godar, 2006 and Litovsky, Johnstone, Godar, Agrawal, et al., 2006; Mok et al., 2007 and Mok et al., 2009). Although this is not a source of bias listed by the Cochrane Handbook for Systematic Reviews of Interventions (Higgins & Green, 2009), using the same participants in multiple studies means that the results from one child may be counted twice when trying to assess the strength of evidence.

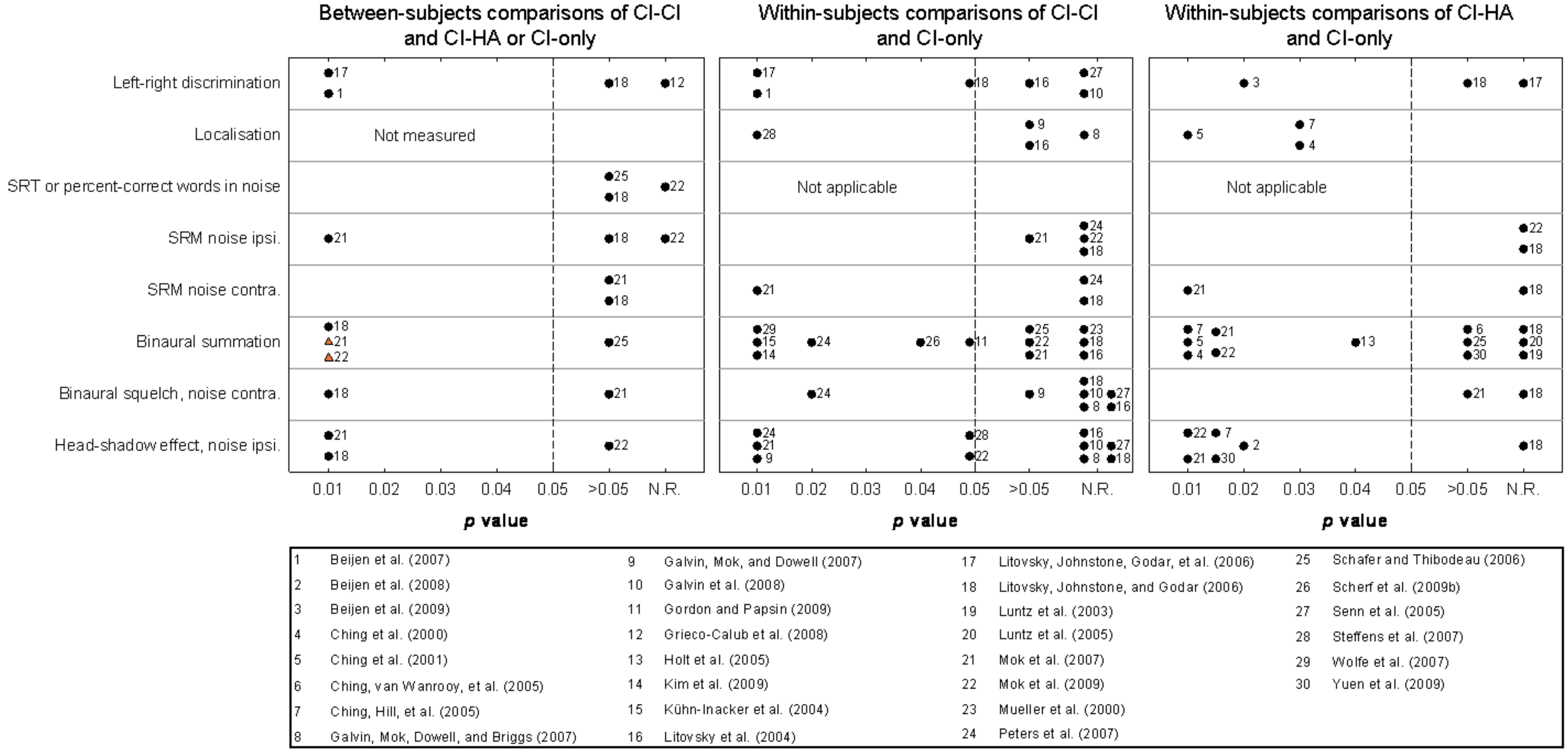
3.6 Summary of literature review

It would be difficult to conduct a meta-analysis of the studies reviewed in this chapter, because of the range of outcome measures and inconsistency in the way that results have been reported (a similar conclusion was reached by Bond et al., 2007 and Johnston, Durieux-Smith, Angus, O'Connor, & Fitzpatrick, 2009). As an alternative to meta-analysis, the results of the studies of listening skill are summarised in Figure 3.6 by plotting the reported p values. The left panel of Figure 3.6 shows the results of between-subjects comparisons of unilaterally- and bilaterally-implanted children. Of those comparisons for which statistical tests were reported, half found a significant difference between the groups. Seven of the nine significant results indicated that bilaterally-implanted children performed better than unilaterally-implanted children, whereas two significant results indicated the opposite pattern. The centre and right panels of Figure 3.6 show the results of within-subjects comparisons of bilaterally-implanted and bimodally-aided children, respectively. Regarding bilaterally-implanted children, of those comparisons for which statistical tests were reported, two-thirds found a significant benefit of using both implants rather than just one. Regarding bimodally-aided children, of those comparisons for which statistical tests were reported, a little over two-thirds found a significant benefit of using bimodal devices rather than just the implant.

Figure 3.6 shows several null results and some contradictory results. A number of factors may have contributed to this inconsistency. First, several studies used small sample sizes. Second, there was heterogeneity both within samples and between samples: the children in these studies differed in age, age at onset of deafness, age at implantation, hearing levels in the nonimplanted ear, and experience using both devices. Third, several studies were at risk of bias, which can increase the variability in results. Fourth, studies used disparate outcome measures and, even when outcome measures were similar, the comparisons that were subjected to statistical tests often differed between studies.

3.6.1 Evaluation of the evidence

On balance, there is evidence that children who use two devices (either bilateral implants or an implant and an acoustic hearing aid) show better listening skills when using both devices than when using only one device. The benefits that have been demonstrated most often are an improved ability to localise sources of sound and to perceive speech in noise (as measured by binaural summation and the head-shadow effect). These demonstrations constitute evidence of the *efficacy* of a second implant or an acoustic hearing aid, meaning that both interventions can provide benefit for some children (Gartlehner, Hansen, Nissman, Lohr, & Carey, 2006). However, the studies were at risk of bias and used a design in which the unilateral condition was unfamiliar to the child. Consequently, there is uncertainty regarding the *effectiveness* of a second implant or a contralateral acoustic hearing aid: it is not clear whether either intervention would benefit the majority of children if it were provided routinely (Gartlehner et al., 2006). Moreover, there is uncertainty regarding whether bilateral implantation or unilateral implantation (with the provision of a contralateral acoustic hearing aid) is more effective in enabling spatial listening skills. The evidence from between-subjects studies is compatible with the idea that bilateral implantation for children is associated with better spatial listening skills than unilateral implantation, but the data are inconclusive and at risk of bias. The evidence suggests that bilaterally- and unilaterally-implanted children have similar language skills and quality of life.



1	Beijen et al. (2007)	9	Galvin, Mok, and Dowell (2007)	17	Litovsky, Johnstone, Godar, et al. (2006)	25	Schafer and Thibodeau (2006)
2	Beijen et al. (2008)	10	Galvin et al. (2008)	18	Litovsky, Johnstone, and Godar (2006)	26	Scherf et al. (2009b)
3	Beijen et al. (2009)	11	Gordon and Papsin (2009)	19	Luntz et al. (2003)	27	Senn et al. (2005)
4	Ching et al. (2000)	12	Grieco-Calub et al. (2008)	20	Luntz et al. (2005)	28	Steffens et al. (2007)
5	Ching et al. (2001)	13	Holt et al. (2005)	21	Mok et al. (2007)	29	Wolfe et al. (2007)
6	Ching, van Wanrooy, et al. (2005)	14	Kim et al. (2009)	22	Mok et al. (2009)	30	Yuen et al. (2009)
7	Ching, Hill, et al. (2005)	15	Kühn-Inacker et al. (2004)	23	Mueller et al. (2000)		
8	Galvin, Mok, Dowell, and Briggs (2007)	16	Litovsky et al. (2004)	24	Peters et al. (2007)		

Figure 3.6. Summary of literature review. Left panel: between-subjects comparisons of bilaterally- and unilaterally-implanted children. Centre panel: within-subjects comparisons of CI-CI and CI-only. Right panel: within-subjects comparisons of CI-HA and CI-only. The vertical axis denotes the outcome measure. Data points plot a study's published *p* value and are labelled with a number to identify the study (see key). N.R. indicates that a statistical test was not reported. All points to the left of the dashed line indicate a statistically-significant result. In the left panel, orange triangles represent studies that reported significantly better performance for CI-HA than CI-CI children; all other significant results in the left panel indicate better performance for CI-CI than CI-HA or CI-only children.

3.7 Variables affecting performance with bilateral implants

This section provides an overview of the variables that predict outcomes for children following bilateral implantation. Correlational analyses have identified three variables that are associated with a better ability to localise sources of sound, and to perceive speech in noise, when using both implants:

- A shorter duration of deafness in both the first- and second-implanted ear (Zeitler et al., 2008).
- A younger age at the first implantation (Scherf et al., 2009b; Van Deun et al., 2010) and the second implantation (Steffens et al., 2007).
- Greater experience with bilateral implants (Litovsky, Johnstone, Godar, Agrawal, et al., 2006; Steffens et al., 2007).

Nonetheless, an older age at second implantation does not preclude benefit from the second implant: Scherf et al. (2009b) found that, on average, children who were over 6 years old when they received their second implant showed significant binaural summation. Potentially, several other variables that influence outcomes following unilateral implantation (see section 3.1.1) will also influence outcomes following bilateral implantation. As yet, the majority of these relationships have not been assessed.

Gordon and Papsin (2009) reported a multiple regression analysis that attempted to measure the effect of several predictors on the speech-perception performance of bilaterally-implanted children. It is difficult to determine the details of the analysis. The paper appears to indicate that the outcome measure was the difference between a child's performance when listening with their first implant in quiet, and their performance in four other conditions. If this interpretation is correct, each child contributed four outcome data points to the regression model, which violates the assumption that the values of the outcome measure are independent (Field, 2005). Also, some of the predictors in the model correlated highly with each other, which violates a further assumption of multiple regression. Thus, although the analysis showed a relationship between a longer time interval between implantations and a poorer outcome, the statistical methods cast doubt over this conclusion.

The relationship between a younger age at unilateral implantation and better listening skills is well established (Geers et al., 2003; O'Donoghue et al., 2000; Stacey et al., 2006). One explanation for this relationship is that there is a sensitive period during which the auditory system is maximally plastic (Sharma, Dorman, & Spahr, 2002). Evidence comes from electrophysiological recordings of neural responses to speech, which reveal a waveform known as P1 that is assumed to be caused by activity in the auditory regions of the thalamus and cortex. The latency of P1 decreases with age in normally-hearing children (Gilley, Sharma, Dorman, & Martin, 2005). Sharma et al. (2002) demonstrated that 57 children who received an implant before the age of 3.5 years, who were tested 3 years after the implant was activated, showed a P1 latency similar to that of age-matched normally-hearing children. Thus, early-implanted children showed a marker of normal auditory development. Twenty-one children who received an implant after the age of 7 years, who were tested 3 years after the implant was activated, showed a P1 component with a longer latency and a different waveform morphology than that of age-matched normally-hearing children, which may indicate abnormal development of the auditory thalamus and cortex (Sharma et al., 2002).

The concept of a sensitive period can also be applied to neural development following bilateral implantation. Sharma, Dorman, and Kral (2005) measured the P1 response in a child who received the first implant at the age of 2 years and the second implant at the age of 10 years. The measurements took place up to 9 months after the activation of the second implant. The child showed a delayed P1 when the second implant was stimulated and an age-appropriate P1 when the first implant was stimulated (Sharma et al., 2005). In contrast, four children who received both implants under the age of 2 years showed age-appropriate P1 responses following stimulation of either implant, within 7 months of the activation of the second implant (Bauer, Sharma, Martin, & Dorman, 2006). The authors concluded that early stimulation of one ear may not preserve the plasticity of the ipsilateral auditory cortex, and suggested that bilateral implantation may be more effective if it is provided at a young age. This proposal is supported by behavioural evidence that a younger age at second implantation is associated with better skills in sound-source localisation (Steffens et al., 2007).

There may also be a sensitive period for the development of the auditory brainstem. Gordon, Valero, and Papsin (2007) measured wave eV, which is thought to be caused by activity in the auditory brainstem, in 13 bilaterally-implanted children. Immediately after the second implantation, children who had received their two implants sequentially showed a wave eV that was of longer latency following stimulation of the second implant than following stimulation of the first implant. Children with a gap shorter than a year between implantations appeared to show a decrease over time in eV latency following stimulation of the second implant, meaning that the latencies from both ears became similar. Theoretically, this may aid the perception of ITDs (Gordon et al., 2007). For older children with a longer gap between implantations, there was a sustained pattern of longer latencies following stimulation of the second implant than following stimulation of the first implant. Gordon et al. (2007) suggested that unilateral stimulation during the sensitive period may lead to auditory brainstem pathways that are dominated by input from one ear, an idea which is supported by animal models of unilateral deafness. This leads to a prediction that a shorter gap between sequential bilateral implantations will result in better outcomes. However, the groups of children in the study by Gordon et al. (2007) were not compared statistically, and the relationship between time and decreasing eV latency in the second ear was weak even for children who had a short gap between implantations ($r^2 = 0.27$).

In summary, a shorter duration of deafness in both ears, and a younger age at implantation in both ears, is correlated with better listening skills following bilateral implantation. Listening skills may take time to emerge after bilateral implantation, meaning that better outcomes are also correlated with greater experience with both implants. Electrophysiological research indicates that the relationship between age at implantation and outcome may be caused by a sensitive period during which the auditory cortex undergoes major developmental change.

3.8 Variables affecting performance with bimodal devices

A search of the literature did not reveal studies that assessed predictors of spatial listening skill following the provision of bimodal devices. Instead, this section provides an overview of studies that assessed predictors of bimodal *benefit*—the difference between bimodal performance and implant-only performance. It should be noted that the previous section reviewed predictors of performance with bilateral implants (not the difference between bilateral and unilateral performance).

Intuitively, it seems likely that children with more residual hearing in the nonimplanted ear will show more benefit from using a contralateral acoustic hearing aid. However, several studies have failed to find such a relationship. Ching et al. (2001) reported that hearing levels at 0.5, 1, and 2 kHz in the nonimplanted ear did not correlate with binaural summation or bimodal benefit for sound-source localisation. Similarly, Ching, Hill, et al. (2005) created a multiple regression model to predict bimodal benefit for speech perception (measured by binaural summation and the head-shadow effect) and found that the average hearing level in the nonimplanted ear (measured at 0.25, 0.5, and 1 kHz) was not a significant predictor. Beijen et al. (2008) used multiple regression to assess whether bimodal benefit for speech perception (measured by binaural summation and the head-shadow effect) could be predicted by hearing levels in the nonimplanted ear. Hearing level was divided into three separate variables (frequencies under 0.5 kHz, 0.5–2 kHz, and over 2 kHz), none of which was a significant predictor of outcome.

In contrast, Mok et al. (2009) found that a greater head-shadow effect was associated with lower hearing levels at 0.25 and 0.5 kHz (i.e. more residual hearing) and higher hearing levels at 4 kHz (i.e. less residual hearing). A separate study of the same children reported that higher thresholds at 2 and 4 kHz were associated with greater SRM (Mok et al., 2007). The authors suggested that mid- to high-frequency signals delivered by the hearing aid could conflict with those from the implant. Consequently, to gain optimal benefit from bimodal stimulation, children need good residual hearing in the low frequencies and poor residual hearing at higher frequencies. Although similar results have been reported for adults (Mok, Grayden, Dowell, & Lawrence, 2006), this evidence cannot be regarded as conclusive because it is based on only nine children. Moreover, it is not clear why this relationship between hearing level and bimodal benefit was not reported by Ching et al. (2001), Ching, Hill, et al. (2005), and Beijen et al. (2008).

Fitting techniques that balance the loudness of the two devices may help children to localise sources of sound (see section 3.3.1.2). A single study has reported that a younger age at implantation is associated with a greater bimodal benefit for sound-source localisation (Ching, Hill, et al., 2005). The same study found that the duration of implant use and the duration of hearing aid use were not significant predictors of the bimodal benefit for speech perception or sound-source localisation. Similarly, Beijen et al. (2008) found that age, experience with both devices, and age at implantation were not significant predictors of binaural summation or the head-shadow effect. Ching's group compared children who had used bimodal devices for 1 to 6 years with unilaterally-implanted children who had been fitted with an acoustic hearing aid 2 months prior to testing (Ching, Hill, et al., 2005). There was no difference in sound-source localisation performance between the two groups, suggesting that long-term experience of bimodal stimulation is not necessary for a child to benefit from a contralateral acoustic hearing aid.

To summarise, despite investigation by several studies, no variables have been consistently identified as predictors of the benefit which unilaterally-implanted children gain from a contralateral acoustic hearing aid. Consequently, it may be difficult for clinicians and parents to decide whether a child is likely to gain the most benefit from bimodal stimulation or bilateral implantation.

3.9 Conclusion

Unilateral implantation for children is effective in improving speech perception, language skills, and quality of life. Some between-subjects comparisons indicate that, compared to unilateral implantation, bilateral implantation for children is effective in improving spatial listening skills. Other studies found no significant difference between the listening skills of unilaterally- and bilaterally-implanted children, despite using similar methods. These studies were nonrandomised and are at risk of several types of bias. There is no evidence that bilaterally-implanted children have better language skills or a higher quality of life than unilaterally-implanted children. Thus, although within-subjects comparisons demonstrate that there can be a benefit of providing unilaterally-implanted children with either a second cochlear implant or a contralateral hearing aid, it is not possible to conclude which of these interventions will be more effective in enabling spatial listening skills.

3.10 Summary

- Compared to amplification using bilateral acoustic hearing aids, unilateral implantation for severely-profoundly deaf children is associated with an improved ability to perceive speech, a faster acquisition of language, higher educational achievements, and a higher quality of life.
- It has been argued that implanting both ears gives children the potential to develop binaural hearing, provides children with a backup device, and ensures that the more-responsive auditory nerve is stimulated.
- Some nonrandomised between-subjects comparisons indicate that, compared to unilaterally-implanted children, bilaterally-implanted children display superior skills in left-right discrimination, greater SRM, and a greater head-shadow effect. Other studies found no significant difference between the listening skills of unilaterally- and bilaterally-implanted children.
- Within-subjects comparisons show that children who use two devices (either a second implant or an acoustic hearing aid) perform better when using both devices than when using only one device, on tests of sound-source localisation and the perception of speech in noise (as measured by binaural summation and the head-shadow effect).
- Studies have found that bilaterally-implanted and bimodally-aided children show SRM with noise contralateral to the first implant, but have not found that these children show SRM with noise ipsilateral to the first implant.
- The majority of the published studies are at risk of selection bias, bias caused by incomplete outcome data, detection bias, and/or reporting bias. None of the studies used statistical techniques to control for either confounding variables or missing data.
- For children with bilateral implants, better listening skills are associated with a younger age at implantation in both ears, a shorter duration of deafness in both ears, and increasing experience with both devices.

- It is difficult to predict how much a unilaterally-implanted child will benefit from a contralateral acoustic hearing aid, because the relationship with residual hearing level is poorly understood.

Chapter 4

Spatial Listening Skills of Children and Adults with Normal Hearing

This chapter reports an experiment that measured the performance of normally-hearing children and adults on a set of tests of spatial listening. The tests were found to be suitable for children between the ages of 18 months and 7 years. Children as young as 3 or 4 years performed at a similar level to adults on tests of the ability to localise sound and of the ability to benefit from SRM when listening to speech. Children's SRTs in quiet and in noise decreased with age. The results will be used in later chapters to compare the performance of children with normal hearing with that of children with cochlear implants.

4.1 Introduction

There is worldwide interest in whether severely-profoundly deaf children should receive unilateral or bilateral cochlear implants. It has been argued that bilateral implants give children the potential to develop skills in spatial listening, meaning the ability to use both ears together to localise sounds and to understand speech in noise (see section 2.3). A set of tests of these skills has been developed, to allow a comparison of outcomes for children with unilateral or bilateral implants. This chapter describes the tests and reports a study of the spatial listening skills of normally-hearing children.

A number of factors influenced the design of the test battery. Children with implants show a range of listening abilities (Stacey et al., 2006), meaning that different individuals may show floor or ceiling effects on the same test. Accordingly, the test battery included a series of tests of the same listening skill, with increasing levels of difficulty. Children with implants also differ in the extent of their vocabulary and their ability to respond verbally. To minimise the impact of these variables on performance, the tests required minimal vocabulary and children responded by pointing rather than speaking. The tests were designed to be engaging and to be completed in a single session lasting under 3 hours. The youngest age at which children routinely receive a cochlear implant in the UK is 12 months. Allowing 6 months for the child to adjust to the implant before assessment, the simplest tests were designed to be suitable for children from the age of 18 months. The reasons for including each test are explained in sections 4.1.1 to 4.1.4. Previous assessments of these skills in normally-hearing children were reviewed in section 2.5.

4.1.1 Sound-source localisation

A potential benefit of bilateral implants is an improved ability to localise the spatial position of a source of sound on the horizontal plane. Accordingly, two tests of sound-source localisation were developed. The first was designed for the youngest children and assessed the ability to discriminate sound sources on the left from those on the right ('left-right discrimination'). The second was designed for older children and assessed the ability to locate a single sound source in an array of three or more possible source locations ('localisation').

The majority of studies that assessed left-right discrimination in normally-hearing children have measured the MAA (see section 2.4.1). The MAA was not measured in the present study because: a) the minimum separation between loudspeakers in the laboratory was 15°; and b) reliably assessing head turns towards sources that are separated by less than 30° requires two observers and only one was available. Accordingly, the principles of visual reinforcement audiometry (Bamford & McSporran, 1993) were adapted to develop a test of left-right discrimination that measured the proportion of correct head turns towards loudspeakers separated by either 60° or 120°. Based on measurements of the MAA (see section 2.5.1.1), one would expect normally-hearing children to show high levels of performance on tasks that use such a wide loudspeaker separation.

A more advanced test was developed to assess children's ability to localise sources of sound when presented with an array of three or five possible locations. The maximum number of locations was restricted to five because only five video screens were available. Studies using an array of between 9 and 13 possible locations showed that children's performance improves between the ages of 4 and 5 years, and that children perform similarly to adults by the age of 5 or 6 years (Bess et al., 1986; Van Deun et al., 2009).

4.1.2 Tracking moving sounds

Potentially, children with bilateral implants could be able to track moving sources of sound more accurately than children with a unilateral implant. Accordingly, a test of movement tracking was developed, with sources of sound on the horizontal plane. Several previous studies have assessed the ability of normally-hearing adults to detect movement of a source of sound (Middlebrooks & Green, 1991), typically using loudspeakers on rotating booms. None of the studies included children. The tasks used with adults are too complex for young children and moving loudspeakers were not available, so a test was developed in which stimuli were presented from a sequence of static loudspeakers. The velocity and duration of apparent movement were fixed. The test was scored by an observer who watched video-recordings of the child's responses during each trial. If the trajectory of movement could be deduced from the child's head-turns or pointing responses, it was inferred that the child could track the apparently-moving source of sound.

4.1.3 Perception of speech in noise

A further potential benefit of bilateral implantation is an improved ability to perceive speech in noise. SRM (see section 3.3) was chosen as the measure of binaural benefit for speech perception because, for children with implants, SRM can be assessed whilst the child listens with the device(s) they use every day. Alternative measures (such as binaural summation, binaural squelch, and the head shadow effect) involve switching off one device during testing, which confounds the unilateral condition with unfamiliarity.

To measure SRM, a test of speech perception was used in which the speech was presented from in front of the child and pink noise (meaning noise with equal energy in each octave) was presented from the left, front, or right. The signal-to-noise ratio was varied adaptively to measure SRTs. The results can be analysed in two ways: 1) the raw SRTs in each condition, or 2) the difference in performance between the noise-front and noise-side conditions, which shows the amount of SRM. There was also a quiet condition in which no noise was presented and the level of the speech was varied adaptively.

Regarding the raw scores, when speech perception in noise is measured using a variety of tests, normally-hearing children consistently require a more advantageous signal-to-noise ratio than adults (Garadat & Litovsky, 2007; Hall, Grose, Buss, & Dev, 2002; Johnstone & Litovsky, 2006; Litovsky, 2005). Similarly, in quiet conditions, children require a more intense speech signal than adults (Litovsky; Papso & Blood, 1989; Summerfield, Foster, Moorjani, & Palmer, 2004). Summerfield et al. (2004) used a version of the test of speech perception that was used in the present study (see section 4.2.2.4 for details). The target stimuli were a closed set of 14 words, presented over headphones. The level of the speech was varied adaptively to measure the SRT at which the child could identify the target word on 70.7% of trials. The test was completed by 113 normally-hearing children, both in quiet and with pink noise at +60 dB(A) SPL. Children's SRTs in noise decreased between the ages of 3 and 10 years, and SRTs in quiet decreased up to the age of 15 years (Figure 4.1).

Regarding SRM, normally-hearing 3- to 7-year-old children show SRM of between 5 and 11 dB (Garadat & Litovsky, 2007; Johnstone & Litovsky, 2006; Litovsky, 2005). It is not clear if the benefit from SRM increases as children get older (see section 2.1).

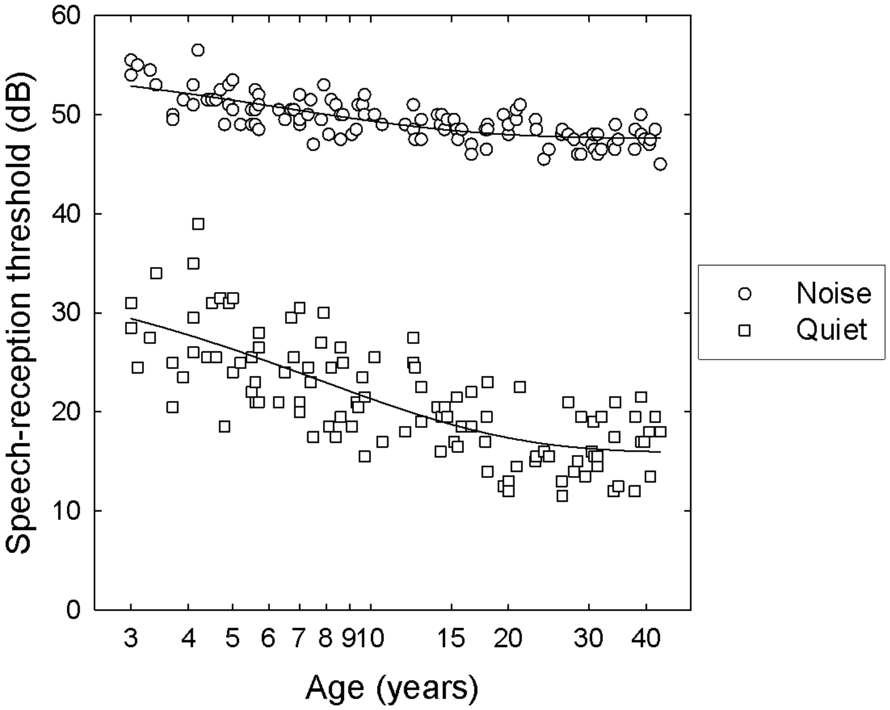


Figure 4.1. The relationship between SRTs and age for normally-hearing children. SRTs in quiet decreased with age for children up to 15 years old. SRTs in pink noise showed a smaller decrease with age that appears to be marginal after the age of 10 years. Data reprinted with permission from Summerfield et al. (2004).

4.1.4 The benefit of a difference in fundamental frequency for the perception of speech in noise

When broadband complex sounds are processed by the normally-functioning cochlea, the resulting signal can be thought of as several relatively narrowband signals, each containing a slowly-varying envelope superimposed onto rapidly-varying temporal fine structure (see section 2.1). Temporal fine structure conveys information about fundamental frequency (F0), which is the main determinant of the pitch of a person's voice. Normally-hearing listeners can use a difference in F0 to segregate concurrent talkers and hence improve the intelligibility of the target speech (Assmann & Summerfield, 1990). The signal processing carried out by a cochlear-implant system removes temporal fine structure (see section 3.1), which may limit implanted listeners' ability to segregate talkers on the basis of F0. Temporal fine structure is, however, represented in the signal delivered by an acoustic hearing aid, so one might expect bimodally-aided listeners to be more able than bilaterally-implanted listeners to segregate concurrent talkers on the basis of a difference in F0. On the other hand, hearing-impaired listeners who use bilateral acoustic hearing aids show an impaired ability to benefit from temporal fine structure (Hopkins et al., 2008; B. C. J. Moore, 2008), so one might expect both bimodally-aided and bilaterally-implanted listeners to be limited in their ability to segregate on the basis of F0. The evidence regarding segregation by bimodally-aided adults is reviewed in section 6.1.2.2.2.

A test was developed in which the difference in F0 between the target speech and a masker was manipulated. The format was the same as for the test of speech perception in noise, but the stimuli were modified. In one condition the speech and masker had the same fixed F0 and in the other condition the F0 of the masker was raised relative to that of the speech.

4.1.5 Aims and hypotheses

This study assessed the performance of normally-hearing children on tests of spatial listening. The aim was to gather a set of data that can be compared with data from implanted children in later studies. The design was cross-sectional with participants stratified by age. A group of normally-hearing adults was tested to assess the upper limit of performance. The data from adults were gathered by Shan Huang, as part of an undergraduate project that was co-supervised by the author. To assist the planning of future studies, the age at which children could complete the tests is reported. The analyses tested whether children's skills in spatial listening improved with age and which groups of children showed poorer performance than adults. Test-retest reliability was measured for a subset of the children. It was predicted that:

1. Older children would be able to complete more of the test battery.
2. Children would be able to discriminate sound sources on the left from those on the right with almost perfect accuracy, for loudspeaker separations of 60° and 120°.
3. Children's performance on localisation tests would improve with age and be similar to that of adults from the age of 5 years.
4. Older children would have lower SRTs than younger children, both in quiet and in noise.
5. Children would show SRM with noise on either side of the head.
6. Children would show lower SRTs when there was a difference in F0 between speech and a masker than when there was no difference in F0 between speech and a masker.

4.2 Method

4.2.1 Participants

Ten adults aged between 20 and 58 years were recruited from the University of York participant pool. Fifty-eight children aged between 1.5 and 7.9 years were recruited via schools and nurseries. Two children were excluded from the study: one because of suspected hearing impairment, and one 22-month-old who was unwilling to sit still. The number of remaining participants, their age and their gender are shown in Table 4.1.

The adults had pure-tone thresholds equal to or better than 25 dB HL at octave frequencies between 0.25 and 8 kHz, inclusive, measured using the British Society of Audiology guidelines (1981). Due to time constraints, children's pure-tone thresholds were not measured. However, the children had passed National Health Service hearing-screening tests (with the exception of two children who were not born in the UK). The hearing-screening test had been completed before the first birthday for 33 children, between the first and second birthdays for 12 children, and after the second birthday for 9 children. Consequently, for some of the older children, the hearing-screening test occurred several years before the child participated in this study. According to parental report, the children had normal hearing, had been in good health in the fortnight prior to testing, and had no disabilities or learning difficulties. All children went to an English-speaking school or nursery and could understand instructions in English. Approval was obtained from the Research Ethics Committee of the Department of Psychology of the University of York. Parents and adult participants gave written informed consent. The parents of child participants were given an inconvenience allowance to cover their travel costs; adult participants were paid for their time.

Table 4.1. Characteristics of the participants. The age range of the eight groups in the study is listed alongside the number of participants in each group (*N*), the mean age of participants in each group (with standard deviations, *SD*, in parentheses) and the number of females in each group. Ages are in years.

Age range	*N*	Mean age (*SD*)	Number of females
1.5 to 1.9	8	1.7 (0.2)	5
2.0 to 2.9	8	2.4 (0.4)	4
3.0 to 3.9	8	3.5 (0.3)	3
4.0 to 4.9	8	4.5 (0.3)	4
5.0 to 5.9	8	5.6 (0.3)	5
6.0 to 6.9	8	6.3 (0.3)	6
7.0 to 7.9	8	7.6 (0.3)	3
Adult	10	25.5 (11.5)	6

4.2.2 Test battery

Testing took place in a 5.3 m × 3.7 m single-walled booth (Industrial Acoustics Company) containing a circle of 24 loudspeakers (Böse Acoustimass 3 Series IV). The circle had a radius of 1.65 m and the loudspeakers were mounted on 1 m high poles, at 15° intervals, facing the centre of the circle. Only the front arc of 13 loudspeakers was used, giving a range of spatial positions from −90° to +90°. The loudspeakers were controlled by software running on a personal computer. The software produced simultaneous output via a 24 I/O channel, 24-bit MOTU digital to analogue converter and an array of 24 power amplifiers. The array of loudspeakers was calibrated using a Brüel and Kjaer Investigator sound-level meter (Type 2260) with a free-field 1/2” microphone (Type 4189) in the centre of the ring at the height of the loudspeakers. The output for each loudspeaker was adjusted so that the level of a one-octave band of white noise centred on 1 kHz was the same for every loudspeaker (within ±0.1 dB). Five independently-controlled video screens could be positioned below any five of the loudspeakers.

The stimuli for the Toy Discrimination test (see section 4.2.2.4) were those recorded by Summerfield, Palmer, Foster, Marshall, and Twomey (1994). All other speech stimuli were recorded in the testing booth using a Sennheiser K3N/ME40 microphone and digitised at 44.1 kHz with 16-bit amplitude quantization. The presentation levels of the stimuli were measured with the sound-level meter and microphone arrangement described in the previous paragraph. The metering software was set to display the peak value in dB(A) SPL in one-second intervals; the maximum value was recorded for each stimulus.

The child sat in either a high chair or a child’s chair in the centre of the ring. The parent sat behind their child. Some children sat on their parent’s lap, in which case the parent listened to music via headphones to mask the acoustical stimuli. The experimenter sat in a corner of the booth, in sight of the child. The experimenter could see a live video feed of the child from a video camera at 0°. The following sections describe the procedure for testing children. The procedure for testing adults was similar and is described in section 4.2.3.

4.2.2.1 Left-Right Discrimination test

The Left-Right Discrimination test used three video screens and loudspeakers situated at −60°, 0°, and +60°. At the beginning of a trial, an audiovisual cartoon clip was presented from 0°. The experimenter viewed the video feed showing the child’s face. When the experimenter judged that the child was looking forwards and paying attention, the cartoon was turned off and an audio-only speech stimulus was presented from either −60° or +60°. The experimenter judged whether the child made an eye movement or a head turn to one side. The direction of the response was entered into the computer controlling the equipment. A response towards the location of the source was rewarded by a display of an audiovisual cartoon at that location. An incorrect response, or no response, resulted in no reward cartoon and a short (c. 5 s) pause before the next trial. The cartoon clips were ordered so that they told a story. The experimenter was blind to the location of the stimulus and listened to music via headphones during the test.

There were two conditions of this test: the ±60° condition described above, and the ±30° condition in which the video screens and loudspeakers were situated at −30°, 0°, and +30°. The ±60° condition began with four practice trials during which the experimenter sat next to the child and pointed towards the source of sound. Data from these trials were discarded. Children attempted 20 test trials in each condition. The dependent variable was the percentage of correct responses. A few young children were very active and/or talkative, which made it difficult to observe their responses during the test. In these cases, an observer (who was blind to the location of the stimuli) watched the video recording after the session had finished and recorded the direction of the child's responses.

The stimulus was a recorded woman's voice saying, "Look over here". The repetitive nature of sound-source localisation tests makes it possible to learn the monaural cues (meaning the level and spectrum of the sound arriving at one ear) associated with a certain source location (Van Wanrooij & Van Opstal, 2004). In everyday life, these monaural cues do not allow accurate localisation of unfamiliar sources of sound on the horizontal plane. To introduce variability into the stimuli for the Left-Right Discrimination test, there were five different talkers, one of whom was selected randomly on each trial. In addition, the level of the stimulus was roved from trial to trial. The average stimulus level was 70 dB (A) SPL, randomly roved by ±5 dB in 1 dB steps. Nonetheless, the spectrum on arrival at one ear will vary with source location for these stimuli, which could provide a monaural cue to localisation. In addition, a monaural listener could move their head and use the resulting changes in level and spectrum to localise the source.

4.2.2.2 Toy Localisation test

The simplest condition of the Toy Localisation test used three video screens and loudspeakers at −60°, 0° and +60°. Seven toy blocks, which differed in their colour and shape, were placed on a table in front of the child. Each screen displayed a photograph of a different block. The photographs were selected randomly and changed following every trial. A speech stimulus was presented from a single loudspeaker, selected randomly on each trial. The child's task was to locate the source of sound and pick up the block displayed on that screen (making this a three-alternative forced-choice task). More advanced conditions used five screens and loudspeakers, with adjacent loudspeakers separated by 30° or 15°. The locations of the active loudspeakers for the different conditions are shown in Figure 4.2. Up to four practice trials were presented, during which the experimenter stood next to a screen and used live voice to present the speech stimulus. Data from these trials were discarded. Children attempted 30 test trials in each condition. The average stimulus level was 70 dB (A) SPL, randomly roved by ±5 dB in 1 dB steps. The root mean square (RMS) error was calculated using the equation $\sqrt{\frac{\sum(x-y)^2}{n}}$, where x was the location of the source in degrees, y was the location of the child's response in degrees, and n was the number of trials.

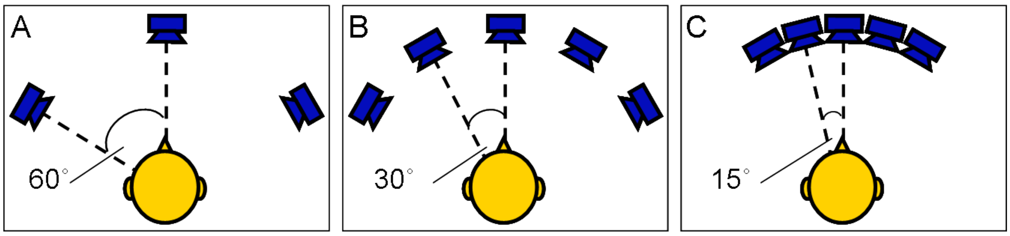


Figure 4.2. Location of the active loudspeakers for the three conditions of the Toy Localisation test. There was a video screen below each loudspeaker. A) 60° separation condition with three alternative locations. B) 30° separation condition with five alternative locations. C) 15° separation condition with five alternative locations. Configuration C was also used for the Toy Localisation test with distractors.

The stimuli were modified to reduce the utility of monaural cues to localisation. The stimulus was a recording of a female voice saying, "Hello, what's this?" There were five talkers. For a single talker, each loudspeaker played slightly different stimuli—loudspeaker 1 played stimulus s_1, loudspeaker 2 played s_2, and so on. Each stimulus (s_1-s_5) was processed so that, when it arrived at a nominated ear (e.g. the right ear), the level and spectrum were similar to those of all the other stimuli from that talker, regardless of the source location. Another set of stimuli were processed to be similar at the left ear. For each trial, the nominated ear and the talker were chosen randomly. Thus, variation was introduced into the monaural cues to localisation. This variation made the task difficult to perform on the basis of the monaural cues that are present when the listener keeps their head still, yet it did not affect binaural cues to source location (see Appendix A).

In the most demanding condition of the Toy Localisation test, two male talkers speaking sentences from the corpus published by the Institute of Electrical and Electronics Engineers (IEEE) were used as distractors (IEEE, 1969). The recordings of the IEEE sentences were concatenated, then split into stimuli with a duration of 4 seconds. Thus, a single distractor stimulus was not a single sentence. The distractors began before, and finished after, the target phrase. The five possible target locations are shown in part C of Figure 4.2. The distractors were presented from one loudspeaker each, randomly selected from seven possible locations between −45° and +45°. Target and distractor did not come from the same loudspeaker. The target was presented at 65 dB (A) SPL. The level of the distractors was varied adaptively to estimate the signal-to-noise ratio at which the child performed with an accuracy of 70.7% correct. The adaptive routine was the same as that for the Toy Discrimination test (see section 4.2.2.4). The maximum noise level was 76 dB (A) SPL.

4.2.2.3 Movement Tracking test

The Movement Tracking test assessed whether children could turn their head or point to track sources of sound that appeared to move. The stimuli were recordings of either footsteps or hoof beats, presented from a sequence of loudspeakers such that, when normally-hearing adults sat in the centre of the ring of loudspeakers, they reported that the sound source moved around the edge of the ring. The speed of movement was 9.2 deg/s for the footsteps and 13.3 deg/s for the hoof beats. The stimuli were low-pass filtered at 5.5 kHz and presented at 71 dB (A) SPL, on average. Four trials were presented in a counterbalanced order: two each of the footsteps and hoof beats, each with a different trajectory of movement (see Figure 4.3). An independent observer attempted to deduce the trajectory of movement during each trial by watching a video recording of the child's responses to the sounds. Performance was scored as the percentage of correct deductions. Pilot testing showed that instructions were generally unnecessary, because most children turned their head to track the source of sound prior to any instructions being given. Moreover, instructions to young children occasionally confused the child. Therefore, children under the age of 4 years received no instructions. Older participants were asked to "Point to show us where the sounds come from." There were no practice trials.

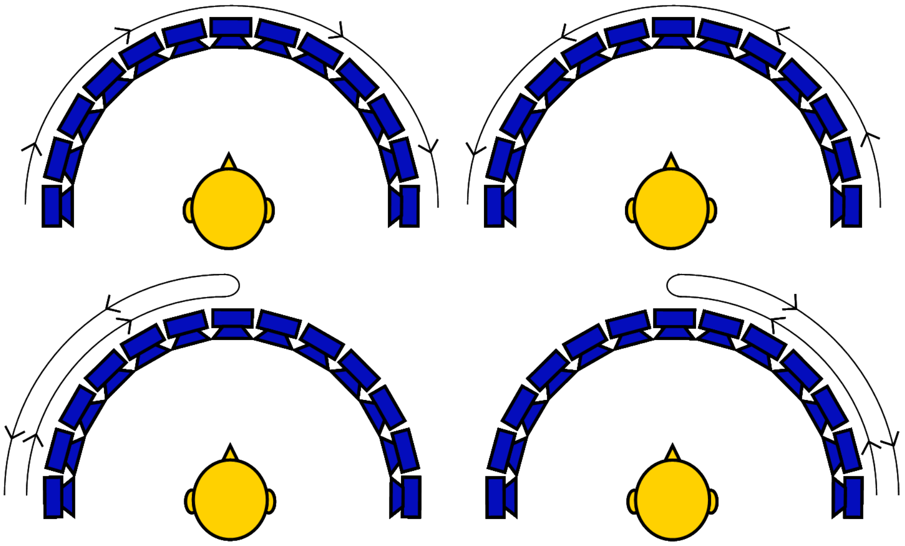


Figure 4.3. The four trajectories of apparent movement in the Movement Tracking test. Arrows denote the apparent movement of the sound source.

4.2.2.4 Toy Discrimination test

The Toy Discrimination test (Summerfield et al., 1994) was used to assess the ability to perceive speech in pink noise. A set of 14 familiar toys was placed on a table in front of the child. A recorded woman's voice was presented saying, "Point to the toy-name," where toy-name was one of the toys. The task was to point to, or say the name of, the correct toy. Younger children used only 4 or 10 toys. This is not a vocabulary test: the experimenter checked that the child knew the names of the toys, and administered some practice trials using live voice, before testing began.

The stimuli were recorded as a complete phrase ("Point to the *toy-name*") and then edited so that the introductory phrase ended after the fricative segment of "the" and the toy-name phrase began with the vocalic segment of "the" (Summerfield et al., 1994). An example pair of recordings would be "Point to th" followed by "e cow." This editing preserved the coarticulation of the voiced segment of "the", whilst allowing a single recording of the introductory phrase to be used in every trial. There was one "toy-name" stimulus for each toy; the level of this stimulus was modified so that all of the toy names were equally intelligible to young normally-hearing adults. The speech was low-pass filtered at 10.5 kHz. There were 10 tokens of broadband pink noise, one of which was randomly selected for each trial. Each token had a duration of 1.4 s with linear onset and offset ramps of 0.2 s duration. The noise began 0.3 s after the start of the speech, so that the noise began before, and finished after, the target word.

There were three conditions of the Toy Discrimination test in pink noise: with noise from −90°, 0°, and +90°. The speech was presented from 0°. The average level of the toy names was fixed at 50 dB(A) SPL and the level of the noise was varied adaptively. A one-down one-up adaptive routine with a step size of 6 dB was used for the first two reversals. A two-down one-up routine with a step size of 3 dB was used for the following six reversals. The average of the midpoints of the final three ascending runs was taken to estimate the 70.7% correct threshold (Levitt, 1971). This signal-to-noise ratio will be referred to as the SRT. The maximum noise level was 69 dB (A) SPL. If a child was inattentive or was talking during a trial, that trial was repeated.

A quiet condition of the Toy Discrimination test was included to ensure that children could understand the speech at the level at which it was presented in noise. The level of the speech was varied adaptively and there was no noise stimulus. The other aspects of the adaptive routine were the same as for the conditions in pink noise.

4.2.2.5 Toy Discrimination test in pulsatile noise

The Toy Discrimination test in pulsatile noise was used to measure the ability to perceive speech in the presence of a masker that either had the same F0 as the speech, or a raised F0 relative to that of the speech. Both speech and masker were presented from 0°. The speech stimuli from the Toy Discrimination test were resynthesised using PRAAT signal processing software (Boersma & Weenink, 2008) on a fixed F0 of 200 Hz. The resulting stimuli had a monotonous pitch. The masker was an acoustical pulse train. There were two conditions: in the Same-F0 condition the pulse train had a repetition rate of 200 Hz; in the Raised-F0 condition it had a repetition rate of 356 Hz. Thus, in the Raised-F0 condition, there was a difference of 10 semitones between the F0 of the speech and the masker. Bird and Darwin (1998) showed that, for normally-hearing adults listening to competing sentences, a difference of 10 semitones between the F0 of target and masker resulted in greater intelligibility than smaller differences in F0. The task and adaptive routine were the same as for the Toy Discrimination test, except the speech was presented at 46 dB(A) SPL. The maximum masker level was 66 dB (A) SPL.

4.2.3 Procedure

Videos of normally-hearing children performing these tests can be viewed at http://tinyurl.com/yorkspatial. Testing took place in a single session lasting up to three hours. Encouragement was given after all trials (e.g. “good girl”, “well done”), even if the child’s response was incorrect. The use of a test was terminated if children became uninterested and unwilling to continue, or if they were unable to understand the instructions. The order in which the tests were presented was tailored to the interests and attention span of each child, and thus varied between participants. Children took several short breaks between tests.

The following protocol was developed after pilot testing. The Left-Right Discrimination test was attempted by all children. The ±60° condition was attempted first, followed by the ±30° condition. The Movement Tracking test was attempted by all children. The Toy Localisation test was attempted by children aged 2 years and above. Children under 5 years attempted the 60° separation condition, followed by the 30° and 15° separation conditions. Older children attempted the 30° separation condition, followed by 15° separation and 15° separation with distractors. The Toy Discrimination test was attempted by children over the age of 2 years. The conditions of the Toy Discrimination test were presented in the following order, interspersed with the other tests:

1. The three conditions in pink noise, in an order counterbalanced across participants.
2. The quiet condition.
3. The two conditions in pulsatile noise, in an order counterbalanced across participants.

An example order of tests for a 7-year-old child is shown in Figure 4.4. To assess test-retest reliability, children in the age groups 3.0–3.9 and 7.0–7.9 years were invited to return for a second visit. These groups were selected because they were the youngest who were able to provide data on all of the tests, and the oldest children in the study.

1) Left-Right Discrimination test, ±60° condition
2) Movement Tracking test, trial 1
3) Left-Right Discrimination test, ±30° condition
4) Movement Tracking test, trial 2
5) Toy Discrimination test in pink noise, condition 1
Play break
6) Toy Discrimination test in pink noise, condition 2
7) Movement Tracking test, trial 3
8) Toy Localisation test, 30° separation
Play break
9) Movement Tracking test, trial 4
10) Toy Localisation test, 15° separation
11) Toy Discrimination test in pink noise, condition 3
12) Toy Discrimination test in quiet
Play break
13) Toy Localisation test, 15° separation with distractors
14) Toy Discrimination test in pulsatile noise, condition 1
15) Toy Discrimination test in pulsatile noise, condition 2

Figure 4.4. An example order of tests for a 7-year-old child. The order of conditions of the Toy Discrimination test in pink noise and in pulsatile noise were counterbalanced across children.

The procedure for testing adults was the same as for children, with the following exceptions. Adults used a touchscreen monitor to record their responses on all tests except for Movement Tracking, for which they drew the trajectory of perceived movement onto a diagram of the ring of loudspeakers. No feedback was given. The adults did not undertake the 15° separation condition of the Toy Localisation test, nor did they undertake the condition with distractors. The level of the speech during the Toy Discrimination test in pink noise was 40 dB (A) SPL (i.e. 10 dB less intense than for the children). The level of the speech during the Toy Discrimination test in pulsatile noise was 41 dB (A) SPL (i.e. 5 dB less intense than for the children). Adults completed two repetitions of all conditions of the Toy Discrimination test; their mean SRTs are reported.

4.2.4 Measures of test-retest reliability

One measure of test-retest reliability is the correlation coefficient between the scores from the first and second test sessions. A high correlation means that the second score can be predicted from the first. However, a high correlation could be obtained despite scores differing by a fixed amount, which could arise if performance improved over time. Conversely, a low correlation may be obtained if there is little variability in scores.

An alternative measure of reliability is the within-subjects standard deviation of scores (Plomp & Mimpen, 1979; Summerfield et al., 1994). If a single subject is tested repeatedly on the same condition, the standard deviation of their scores (σ) can be calculated. A reliable test, which gives similar results every time, will result in small σ. However, researchers are generally more interested in the reliability of a test for a group of participants. Thus, the members of a group can be tested a few times each. The mean within-subjects standard deviation (σ_ω) can then be calculated using the equation:

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

where k is the number of participants tested, n is the number of repetitions of the test, x_{ij} is the i^{th} participant's score on the j^{th} repetition, and μ_i is the i^{th} participant's mean score (Summerfield et al., 1994). The probability of a randomly selected participant's true score lying within $\pm 1.96\sigma_\omega$ of their observed score is ≥ 0.95.

A third measure of reliability is stability. If a child is tested twice in identical conditions, the difference between the two scores can be calculated. The standard deviation of these differences, σ_δ, represents the stability of scores for a group of participants. If a child is tested on two different conditions (e.g. noise-front and noise-left), the difference is significant at the $p < .05$ level if it is greater than $1.96\sigma_\delta$.

4.2.5 Analyses

Statistical analyses are presented separately for each test. The aim was to assess:

1. Whether performance on the tests improved with age, and whether children showed poorer performance than adults.
2. For the Toy Discrimination test in pink noise, whether the noise location had an effect on performance and whether there was an interaction between noise location and age.
3. For the Toy Discrimination test in pulsatile noise, whether the condition had an effect on performance and whether there was an interaction between condition and age.

Statistics were computed using SPSS 16.0 for Windows. Throughout this thesis, all p values are two-tailed and a comparison was considered statistically significant if $p < .05$. Where multiple comparisons were carried out on the same data, a Bonferroni correction was applied. Bonferroni-adjusted p values (p_{bf}) are reported, calculated as p*n where n is the number of comparisons. Thus, for three comparisons, a p value of .017 corresponds to a p_{bf} value of .05. A comparison was considered statistically significant if $p_{bf} < .05$.

4.2.5.1 Presentation of results

The scores from the Left-Right Discrimination, Toy Localisation, and Movement Tracking tests did not distribute normally, so box plots were used to display the results. There is a convention to show 'whiskers' on box plots to illustrate the 10^{th} and 90^{th} percentile scores, and to plot individual data points that fall outside this range. There were only eight participants in each group of children, meaning that the 10^{th} and 90^{th} percentile scores could not be calculated. The scores of individual participants were overlaid onto the box plots to illustrate the distribution of scores. Occasionally, several children within an age group obtained the same score. Accordingly, a number to the right of each data point shows how many children obtained that score. The SRTs from the Toy Discrimination test had a normal distribution (confirmed by the Kolmogorov-Smirnov test), so bar charts were used to display the mean and standard error. Some children did not complete all of the tests—numbers at the top of each figure indicate how many participants in each age group contributed data.

4.2.5.2 The relationship between age and performance

To assess whether there was an effect of age on performance on the Left-Right Discrimination, Toy Localisation, and Movement Tracking tests, Kruskal-Wallis tests were carried out with age group as the independent variable. There were eight age groups, as defined in Table 4.1. Post-hoc Mann-Whitney tests with a Bonferroni correction were used to assess whether the children performed worse than the adults. The post-hoc analyses were carried out if: (a) the Kruskal-Wallis test was statistically significant, and (b) the age group had a median score that was lower than that of the adults.

Effect sizes for Mann-Whitney tests were calculated using the formula $r = z/\sqrt{N}$ where z is the standardised test statistic and N is the number of participants (Field, 2005). Effect sizes can be interpreted in a similar way as correlation coefficients—an effect size of zero indicates that there was no relationship between the independent variable and outcome, an effect size of one indicates a perfect relationship. The proportion of variance accounted for by the independent variable is r^2. Cohen (1992) suggested the following guidelines for interpreting effect sizes: $r = 0.1$ is a small effect, $r = 0.3$ is a medium effect, and $r = 0.5$ is a large effect.

It was expected that the SRTs would be affected by the number of toys the child used during the Toy Discrimination test. Accordingly, statistical analyses of SRTs excluded children who used fewer than 14 toys (only a few children used 4 or 10 toys, so separate analyses of these groups would not be informative). To assess whether there was an effect of age and/or noise location on SRTs in pink noise, a two-way mixed analysis of variance (ANOVA) was carried out with the factors of age group (eight levels) and noise location (three levels). There were no *a priori* predictions regarding which age groups would differ, so Tukey HSD post-hoc comparisons were used to analyse the differences between groups. There was an *a priori* prediction regarding the effect of noise location, so planned comparisons with a Bonferroni correction were used to assess whether SRTs were lower in the noise-side conditions than in the noise-front condition (i.e. whether the participants showed SRM). Throughout this thesis, effect sizes for planned comparisons were calculated using the formula $r = \sqrt{F/(F+df_R)}$, where F is the test statistic for the planned comparison and df_R are the residual degrees of freedom (Field, 2005).

To assess whether there was an effect of age on SRTs in quiet, a one-way independent ANOVA was carried out with age group as the independent variable. Tukey HSD post-hoc comparisons were used to analyse the differences between age groups.

The SRTs in the two conditions of the Toy Discrimination test in pulsatile noise did not have equal variance, meaning they could not be analysed using an ANOVA. To assess whether there was an effect of age on SRTs in each condition, Kruskal-Wallis tests were carried out with age group as the independent variable. Post-hoc Mann-Whitney tests with a Bonferroni correction were used to assess whether children had higher SRTs than adults.

Based on the results of Johnstone and Litovsky (2006) with adults, it was expected that the difference in SRT between conditions of the Toy Discrimination test would not be affected by the number of toys the child used during the test. Accordingly, analyses of difference scores included all children. SRM was calculated by subtracting the average of the SRTs in the noise-left and noise-right conditions from the SRT in the noise-front condition. To assess whether there was an effect of age on SRM, a one-way independent ANOVA was carried out with age group as the independent variable. Post-hoc analyses were not necessary as the ANOVA was not statistically significant. For the Toy Discrimination test in pulsatile noise, the difference between conditions was calculated by subtracting the SRT in the Raised-F0 condition from the SRT in the Same-F0 condition. A within-subjects t-test was used to assess whether, for all participants together, the difference between conditions was significant. To assess whether there was an effect of age on the difference between conditions, a one-way independent ANOVA was carried out with age group as the independent variable. Post-hoc analyses were not necessary as the ANOVA was not statistically significant.

4.2.5.3 Test-retest reliability

The scores from the Left-Right Discrimination, Toy Localisation, and Movement Tracking tests did not distribute normally and had several tied ranks, so Kendall's rank-order correlation coefficients (tau) were calculated (Field, 2005). Pearson's product-moment correlation coefficients were calculated for the Toy Discrimination test. Other measures of reliability were calculated according to the formulae in section 4.2.4.

4.3 Results

4.3.1 The relationship between age and the ability to complete listening tests

The ability to complete each listening test was quantified by the number of trials completed. The Toy Discrimination test is adaptive, so the number of conditions completed was calculated: a condition was considered complete if the child finished at least two reversals in the second phase of the adaptive routine. The number of trials or conditions of each test that were completed by the seven groups of children is shown in Table 4.2.

The maximum number of trials of the Left-Right Discrimination test was 40. All children completed some trials of this test; all children aged over 3.8 years completed 40 trials. The maximum number of trials of the Toy Localisation test was not fixed because the test with distractors used an adaptive routine. The test could not be performed by children younger than 2.3 years. All children aged 3.0 years and above completed at least 30 trials. Due to experimenter error, three 4-year-old children did not attempt the 60° separation condition. The maximum number of trials of the Movement Tracking test was four. All except two children (both aged 1.5 years) completed four trials. The maximum number of conditions of the Toy Discrimination test was six. The test could not be completed by children below 2.7 years. All children aged over 3.2 years completed at least three conditions (the number required to measure SRM with noise on either side of the head). Only two children under 5 years old had the stamina to complete the Toy Discrimination test in pulsatile noise, as it was usually attempted at the end of the session.

To summarise, older children completed more listening tests. All children provided data on the Left-Right Discrimination test, all children over 1.6 years completed the Movement Tracking test, all over 3.0 years completed 30 trials of the Toy Localisation test, and all over 3.2 years completed three conditions of the Toy Discrimination test.

Table 4.2. The median (and range) of trials of each test that were completed by the seven groups of children. For the Toy Discrimination test, the number of conditions completed is shown. Practice trials are not included. Ages are in years.

Age range	Left-Right Discrimination	Toy Localisation	Movement Tracking	Toy Discrimination[a]
1.5 to 1.9	38 (13–40)	0 (0–0)	4 (0–4)	0 (0)
2.0 to 2.9	40 (25–40)	0 (0–43)	4 (4–4)	0 (0–3)
3.0 to 3.9	40 (17–40)	60 (37–90)	4 (4–4)	4 (2–5)
4.0 to 4.9	40 (40–40)	90 (34–129)	4 (4–4)	4 (3–6)
5.0 to 5.9	40 (40–40)	94 (86–115)	4 (4–4)	6 (4–6)
6.0 to 6.9	40 (40–40)	90 (83–129)	4 (4–4)	6 (6–6)
7.0 to 7.9	40 (40–40)	90 (85–94)	4 (4–4)	6 (6–6)

[a] Includes the conditions in quiet, in pink noise, and in pulsatile noise.

4.3.2 Left-Right Discrimination test

The results of the Left-Right Discrimination test are shown in Figure 4.5. With two exceptions, participant's scores were better than would be expected by chance. There was an effect of age on performance in the ±60° condition [$H(7) = 26.05$, $p < .001$] and the ±30° condition [$H(7) = 39.98$, $p < .001$]. In the ±60° condition, the 2-year-olds had lower scores than the adults [$z = -3.18$, $p < .01$, $r = .75$]. All other age groups had a median score of 100% correct. In the ±30° condition, the 1- and 2-year-olds had lower scores than the adults and the 3-year-olds had scores that were similar to those of the adults (Table 4.3).

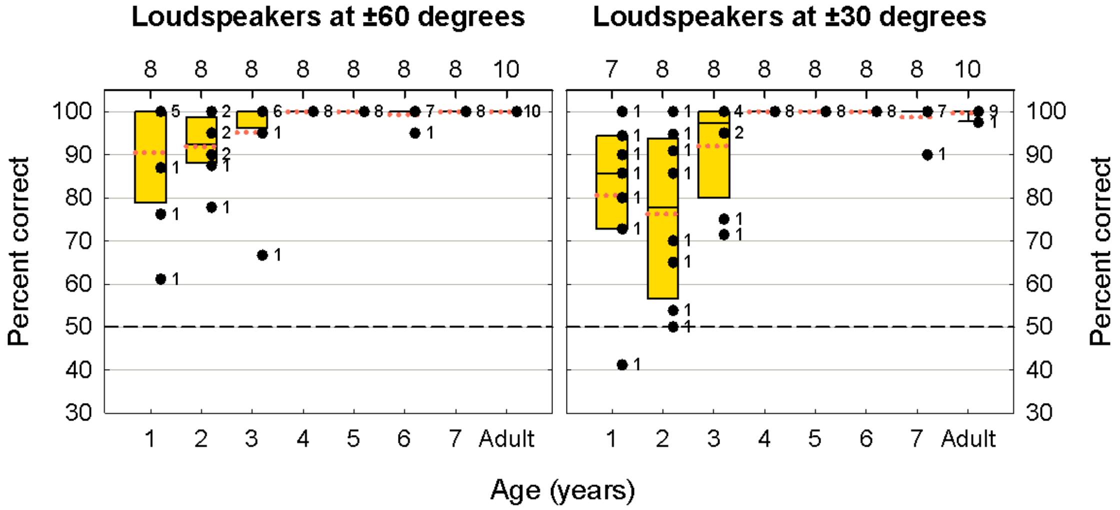


Figure 4.5. Results of the Left-Right Discrimination test: ±60° condition (left panel) and ±30° condition (right panel). The yellow boxes show the area between the 25th and 75th percentile scores. The solid black horizontal lines within the boxes show the median; the dotted orange lines show the mean. Where the median line is not visible, the median is 100%. The circles show individual scores, the number to the right of each circle indicates how many participants in that age group showed that score. For adults, the whiskers show the 10th and 90th percentile scores. The black dashed lines show the level of performance expected by chance. The numbers above the upper horizontal axis indicate how many participants in each age group provided data.

Table 4.3. The results of Mann-Whitney tests to compare the scores of 1-, 2-, and 3-year-olds with those of adults on the ±30° condition of the Left-Right Discrimination test. All other age groups had a median score of 100% correct.

Comparison	z	p_{bf}	r
1-year-olds versus adult	−3.22	< .01	.78
2-year-olds versus adult	−3.37	< .01	.79
3-year-olds versus adult	−2.03	.16	.48

4.3.3 Toy Localisation test

The results of the three conditions of the Toy Localisation test without distractors are shown in Figure 4.6. With a single exception, participants' scores were better than would be expected by chance. There was an effect of age on performance in the 60° separation condition [$H(3) = 15.66$, $p < .001$]. The 2- and 3-year-olds had larger error scores than the adults [2-year-olds: $z = -3.43$, $p_{bf} < .01$, $r = .95$; 3-year-olds: $z = -2.63$, $p_{bf} < .15$, $r = .73$]. There was no significant effect of age on performance in the 30° separation condition [$H(6) = 9.26$, $p = .16$], or on performance in the 15° separation condition [$H(4) = 4.96$, $p = .29$].

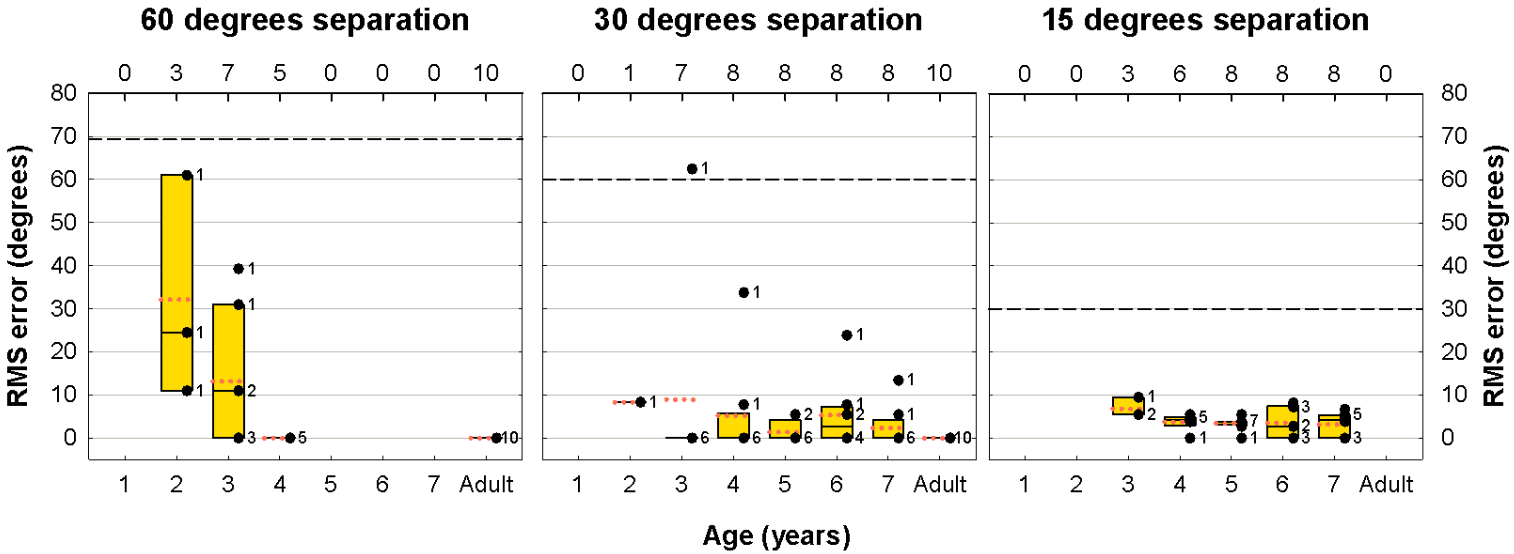


Figure 4.6. Results of the Toy Localisation test without distractors. Left panel: three-alternative task with 60° separation between loudspeakers. Centre panel: five-alternative task with 30° separation. Right panel: five-alternative task with 15° separation. The yellow boxes show the area between the 25th and 75th percentile scores. The solid black horizontal lines within the boxes show the median; the dotted orange lines show the mean. Where the median line is not visible, the median is on the lower boundary of the box. The circles show individual scores, the number to the right of each circle indicates how many participants in that age group showed that score. The dashed line indicates the level of performance expected by chance. The numbers above the upper horizontal axis indicate how many participants in each age group provided data. The 5, 6, and 7-years olds did not attempt the 60° separation condition and the adults did not attempt the 15° separation condition.

The results of the Toy Localisation test with distractors are shown in Figure 4.7. There was no significant effect of age on performance [$H(3) = 0.88$, $p = .83$]. During this test, a limit on the level of the noise was imposed by the software to prevent the noise level becoming uncomfortable. Consequently, the minimum signal-to-noise ratio was −11 dB. Thus, it is possible that some of the children with thresholds between −9 and −11 dB (the two highest noise levels on the adaptive routine) were scoring at ceiling.

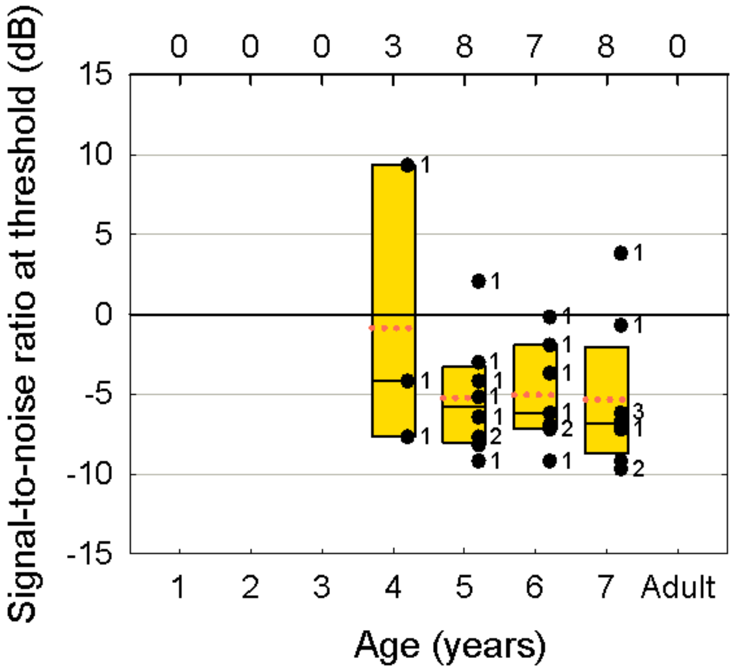


Figure 4.7. Results of the Toy Localisation test with distractors. The yellow boxes show the area between the 25th and 75th percentile scores. The solid black horizontal lines within the boxes show the median; the dotted orange lines show the mean. The circles show individual scores, the number to the right of each circle indicates how many participants in that age group showed that score. The numbers above the upper horizontal axis indicate how many participants in each age group provided data. The adults did not attempt this test.

4.3.4 Movement Tracking test

The results of the Movement Tracking test are shown in Figure 4.8. With a single exception, participants' scores were better than would be expected by chance. All age groups had a median score of 100% correct.

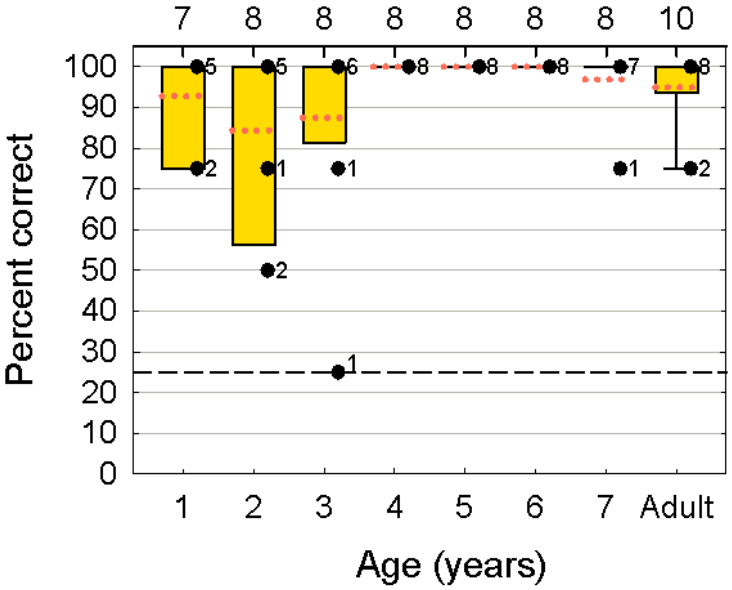


Figure 4.8. Results of the Movement Tracking test. The yellow boxes show the area between the 25th and 75th percentile scores. The solid black horizontal lines within the boxes show the median; the dotted orange lines show the mean. Where the median line is not visible, the median is 100%. The circles show individual scores, the number to the right of each circle indicates how many participants in that age group showed that score. For adults, the whiskers show the 10th and 90th percentile scores. The dashed line indicates the level of performance expected by chance. The numbers above the upper horizontal axis indicate how many children in each age group provided data.

4.3.5 Toy Discrimination test in pink noise

The results of the Toy Discrimination test in pink noise are shown in Figure 4.9. For participants who used 14 toys, there was an effect of age on SRTs [$F(5, 38) = 9.66$, $p < .001$]. Post-hoc tests revealed that the groups of children had thresholds that did not differ significantly from each other [all $p > .05$]. All of the groups of children had higher thresholds than the adults [all $p < .05$].

For participants who used 14 toys, there was an effect of noise location on SRT [$F(2, 76) = 67.86$, $p < .001$]. Planned comparisons revealed that, compared to the noise-front condition, SRTs were significantly lower in the noise-left [$F(1,38) = 138.93$, $p_{bf} < .001$, $r = .89$] and noise-right conditions [$F(1,38) = 69.60$, $p_{bf} < .001$, $r = .80$]. These results indicate that, on average, participants showed SRM both when noise was shifted to the left and when noise was shifted to the right. The interaction between age group and noise location was not significant [$F(10,76) = 1.23$, $p = .28$]. The nonsignificant interaction indicates that, for participants who used 14 toys, SRM did not vary with age. SRM is examined for the whole group of participants (including those who used 4 or 10 toys) in the following section.

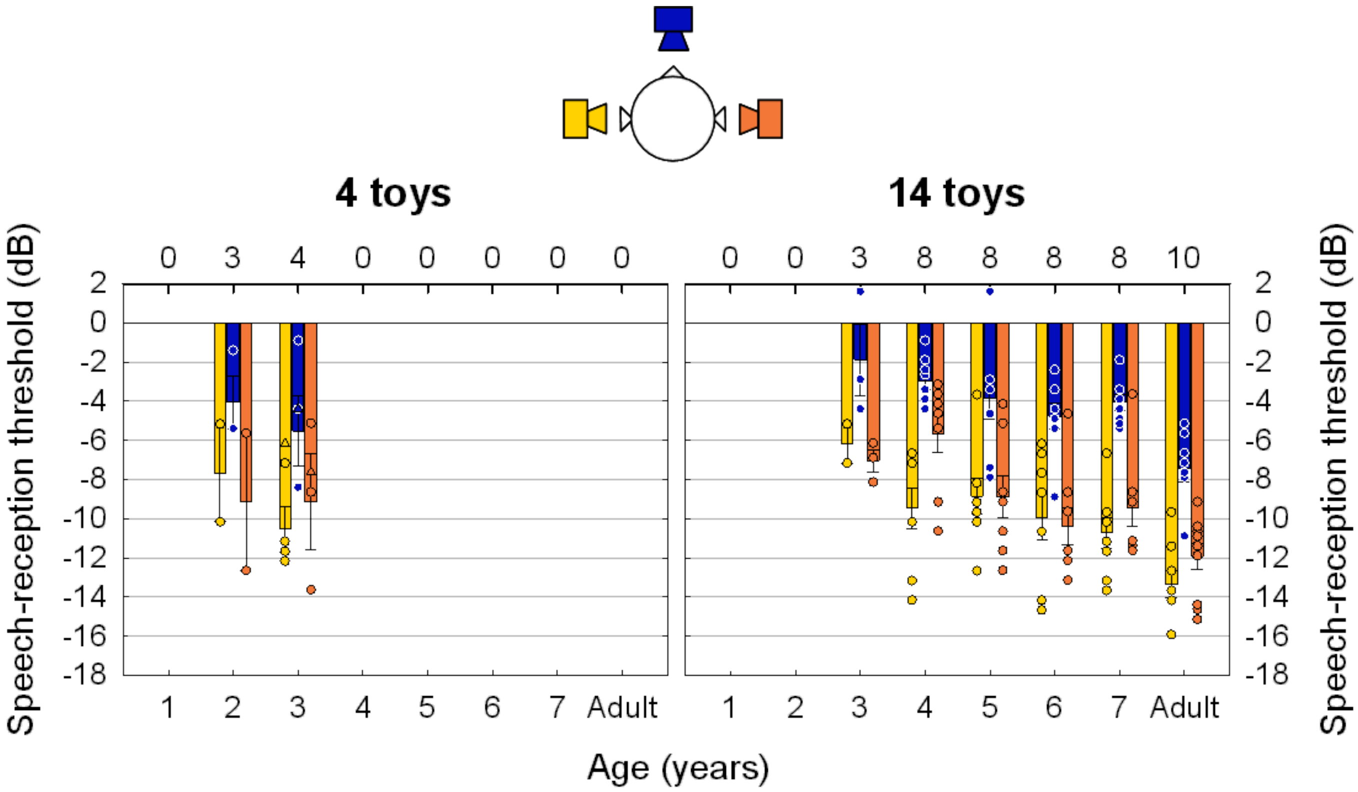


Figure 4.9. Results of the Toy Discrimination test in pink noise for participants who used 4 toys (left panel) or 14 toys (right panel). The bars show the mean SRT, error bars show the standard error of the mean. The circles show individual scores. Yellow bars and circles: noise-left condition. Blue bars and circles: noise-front condition. Orange bars and circles: noise-right condition. The numbers above the upper horizontal axis indicate how many children in each age group provided data. A single child used ten toys; these scores are shown by the triangles in the left panel.

4.3.5.1 Spatial release from masking

The amount of SRM shown by all of the participants is plotted in Figure 4.10.[1] With one exception, the individual scores were positive, indicating that SRTs were lower with noise from the side than with noise from the front. There was no significant effect of age group on SRM [$F(6,51) = 0.62$, $p = .71$].

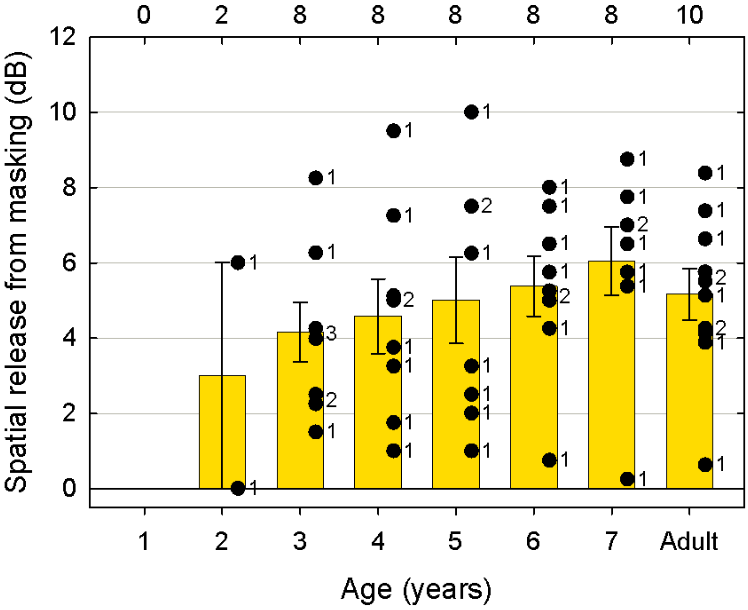


Figure 4.10. The amount of SRM shown by the eight age groups. SRM was calculated by subtracting the average of the SRTs in the noise-left and noise-right conditions from the SRT in the noise-front condition. The yellow bars show the mean SRM. The error bars show standard error of the mean. The circles show individual scores, the number to the right of each circle indicates how many participants in that age group showed that score. The numbers above the upper horizontal axis indicate how many participants in each age group provided data.

4.3.6 Toy Discrimination test in quiet

The results of the Toy Discrimination test in quiet are shown in Figure 4.11. All children who completed the quiet condition displayed SRTs that were lower than the level at which the speech was presented in pink noise (50 dB (A) SPL). For participants who used 14 toys, there was an effect of age on SRTs [$F(5,37) = 9.45$, $p < .001$]. Post-hoc tests revealed that the 3-year-olds had higher thresholds than the 7-year-olds [$p < .01$]. The 3- to 6-year-olds all had higher thresholds than the adults [$p < .05$], whereas the 7-year-olds had thresholds that were not significantly different from those of the adults [$p = .18$]. The other post-hoc comparisons were not significant.

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[1] Figure 4.9 shows data from three 2-year-old children, whereas Figure 4.10 shows data from two 2-year-old children. The difference in the number of children arose because one 2-year-old child completed only the version of the test with noise from the front, meaning it was not possible to calculate SRM for that child.

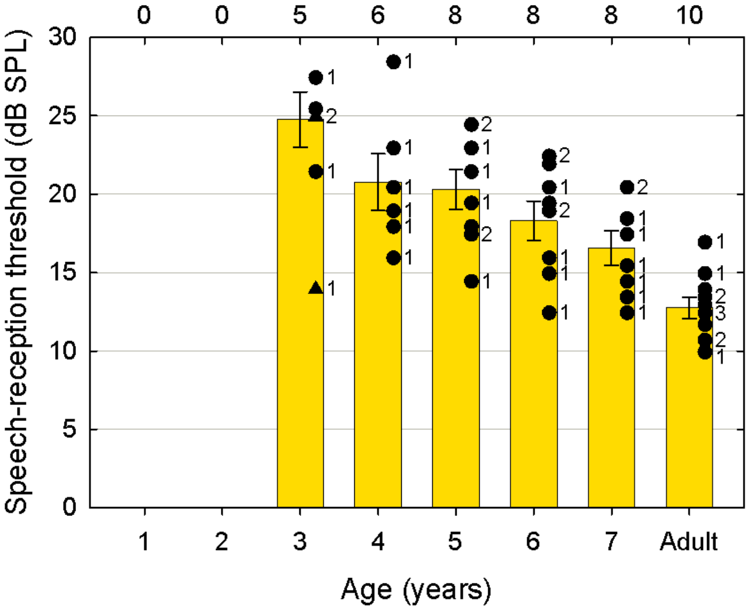

Figure 4.11. Results of the Toy Discrimination test in quiet. The yellow bars show mean SRTs for participants who used 14 toys, the error bars show standard error of the mean. The circles show individual scores for participants who used 14 toys, the triangles show individual scores for two participants who used 4 toys. The numbers to the right of each data point indicate how many participants in that age group showed that score. The numbers above the upper horizontal axis indicate how many participants in each age group provided data.

4.3.7 Toy Discrimination test in pulsatile noise

The results of the Toy Discrimination test in pulsatile noise are shown in Figure 4.12. Children aged 3 and 4 years were excluded from the analysis of SRTs, because only small numbers of children in these age groups completed the test. There was an effect of age on SRT in the Same-F0 condition [$H(3) = 17.07$, $p < .01$] and the Raised-F0 condition [$H(3) = 20.47$, $p < .001$]. In both conditions, the 5- 6- and 7-year-old children had higher SRTs than the adults (Table 4.4).

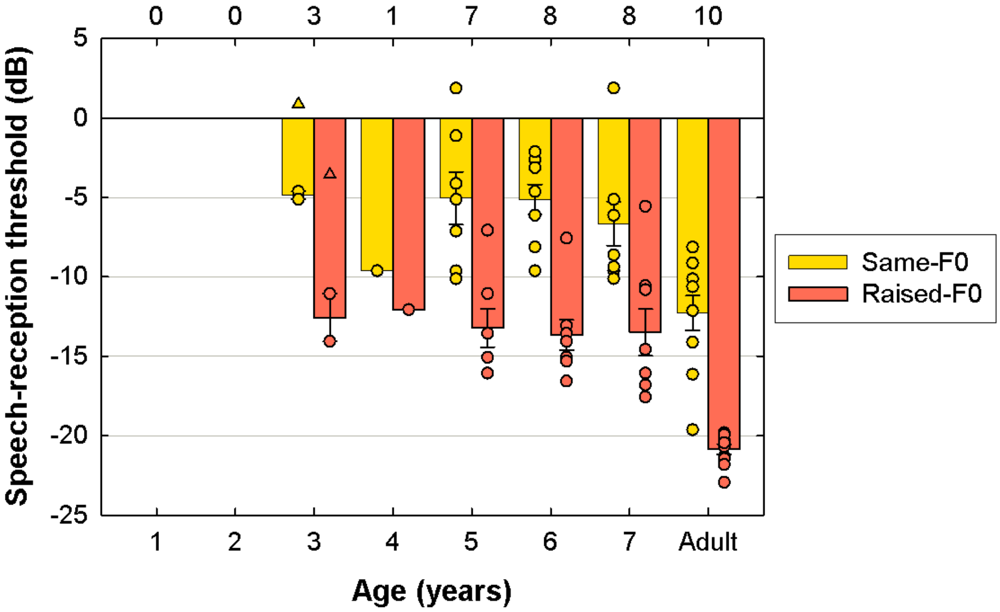

Figure 4.12. Results of the Toy Discrimination test in pulsatile noise. For participants who used 14 toys, the bars show mean SRTs for the Same-F0 condition (yellow bars) and Raised-F0 condition (orange bars). The error bars show standard error of the mean. The circles show individual scores for participants who used 14 toys, the triangles show individual scores for the participant who used 10 toys. The numbers above the upper horizontal axis indicate how many participants in each age group provided data.

Table 4.4. The results of Mann-Whitney tests to compare the SRTs of 5-, 6-, and 7-year-olds with those of adults on the Toy Discrimination test in pulsatile noise.

Comparison	z	p_{bf}	r
Same-F0			
5-year-olds versus adults	−3.03	< .01	.73
6-year-olds versus adults	−3.38	< .01	.80
7-year-olds versus adults	−2.94	< .01	.69
Raised-F0			
5-year-olds versus adults	−3.42	< .01	.83
6-year-olds versus adults	−3.56	< .01	.84
7-year-olds versus adults	−3.56	< .01	.84

The difference between conditions

The difference in SRT between the Same-F0 condition and the Raised-F0 condition is plotted in Figure 4.13. A positive score indicates that SRTs were lower in the Raised-F0 condition than the Same-F0 condition. For the group of participants as a whole, the mean SRT in the Raised-F0 condition [−15.12 dB] was lower than the mean SRT in the Same-F0 condition [−7.33 dB; $t(36) = 10.09$, $p < .001$]. There was no significant effect of age group on the difference between conditions [$F(5,31) = 0.43$, $p = .82$].

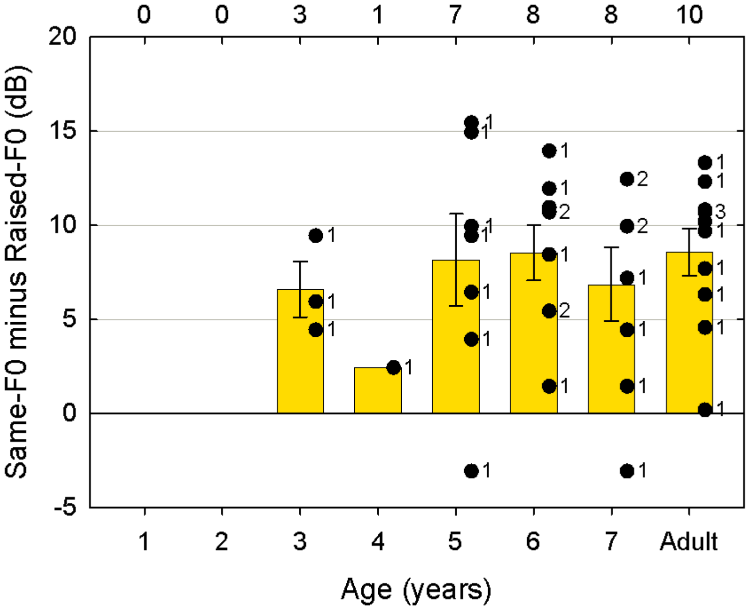

Figure 4.13. The difference in SRT between the Same-F0 condition and the Raised-F0 condition of the Toy Discrimination test in pulsatile noise. The yellow bars show the mean difference, the error bars show the standard error of the mean. The circles show individual scores, the number to the right of each circle indicates how many participants in that age group showed that score. The numbers above the upper horizontal axis indicate how many participants in each age group provided data.

4.3.8 Test-retest reliability

One 7-year-old child was unable to return for a second visit, so data on test-retest reliability are available for eight 3-year-olds and seven 7-year-olds. Some of the 3-year-olds did not complete all of the tests. The mean interval between test sessions was 21 days (range 2–55 days). The test-retest statistics for the Left-Right Discrimination, Toy Localisation, and Movement Tracking tests are shown in Table 4.5 and for the Toy Discrimination test in Table 4.6. As a guide to interpreting these tables, consider the statistics for the 3-year-olds for the ±60° condition of the Left-Right Discrimination test. A randomly-selected participant's true score will lie within $\pm 1.96\sigma_{\omega}$ of their observed score with a probability $\geq .95$. Thus, a randomly-selected 3-year-old's true score lies within ±6.21% of their observed score with a probability

≥ .95. If a participant is tested in two conditions (e.g. aided and unaided), the difference in scores is significant at the $p < 0.05$ level if it is greater than $\pm 1.96\sigma_\delta$. Thus, for a 3-year-old, a difference between conditions would be considered significant if it were greater than 8.09%. The test-retest reliability statistics will be compared with those from previous studies in section 4.4.5.

Table 4.5. Test-retest statistics for 3- and 7-year-old children for the Left-Right Discrimination, Toy Localisation, and Movement Tracking tests. The Kendall's tau correlation coefficient (τ), the within-subjects standard deviation of scores (σ_ω), the standard deviation of the differences between children's first and second scores (σ_δ), and the number of children who provided data (N) are listed.

	3-year-olds				7-year-olds			
Test	τ	σ_ω	σ_δ	N	τ	σ_ω	σ_δ	N
Left-right discrim.								
± 60° condition	−.52	3.17%	4.13%	6	[a]	0.00%	0.00%	7
± 30° condition	+.30	4.12%	6.25%	6	[a]	2.67%	3.78%	7
Toy localisation								
60° separation	+.67	6.32°	7.03°	6				0
30° separation	+.67	12.56°	19.04°	5	−.17	4.33°	5.38°	7
15° separation				0	+.44	1.98°	2.96°	7
15° separation with distractors				0	+.31	3.63 dB	5.27 dB	7
Movement Tracking	[a]	19.76%	26.73%	8	[a]	0.00%	0.00%	7

[a] Correlations could not be computed because all children had identical scores in the second test session.

Table 4.6. Test-retest statistics for the Toy Discrimination test for 3- and 7-year-old children. The Pearson correlation coefficient (r), the within-subjects standard deviation of scores (σ_ω), the standard deviation of the differences between children's first and second scores (σ_δ), and the number of children who provided data (N) are listed.

	3-year-olds				7-year-olds			
Test	r	σ_ω (dB)	σ_δ (dB)	N	r	σ_ω (dB)	σ_δ (dB)	N
Toy discrimination								
Noise left	−.40	3.18	4.68	5	+.48	1.98	2.60	7
Noise front	−.53	3.38	4.46	6	+.34	3.09	3.07	7
Noise right	+.25	2.52	2.72	5	+.59	2.44	2.52	7
Quiet	+.39	3.73	3.01	3	+.35	2.76	3.86	7
Toy discrimination in pulsatile noise								
Same-F0	[a]	5.30	[a]	1	+.08	4.36	5.18	6
Raised-F0	[a]	1.41	[a]	1	−.07	3.00	4.49	6

[a] Could not be computed because only one child completed the test in both sessions.

4.3.9 Summary

The age at which children could complete tests, and the age at which performance was similar to that of adults, are summarised in Figure 4.14.

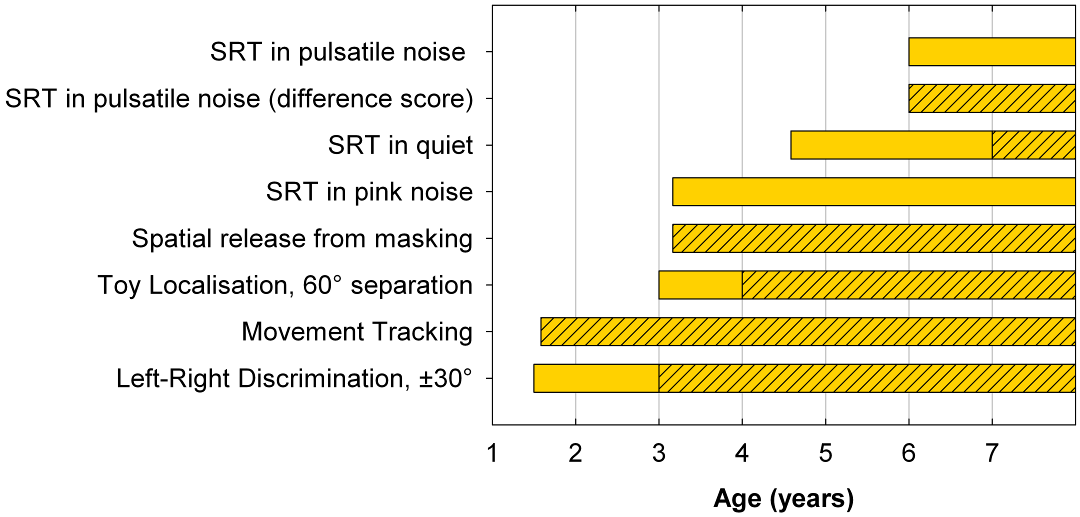

Figure 4.14. Summary of results. The yellow bars show the age at which all children met a criterion of being able to complete a listening test. The striped bars show the age at which performance was not significantly different to that of adults. Tests without a striped bar indicate that the oldest group of children in the study did not perform as well as adults. The criteria were: completed 13 trials (Left-Right Discrimination), completed 4 trials (Movement Tracking), completed 30 trials (Toy Localisation), completed 3 conditions (SRT in pink noise & SRM), completed 1 condition (SRT in quiet), completed 2 conditions (SRT in pulsatile noise).

4.4 Discussion

4.4.1 Summary of main findings

The aim of this study was to assess the performance of normally-hearing children and adults on tests of spatial listening, in order to allow comparisons with the performance of implanted children in later studies. Normally-hearing children showed high levels of performance on tests of left-right discrimination, localisation, and movement tracking; by the age of 3 or 4 years children's performance on these tests was at ceiling and similar to that of adults. Both children and adults benefited from SRM: a spatial separation of speech from noise improved SRTs by 5 dB, on average. The amount of SRM did not differ significantly between the age groups. On average, participants' SRTs were 8 dB lower when there was a difference in F0 between speech and a pulsatile masker than when there was no difference in F0, and the difference between conditions was similar for all of the age groups. In contrast, SRTs varied with age. On tests of speech perception in pink noise and in pulsatile noise, 7-year-olds (the oldest children in the study) did not perform as well as adults.

4.4.2 Comparison with previous findings

These results are consistent with previous estimates of the spatial listening skills of normally-hearing children (see section 2.5), with the following exceptions. Children's ability to discriminate a sound source on the left from a source on the right improved between the ages of 1 and 3 years. This result was unexpected, as the loudspeaker separations were greater than estimates of normally-hearing children's MAA (Ashmead et al., 1998; Grieco-Calub et al., 2008; Litovsky, 1997; Morrongiello, 1988). It is possible that the difference in results occurred because the present study measured the percentage of correct responses, whereas previous studies used an adaptive routine to measure MAA. Lapses in attention result in a decreased percentage-correct score, but may have a smaller effect on scores that are calculated from an adaptive routine. There are also differences in data analysis: the present study included data from all trials, whereas Litovsky (1997) and Grieco-Calub et al. (2008) discarded data from consecutive incorrect trials and trials on which the child made no response. Similarly, Morrongiello discarded data from trials on which children were inattentive.

On tests of sound-source localisation in which there were five possible locations, children over 3 years old showed levels of performance that were similar to those of adults, and many children performed at a ceiling level. Accordingly, this study may under-estimate the age at which children's localisation skills are similar to those of adults. Previous studies using more complex tasks with at least nine possible sound-source locations have found that performance improves up to the age of 6 years (Bess et al., 1986; Van Deun et al., 2009). Regarding the ability to complete tests, Van Deun and colleagues reported that, in a pilot experiment, 3-year-olds were unable to discriminate among three loudspeakers at −90° , 0° , and +90°. We found that 3-year olds, and some 2-year-olds, were able to perform a similar task. The difference between studies may be caused by the use of pointing responses in the present study, which meant that children did not need to make a verbal response (in contrast to the task used by Van Deun et al.).

Regarding speech perception, the present study found that the groups of children aged between 3 and 7 years had similar SRTs in pink noise, on average. In contrast, Summerfield et al. (2004) reported a trend for improved SRTs over this age range, and Garadat and Litovsky (2007) found that 5-year-olds showed significantly lower SRTs than 3-year-olds. In the present study, several 2- and 3-year old children completed a version of the Toy Discrimination task with fewer than 14 toys, and were therefore not compared with older children. It is possible that there would have been an effect of age if all children had completed the same test. Another anomalous result was that the 7-year-olds' SRTs in quiet were similar to the SRTs of the adults, whereas Summerfield et al. (2004) used the same test and found that SRTs improved up to the age of 15 years. It is possible that the present study was underpowered to detect the slower rate of improvement in SRTs after the age of 6 years.

4.4.3 The causes of the improvement in speech perception with age

On average, children had higher SRTs than adults in quiet and in pink noise, a finding that is a replication of several previous studies (Hall et al., 2002; Johnstone & Litovsky, 2006; Litovsky, 2005; Papso & Blood, 1989). A similar developmental trend is observed for the detection of pure tones and noise bursts (Roche, Siervogel, Himes, & Johnson, 1978; Schneider, Trehub, Morrongiello, & Thorpe, 1986; Yoneshige & Elliott, 1981). These differences in performance between children and adults may be due to sensory variables (meaning variables related to the ear and auditory nervous system) and/or non-sensory variables (such as attention, memory, and language skills). Evidence that sensory variables may play a role comes from post-mortem studies, which indicate that the auditory nervous system is still developing over the age range of the children in the present study. Up to the age of 6 years, there is maturation of the projections from the thalamus to the cortex; up to the age of 12 years there is maturation of the connections within the auditory cortex (J. K. Moore & Linthicum, 2007).

Evidence that non-sensory variables contribute to the differences in performance between children and adults comes from simulations of the effects of inattention or forgetting task instructions: the simulations result in psychometric functions that are similar to those measured in children (Wightman & Allen, 1992). It is possible that children with better language skills are more familiar with the target words, and are more able to generate potential answers from a partially-perceived word, than children with poorer language skills. In support of this idea, scores on a test of vocabulary predict children's SRTs, even when the words in the test of speech perception are familiar and within the child's vocabulary (Elliott et al., 1979). On the other hand, some studies have found that cognitive abilities do not correlate with SRTs (Talarico et al., 2007).

4.4.4 The causes of the difference between the Raised-F0 and Same-F0 conditions

On average, all of the age groups showed lower SRTs in the Raised-F0 condition than the Same-F0 condition of the Toy Discrimination test in pulsatile noise. Potentially, participants could use a difference in F0 to segregate the target speech from the masking pulse train in the Raised-F0 condition but not the Same-F0 condition (Assmann & Summerfield, 1990). Thus, segregation on the basis of F0 is likely to have contributed to the observed difference between conditions. However, segregation on the basis of F0 may not have been the sole cause of the difference between conditions. The maskers were presented at an equal level (in dB(A) SPL), but the Same-F0 masker contained energy above 200 Hz whereas the Raised-F0 masker only contained energy above 356 Hz. Consequently, low-frequency phonetic information (such as the F0, which provides a cue to voicing) will have been distorted to a lesser degree by the Raised-F0 masker than the Same-F0 masker. This difference in masking at low frequencies may have contributed to the difference in SRT between conditions.

4.4.5 Test-retest reliability

On the Left-Right Discrimination, Toy Localisation, and Movement Tracking tests, normally-hearing children often scored 100% correct. This may mean that the estimates of σ_ω and σ_δ for these tests are artificially low: the values may be higher if measured in a sample that does not show ceiling effects (such as children with cochlear implants). The test-retest reliability measures for the Toy Discrimination test can be compared with those from Summerfield et al. (1994), who used the Toy Discrimination test in quiet. For 136 children aged between 2 and 13 years, the correlation coefficient between first-test SRT and second-test SRT was .95. The average σ_ω for all children was 2.5 dB, and children over the age of 4 years had values of σ_ω similar to that of adults (2.3 dB). The average σ_δ for all children was 3.5 dB. In the present study, the test-retest correlation coefficients were typically lower, the values of σ_ω were typically higher, and the values of σ_δ were comparable to those of Summerfield and colleagues. The present test-retest correlation coefficients were higher and the values of σ_ω were comparable to those of Ousey, Sheppard, Twomey, and Palmer (1989). Thus, the Toy Discrimination test shows somewhat poorer test-retest reliability than has been estimated previously. This is most likely because the second test session took place on a different day to the first session, whereas previous studies repeated the test on the same day.

4.4.5.1 Which test is the most reliable?

Identifying the most-reliable test within this battery is not straightforward, for a number of reasons. Two of the measures of reliability (σ_ω and σ_δ) are expressed in the original units of measurement and therefore cannot be compared across tests. The third measure of reliability (the correlation between the first and second test scores) was calculated using Pearson's r for the Toy Discrimination test (to allow for comparison with previous studies) and Kendall's tau for the other tests (because the data were not normally distributed). Consequently, the correlation coefficients cannot be compared across tests. In order to identify the most-reliable test, the correlation between the first and second scores on the Toy Discrimination test was calculated using Kendall's tau. For 3-year-old children, when using Kendall's tau as the measure of reliability, Toy Localisation with a separation of 60° or 30° was the most-reliable test, and Left-Right Discrimination with loudspeakers at ±60° was the least-reliable test. For 7-year-old children, when using Kendall's tau as the measure of reliability, Toy Localisation with a separation of 15° was the most-reliable test, and Toy Localisation with a separation of 30° was the least-reliable test.

4.4.6 Evaluation of the tests of spatial listening

This battery of tests is suitable for assessing the spatial listening skills of normally-hearing children between the ages of 18 months and 7 years. The tests measure abilities in both sound-source localisation and speech perception in noise. The tests of sound-source localisation employ a series of tasks with an ascending degree of difficulty, and the tests of speech perception use an adaptive routine. Consequently, the tests can be used with children who vary in age and in listening skill. Moreover, the tests do not require verbal responses. Parents and children found the testing environment to be comfortable and children found the tests engaging. On most of the tests of sound-source localisation, and the measure of SRM, the performance of 3- to 4-year-old children was similar to that of adults. A lack of age effects is an advantage when comparing outcomes for children with cochlear implants, because it can be difficult to recruit groups of children of the same age.

The test sessions for this study took between two and three hours. This may be rather long: it is possible that children would complete more tests, and show higher levels of performance, if the tests were administered during several shorter sessions. However, the data are suitable for comparisons with those for other children who were tested in a single session.

The tests of spatial listening were designed for the assessment of children with cochlear implants, but they could also be used in other areas of research. Some children appear to have poor listening skills, despite normal hearing levels and an absence of higher-level cognitive deficits (Witton, 2010). The listening skills of this population of children could be assessed using the tests of spatial listening described in this chapter.

4.4.7 Conclusion

Normally-hearing children as young as 3 years can localise sounds, track moving sounds, and benefit from SRM. The ability to perceive speech in quiet and in noise improves with age.

4.5 Summary

- A battery of tests was developed to compare outcomes between children who use a unilateral cochlear implant and children who use bilateral cochlear implants.
- The tests were attempted by normally-hearing adults and normally-hearing children between 18 months and 7 years old.
- Older children completed more tests, yet the two simplest tests were completed by the majority of 18- to 24-month-old children.
- On tests of left-right discrimination, localisation, and movement tracking, children's performance was similar to that of adults by the age of 3 or 4 years.
- Older participants had lower SRTs in quiet and in noise.
- Both children and adults showed SRM with noise on either side of the head. All age groups showed a similar amount of SRM.
- On average, participants' SRTs were 7 dB lower when there was a difference in F0 between speech and a masker than when there was no difference in F0, and the difference between conditions did not vary with age.
- Test-retest reliability was somewhat poorer than had been estimated previously.

Chapter 5

Spatial Listening Skills of Children with Unilateral or Bilateral Cochlear Implants

This chapter reports a study that compared the spatial listening skills of children with unilateral or bilateral cochlear implants. The children attempted the tests of spatial listening described in the previous chapter. On average, bilaterally-implanted children performed better than unilaterally-implanted children on tests of left-right discrimination, localisation, movement tracking, and SRM with noise ipsilateral to the first implant. Significant differences between the groups were sustained following imputation of missing data and statistical control of confounds. The group of bilaterally-implanted children included those who had received two implants in a single surgery and those who had a gap between surgeries. There were no significant differences between the performance of these two subgroups.

5.1 Introduction

Recently, one of the issues facing clinicians and parents has been whether severely-profoundly deaf children should receive bilateral cochlear implants rather than a unilateral cochlear implant. It has been argued that bilateral implantation creates the potential for binaural hearing, provides a backup in the event of device failure, and ensures that the more-responsive auditory nerve is stimulated (see section 3.1.2). Evidence that these benefits are realised by children with bilateral implants is required to justify the additional surgery and incremental discounted lifetime cost of £27,000 per child (at 2007 cost levels, Bond et al., 2007). This chapter reports a between-subjects study that assessed the effectiveness of bilateral implantation in enabling spatial listening skills, meaning the ability to use both ears together to localise sources of sound and to improve the perception of speech in noise. These skills may help children to avoid hazards outdoors and to understand speech better at home and at school.

The review of the literature in Chapter 3 concluded that there is uncertainty regarding the effectiveness of paediatric bilateral implantation in improving spatial listening skills. The uncertainty arises because of three main factors. First, many studies reported null results or contradictory results. Second, the majority of studies used a within-subjects design in which the unilateral condition was confounded with unfamiliarity. Third, the published studies are at risk of several types of bias, and did not use statistical techniques to control for the effects of confounding variables and missing data.

Some between-subjects comparisons reported significantly better left-right discrimination skills in bilaterally-implanted children than unilaterally-implanted children (Beijen et al., 2007; Litovsky, Johnstone, Godar, Agrawal, et al., 2006). Other studies did not find a significant difference between the groups, despite using similar methods and testing some of the same children (Litovsky, Johnstone, & Godar, 2006). No study has demonstrated that the SRTs of bilaterally-implanted children are significantly lower than those of unilaterally-implanted children, when listening with the device(s) they use everyday (Litovsky, Johnstone, & Godar, 2006; Mok et al., 2009; Schafer & Thibodeau, 2006). An alternative measure of the binaural advantage for speech perception in noise is SRM (see Figure 3.3 on page 35). A single study reported that bilaterally-implanted children show significantly more SRM than unilaterally-implanted children, with noise ipsilateral to the first implant (Mok et al., 2007). The difference in SRM was small (less than 1 dB), and it was measured using a test in which children reported the presence, rather than the content, of target speech. The relationship between performance on this test and the ability to understand speech in noise is unknown. Other studies found that SRM did not differ significantly between bilaterally- and unilaterally-implanted children (Litovsky, Johnstone, & Godar, 2006; Mok et al., 2009). Thus, previous between-subjects comparisons do not provide consistent evidence that bilateral implantation for children is more effective than unilateral implantation in enabling spatial listening skills.

As well as comparing the amount of SRM shown by bilaterally- and unilaterally-implanted children, one can assess whether either group shows significant SRM (see section 3.3.2). Normally-hearing children show significant SRM with noise on either side of the head (Chapter 4; Garadat & Litovsky, 2007; Mok et al., 2007). Bilaterally- and unilaterally-implanted children have shown significant SRM with noise contralateral to their first implant (Litovsky, Johnstone, & Godar, 2006; Mok et al., 2007, 2009; Peters et al., 2007). Given this finding, one would expect bilaterally-implanted children to also show SRM with noise ipsilateral to their first implant, because they use an implant in both ears. However, neither bilaterally- nor unilaterally-implanted children have shown significant SRM with noise ipsilateral to their first implant (Litovsky, Johnstone, and Godar; Mok et al., 2007, 2009; Peters et al.). If bilateral implantation is effective in improving speech perception in noise, bilaterally-implanted children should, to a greater degree than unilaterally-implanted children, show SRM with noise ipsilateral to their first implant.

There is also uncertainty regarding the effectiveness of bilateral implantation in improving quality of life, an issue that is discussed in detail in Chapter 7. The uncertainty surrounding the evidence was reflected by the decision-making process of the National Institute for Health and Clinical Excellence (NICE), an independent organisation responsible for providing national guidance on promoting good health and preventing and treating ill health. In December 2007, NICE published provisional guidance recommending that severely-profoundly deaf children should have the option of receiving bilateral implants (NICE, 2007). Subsequent provisional guidance recommended unilateral implantation only (NICE, 2008a). In January 2009, the final policy was published and recommended bilateral implantation for children (NICE, 2009). The study described in this chapter was carried out to provide evidence about the effectiveness of bilateral implantation in improving children's spatial listening skills. The studies described in Chapter 7 provide evidence about the effectiveness of bilateral implantation in improving children's quality of life. Provisional results from these studies were submitted to NICE and are referred to in the final guidance.

5.1.1 Aims and hypotheses

This study compared the performance of bilaterally- and unilaterally-implanted children on tests of spatial listening. A nonrandomised cross-sectional design was used, which included an embedded comparison of outcomes from bilateral implantation in a single surgery with bilateral implantation in sequential surgeries. Variables which predict success with a unilateral implant were measured (see section 3.1.1); confounding differences between the bilateral and unilateral groups were controlled statistically. The performance of the bilaterally-implanted children was compared with that of the entire group of normally-hearing children whose results were described in Chapter 4. The results of the normally-hearing adults from Chapter 4 are shown for comparison, but were not included in statistical analyses.

It was predicted that bilaterally-implanted children would show better performance than unilaterally-implanted children on tests of left-right discrimination, localisation, movement tracking, and SRM with noise ipsilateral to the first implant. It was predicted that these differences would be maintained after imputation of missing data and statistical control of confounds. It was expected that bilaterally-implanted children would not perform as well as normally-hearing children. A search of the literature did not reveal any studies that compared the performance of simultaneous and sequential bilaterally-implanted children. Therefore, it was not known whether the performance of these two groups would differ.

In the UK, some unilaterally-implanted children use a contralateral acoustic hearing aid and some do not. For example, the Yorkshire Cochlear Implant Service provided 131 children with a unilateral implant between 2004 and 2008, inclusive. At the end of 2008, 61 of these children were using a contralateral acoustic hearing aid (S. Morgan, personal communication, February 19, 2010). Some children with little residual hearing are encouraged to use a hearing aid in the hope, rather than the expectation, that they will benefit. Consequently, the fact that a child uses a hearing aid does not guarantee that they are obtaining benefit from it. The sample of unilaterally-implanted children in this study included children who did, and children who did not, use a contralateral acoustic hearing aid. The performance of the two subgroups was compared, but the study was not designed to detect differences between these subgroups.

5.2 Method

5.2.1 Participants

Eligible participants were children aged 2 to 16 years without disabilities that precluded performance testing. They had a parental declaration of severe-profound deafness and had been using unilateral or bilateral cochlear implants for over six months. The participants used cochlear implants made by Advanced Bionics Corporation (Sylmar, USA), Cochlear Ltd. (Lane Cove, Australia), or Med-El GmbH (Innsbruck, Austria). The study was designed to detect differences of one standard deviation between unilaterally- and bilaterally-implanted children with 90% power at $p < .05$. The participants were sequential volunteers recruited via a charity and the UK National Health Service. Seventy-five eligible families with deaf children contacted the author. Eighteen families declined to take part (12 with a bilaterally-implanted child). Two children were excluded following testing because they fell asleep or did not sit still (both bilateral). Twenty unilaterally-implanted and 35 bilaterally-implanted children completed the study.

Table 5.1 contains biographical data for the children who completed the study.[1] Biographical data are also shown for the entire group of normally-hearing children. Nine of the unilaterally-implanted children used a contralateral acoustic hearing aid. Fifteen of the bilaterally-implanted children received their implants with under a month between surgeries (simultaneous bilaterals); 20 had over a month between

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[1] Lovett, Kitterick, Hewitt, and Summerfield (2010) presented the results of this experiment with 50 participants. Five extra participants were subsequently recruited to increase the power of the comparison of simultaneous and sequential bilaterally-implanted children. Consequently, this chapter and the published paper show slightly different results.

surgeries (sequential bilaterals). For implanted children, the term 'hearing age' refers to the length of time for which the child has used at least one implant. For normally-hearing children, hearing age is the same as chronological age. There is some evidence that, on measures of outcome such as receptive vocabulary, the performance of implanted children is, on average, appropriate for their hearing age rather than their chronological age (Fagan & Pisoni, 2010). In the present sample of children, the average hearing age was similar for unilaterally-implanted children, the entire group of bilaterally-implanted children, and normally-hearing children.

Approval was obtained from the North West Research Ethics Committee of the National Research Ethics Service. Parents gave written informed consent. The parents of participants received a reimbursement of the costs of travel and overnight accommodation (where necessary).

Table 5.1. Biographical data for the participants. For ages and durations, means and standard deviations (*SD*) are in years. Hearing age is time since first implantation for deaf children, and chronological age for normally-hearing children. Duration of deafness is time between diagnosis and first implantation. N/A: not applicable.

	Unilateral	Bilateral			Normally-hearing
		ALL	Simultaneous	Sequential	
Number of children	20	35	15	20	56
Chronological age, mean (*SD*)	7.20 (3.68)	6.83 (3.77)	4.90 (3.49)	8.28 (3.36)	4.52 (2.02)
Hearing age, mean (*SD*)	3.90 (3.03)	3.96 (2.99)	1.69 (0.89)	5.66 (2.89)	4.52 (2.02)
Family income, mean (*SD*)	£59,000 (£29,600)	£58,500 (£28,600)	£58,300 (£32,200)	£58,700 (£26,300)	Data not gathered
Gender, *n* (%)					
Male	8 (40.0)	17 (48.6)	8 (53.3)	9 (45.0)	26 (46.4)
Female	12 (60.0)	18 (51.4)	7 (46.7)	11 (55.0)	30 (53.6)
Number of additional disabilities, *n* (%)					
None	18 (90.0)	28 (80.0)	13 (86.7)	15 (75.0)	56 (100)
One or more	2 (10.0)	7 (20.0)	2 (13.3)	5 (25.0)	0 (0)
Age at diagnosis of deafness, mean (*SD*)	0.82 (1.00)	1.66 (2.58)	2.24 (3.32)	1.23 (1.82)	N/A
Duration of deafness at time of first implantation, mean (*SD*)	2.48 (2.07)	1.20 (1.03)	0.95 (0.92)	1.40 (1.09)	N/A
Duration of deafness at time of second implantation, mean (*SD*)	N/A	3.58 (3.57)	0.95 (0.92)	5.55 (3.55)	N/A

Table 5.1. (Continued). Biographical data for the participants. For ages and durations, means and standard deviations (*SD*) are in years. Hearing age is time since first implantation for deaf children, and chronological age for normally-hearing children. Duration of deafness is time between diagnosis and first implantation. N/A: not applicable.

	Unilateral	Bilateral			Normally-hearing
		ALL	Simultaneous	Sequential	
Experience with current device(s), mean (*SD*)	3.76 (3.08)	1.59 (0.93)	1.71 (0.88)	1.51 (0.97)	N/A

5.2.2 Listening tests

The listening tests were identical to those described in section 4.2.2, with the following exceptions. During pilot testing, children with cochlear implants reported that the level of the speech was too low in the Toy Discrimination test in pulsatile noise. Accordingly, the level of the speech for this test was increased to 51 dB (A) SPL (5 dB more intense than for normally-hearing children). For the Toy Discrimination test in pink noise, two participants (in the main study rather than the pilot study) could not identify the speech stimuli at the most advantageous signal-to-noise ratio in the adaptive routine (+26 dB). For these two children, the level of the speech was increased from 50 dB(A) SPL to 60 dB(A) SPL. The increased level of the speech was taken into account when calculating SRTs. Due to time constraints, the deaf children did not undertake the 15° separation condition of the Toy Localisation test, nor did they undertake the 15° separation condition with distractors. The deaf children attempted an additional test of sentence perception in quiet (see following section for details).

5.2.2.1 Bamford-Kowal-Bench Sentences

Bamford-Kowal-Bench (BKB) sentences were used to assess children's ability to understand speech in quiet conditions (Bench, Kowal, & Bamford, 1979). There are 20 lists, each containing 16 sentences, with 50 keywords per list. The sentences were spoken by a male talker and presented at 70 dB (A) SPL. Children were asked to repeat the sentence. The child's responses were scored using a loose keyword method in which the root of the keyword had to be correct but other details, such as the inflexion or precise word ending, did not need to be correct. The dependent variable was the percentage of correct keywords.

For children with two devices (either two implants or an implant and a hearing aid) there were three conditions of the BKB Sentence test: 1) both of the child's devices were switched on; 2) only the device on the left ear was switched on; and 3) only the device on the right ear was switched on. Bilaterally-implanted children attempted the three conditions in an order counterbalanced across participants. Bimodally-aided children attempted the binaural and implant-only conditions first, in an order counterbalanced across participants, and then attempted the hearing-aid-only condition. This order of conditions was chosen for the bimodally-aided children because, during pilot testing, several children were unwilling to listen with only their hearing aid. Children attempted one list of sentences per condition; the list for each condition was selected at random and not repeated for that child. Children who used a unilateral implant without a hearing aid completed a single list of sentences.

5.2.3 Procedure

The protocol was the same as for normally-hearing children (described in section 4.2.3), with the following modifications. Testing took place in a single session lasting up to three hours, with the exception of one child who attended two sessions. Regardless of their age, the children attempted the 60° separation condition of the Toy Localisation test, followed by the 30° separation condition. (The normally-hearing children did not attempt the 60° separation condition unless they were under the age of 5 years.) Some older children completed two repetitions of the conditions of the Toy Discrimination test; their mean SRTs are reported. The BKB sentences were attempted at the end of the test session. For all tests except the BKB sentences, children listened with the device(s) and settings that they used everyday. To gather biographical information about the child, parents completed a questionnaire about the child's date of birth, age at diagnosis of deafness, age at implantation, and disabilities in addition to deafness. Parents also estimated the annual family income.

5.2.4 Analyses

5.2.4.1 Calculation of spatial release from masking

For the remainder of this chapter, 'device' refers to either an implant or a hearing aid. The child's 'first device' was defined as the only implant (for unilaterals), the first implant (for sequential bilaterals), or randomly assigned to be the left or right implant (for simultaneous bilaterals). The child's 'second device' was therefore a hearing aid or no device (for unilaterals), the second implant (for sequential bilaterals), or the implant contralateral to the first device (for simultaneous bilaterals).

SRM was calculated by subtracting the SRT with noise at the side from the SRT with noise at the front, giving two measures of SRM: with noise ipsilateral, and contralateral, to the first device. A positive score indicates that the child could tolerate more noise in the condition with noise at the side. For normally-hearing children and adults, a single measure of SRM was calculated: the mean of the SRM with noise on the left and the SRM with noise on the right.

5.2.4.2 Setting age limits for tests

Older children completed more tests (the same tendency was observed with normally-hearing children in Chapter 4). Some analyses involved the imputation of data that were missing because children did not complete all of the outcome measures (Donders et al., 2006). If imputation had been carried out on the entire data set, there would have been a large amount of imputed data for the young children. Accordingly, a *post-hoc* age limit was defined for each test. The sample of deaf children was split into 12-month age bands starting from 24 months. For each test, the age limit was defined as the lower edge of the first band in which over 50% of deaf children provided data. For the Left-Right Discrimination and Movement Tracking tests, the limit was the same as the age of the youngest children in the study (24 months). For the 60° separation condition of the Toy Localisation test the limit was 48 months; for the 30° separation condition it was 72 months. For the Toy Discrimination test the limit was 36 months. For the sake of consistency, children younger than these limits who *did* provide data were excluded from all analyses of that test. For the 60° separation condition of the Toy Localisation test, two children were excluded (one was bilateral). For the 30° separation condition of the Toy Localisation test, five children were excluded (all were bilateral). For the Toy Discrimination test, no children were excluded. The BKB Sentence test was not subjected to imputation of missing data, so no age limit was set and no children were excluded. The age limits were also applied to the data from normally-hearing children that are presented in this chapter.

5.2.4.3 Presentation of results

With the exception of the measures of SRM, the outcome measures did not distribute normally. The primary aim of the study was to compare unilaterally- and bilaterally-implanted children. Box plots, scatterplots, and tables of medians were used to summarise the performance of these two groups; the results from the normally-hearing children and adults from Chapter 4 were included for comparison and to illustrate the upper limit of performance. Some children did not complete all of the tests, so numbers at the top of figures indicate how many children in each group contributed data. Tables of medians were used to summarise the performance of subgroups.

5.2.4.4 Statistical analyses

In this and subsequent chapters, statistics were computed using SPSS 17.0 for Windows. The aim of the statistical analyses was to assess:

1. Whether the performance of the bilaterally-implanted group was different to that of the unilaterally-implanted group.
2. Whether the performance of the normally-hearing group was different to that of the bilaterally-implanted group.
3. Whether the bilaterally-implanted group and/or the unilaterally-implanted group showed SRM and a difference in SRT between the Same-F0 and Raised-F0 conditions of the Toy Discrimination test.
4. Whether statistically-significant differences between the bilateral and unilateral groups were maintained following imputation of missing data and statistical control of confounds.

5. Whether biographical variables were related to the performance of unilaterally- or bilaterally-implanted children.

6. Whether the performance of simultaneous bilaterally-implanted children was different to that of sequential bilaterally-implanted children.

7. Whether the performance of unilaterally-implanted children who used an acoustic hearing aid was different to that of unilaterally-implanted children who did not use an acoustic hearing aid.

5.2.4.4.1 Comparing children with a unilateral implant, bilateral implants, or normal hearing Mann-Whitney tests with a Bonferroni correction were used to compare the performance of the unilateral and bilateral groups, and the bilateral and normally-hearing groups. Effect sizes for Mann-Whitney tests were calculated using the formula in section 4.2.5.2. Children were excluded from analyses of outcome measures for which their data were missing.

5.2.4.4.2 Within-subjects comparisons of implanted children Wilcoxon signed-rank tests with a Bonferroni correction were used to assess whether the groups showed SRM and a difference in SRT between the Same-F0 and Raised-F0 conditions of the Toy Discrimination test. Wilcoxon signed-rank tests with a Bonferroni correction were used to assess whether there was an effect of condition on bilaterally-implanted children's performance on the BKB Sentence test. Unilaterally-implanted children did not provide enough data on the BKB Sentence test to make statistical comparisons between conditions. Children were excluded from analyses of outcome measures for which their data were missing. Effect sizes for Wilcoxon tests were calculated using the formula $r = z/\sqrt{N}$ where z is the standardised test statistic and N is the number of observations.

5.2.4.4.3 Analyses to control for missing data and confounds Missing data were imputed as the median of the other group (either unilateral or bilateral). An alternative method of imputation is to predict, based on a subject's known characteristics, what their score on the missing variable might have been. Analyses can then be repeated several times with different imputed values. This technique of multiple imputation may give a more accurate estimate of the effect size than imputation using the median (Donders et al., 2006). Multiple imputation was not used in the present study because reliable predictors of which data were likely to be missing could not be identified (C. Hewitt, personal communication, August 26, 2009). Following imputation, multiple linear regression analyses were carried out to control the influence of confounds. Two measures which met the assumptions of linear regression (Bland, 2000) were analysed: 1) a composite localisation score, calculated as the mean of the scores for both conditions of Left-Right Discrimination, the 60° separation condition of Toy Localisation, and Movement Tracking; 2) SRM with noise ipsilateral to the first device. For the calculation of the composite localisation score, the Toy Localisation test was re-scored to yield the percentage of correct responses. The lower age limit for the 60° separation condition of the Toy Localisation test was 48 months; accordingly, the analysis of the composite localisation score only included children above this age. Likewise, the analysis of SRM only included children aged 36 months and above.

The number of variables in each regression model was limited to four by the sample size (Bland, 2000). The following variables were included in each model: group (unilateral or bilateral), number of additional disabilities, age at diagnosis of deafness, and duration of deafness at time of first implantation. The choice of variables was informed by differences observed between the groups (see Table 5.1), and by previous research that demonstrated a relationship between these variables and outcome (Stacey et al., 2006; Zeitler et al., 2008). The number of additional disabilities had a skewed distribution, so it was transformed to a dichotomous variable with the categories 'none' and 'more than one.'

5.2.4.4.4 Analyses of the relationship between biographical variables and outcome Kendall's rank-order correlation coefficients (tau) were used to assess whether the biographical variables in Table 5.1 were related to the listening skills of unilaterally- or bilaterally-implanted children. The measures of outcome were the ±30° condition of the Left-Right Discrimination test and SRM with noise ipsilateral to the first device. These measures were chosen because they led to a range of performance and few children had missing data. Children were excluded from analyses of outcome measures for which their data were missing.

5.2.4.4.5 Subgroup analyses The performance of the simultaneous and sequential bilaterally-implanted children was compared using Mann-Whitney tests, as was the performance of unilaterally-implanted children who did or did not use a hearing aid. Children were excluded from analyses of outcome measures for which their data were missing. If fewer than five children in a subgroup provided data on a test, that test was excluded from the subgroup tables and statistical analyses.

5.3 Results

5.3.1 Comparing children with a unilateral implant, bilateral implants, or normal hearing

5.3.1.1 Left-Right Discrimination test

The results of the Left-Right Discrimination test are shown in Figure 5.1. The bilaterally-implanted children had higher scores than the unilaterally-implanted children on the ±60° condition [$z = -3.68$, $p_{bf} < .01$, $r = .50$] and the ±30° condition [$z = -3.25$, $p_{bf} < .01$, $r = .46$]. There was no significant difference between the normally-hearing and bilaterally-implanted children on the ±60° condition [$z = -2.21$, $p_{bf} > .05$, $r = .23$]. The normally-hearing children had higher scores than the bilaterally-implanted children on the ±30° condition [$z = -4.26$, $p_{bf} < .01$, $r = .45$].

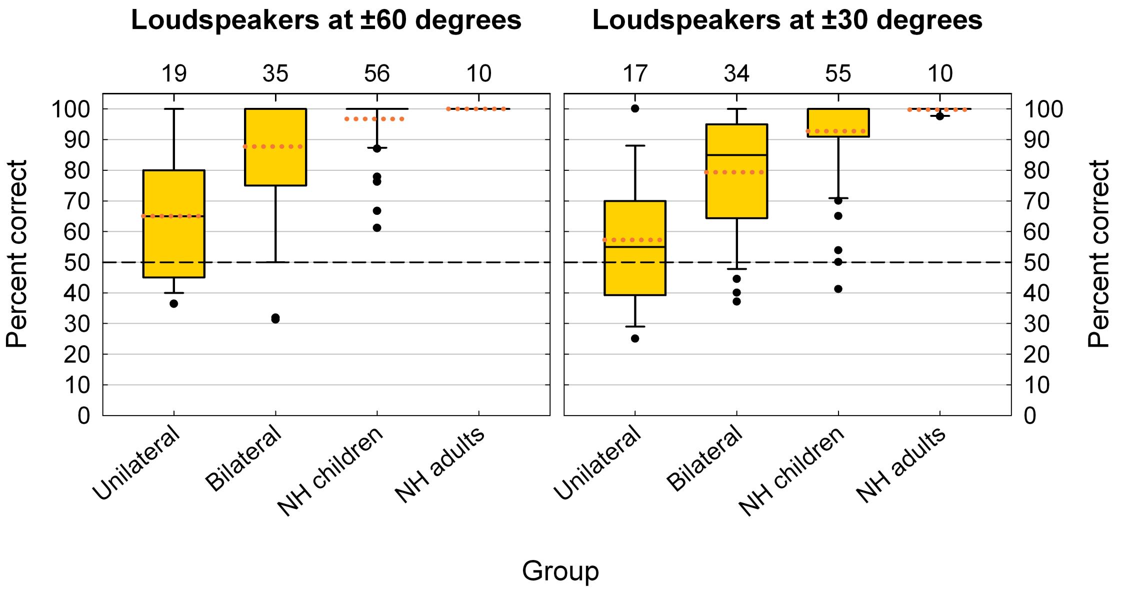

Figure 5.1. Results of the Left-Right Discrimination test: ±60° condition (left panel) and ±30° condition (right panel). The yellow boxes show the area between the 25th and 75th percentiles for unilaterally-implanted children, bilaterally-implanted children, normally-hearing (NH) children, and normally-hearing adults. The solid black horizontal lines within the boxes show the median; the dotted orange lines show the mean. Where the median line is not visible, the median is 100%. The whiskers show the 10th and 90th percentiles, scores outside this range are plotted as black circles. The dashed black line shows the level of performance expected by chance. The numbers above the upper horizontal axis indicate how many participants in each group provided data.

5.3.1.2 Toy Localisation test

The results of the Toy Localisation test are shown in Figure 5.2. The bilaterally-implanted children had lower error scores than the unilaterally-implanted children on the 60° separation condition [$z = -2.84$, $p_{bf} < .01$, $r = .47$] and the 30° separation condition [$z = -3.30$, $p_{bf} < .01$, $r = .61$]. The normally-hearing children had lower error scores than the bilaterally-implanted children on the 60° separation condition [$z = -2.86$, $p_{bf} < .01$, $r = .55$] and the 30° separation condition [$z = -4.60$, $p_{bf} < .01$, $r = .81$].

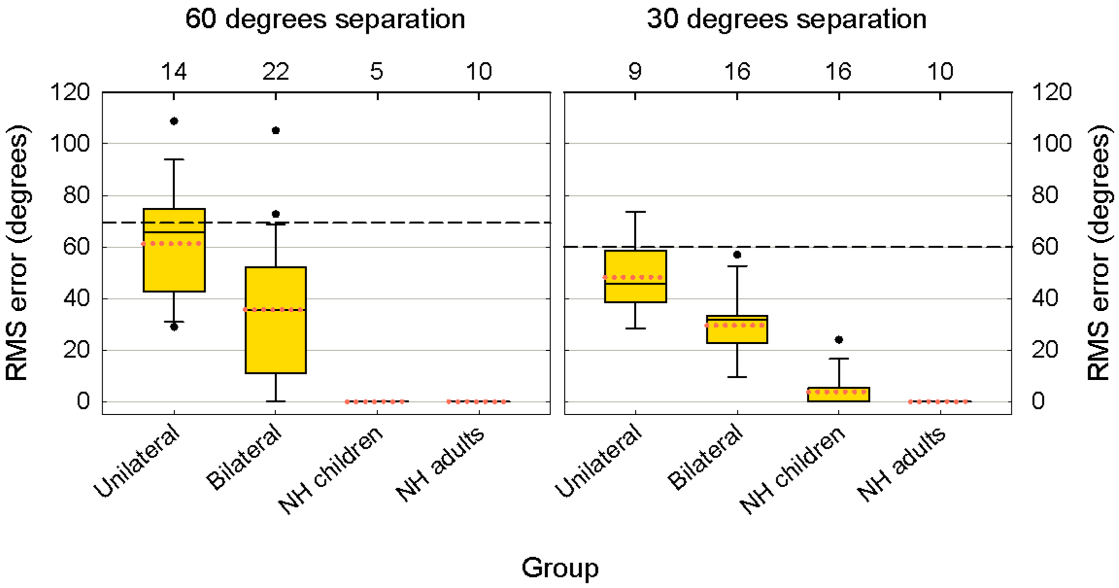

Figure 5.2. Results of the Toy Localisation test: three-alternative task with 60° separation between loudspeakers (left panel) and five-alternative task with 30° separation (right panel). The yellow boxes show the area between the 25th and 75th percentiles for unilaterally-implanted children, bilaterally-implanted children, normally-hearing (NH) children, and normally-hearing adults. The solid black horizontal lines within the boxes show the median; the dotted orange lines show the mean. Where the median line is not visible, the median is 0°. The whiskers show the 10th and 90th percentiles, scores outside this range are plotted as black circles. The dashed black line shows the level of performance expected by chance. The numbers above the upper horizontal axis indicate how many participants in each group provided data.

5.3.1.3 Movement Tracking test

The results of the Movement Tracking test are shown in Figure 5.3. The bilaterally-implanted children had higher scores than the unilaterally-implanted children [$z = -3.33$, $p_{bf} < .01$, $r = .45$]. The normally-hearing children had higher scores than the bilaterally-implanted children [$z = -5.32$, $p_{bf} < .01$, $r = .56$].

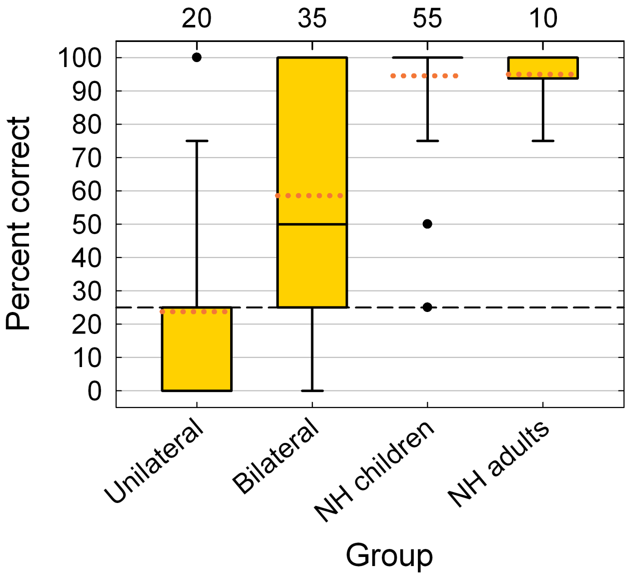

Figure 5.3. Results of the Movement Tracking test. The yellow boxes show the area between the 25th and 75th percentiles for unilaterally-implanted children, bilaterally-implanted children, normally-hearing (NH) children, and normally-hearing adults. The solid black horizontal lines within the boxes show the median; the dotted orange lines show the mean. Where the median line is not visible, the median is on the upper edge of the yellow box. The whiskers show the 10th and 90th percentiles, scores outside this range are plotted as black circles. The dashed black line shows the level of performance expected by chance. The numbers above the upper horizontal axis indicate how many participants in each group provided data.

5.3.1.4 Toy Discrimination test

The results of the Toy Discrimination test for participants who used 14 toys are shown in Table 5.2. The bilaterally-implanted children had lower SRTs than the unilaterally-implanted children in the condition with noise ipsilateral to the first device [$z = -3.77$, $p_{bf} < .01$, $r = .69$]. In the other conditions, the SRTs of the bilaterally- and unilaterally-implanted children did not differ significantly [all $p_{bf} > .05$]. The normally-hearing children had lower SRTs than the bilaterally-implanted children on all conditions [all $p_{bf} < .01$]. Nine deaf children completed the Toy Discrimination test using 10 toys and an additional seven deaf children used 4 toys. Due to the small numbers of children, the SRTs from these data are not shown and were not included in these statistical comparisons.

Table 5.2. Results of the Toy Discrimination test for participants who used 14 toys. Noise front, Noise ipsi., and Noise contra. refer to conditions with noise from the front, from the side ipsilateral to the first device, and from the side contralateral to the first device. The 25th percentile (25th), 50th percentile (Median), 75th percentile (75th), and the number of participants contributing data (*N*) are listed for each group. The scores for the Quiet condition are in dB (A) SPL; the scores for all other conditions are a signal-to-noise ratio in dB. For normally-hearing children and adults, the rows for Noise ipsi. and Noise contra. both show the mean of SRTs with noise on the left and SRTs with noise on the right.

	Unilateral				Bilateral				Normally-hearing children				Normally-hearing adults			
	25th	Median	75th	*N*	25th	Median	75th	*N*	25th	Median	75th	*N*	25th	Median	75th	*N*
Noise front	−0.40	+0.60	+4.35	11	−1.40	+0.10	+2.10	19	−4.65	−3.90	−2.90	35	−8.65	−7.15	−5.65	10
Noise ipsi.	+2.08	+4.83	+7.83	11	−4.17	−2.14	−0.14	19	−10.9	−9.66	−6.66	35	−15.2	−11.9	−11.0	10
Noise contra.	−4.64	−3.48	−0.54	12	−7.67	−5.17	−2.64	19	−10.9	−9.66	−6.66	35	−15.2	−11.9	−11.0	10
Quiet	+30.5	+34.7	+39.6	8	+30.3	+32.2	+33.4	18	+15.9	+19.4	+22.2	33	+10.7	+12.7	+14.2	10
Same-F0	−3.63	+1.37[a]	+3.24	8	−2.63	+1.37[a]	+3.87	15	−9.44	−5.63	−3.88	26	−14.6	−11.4	−9.9	10
Raised-F0	−5.36	−2.07[a]	+3.30	8	−8.07	−2.07[a]	+0.43	15	−16.1	−14.1	−11.1	26	−21.5	−20.6	−19.9	10

[a] The median scores were identical for the unilateral and bilateral groups in the Same-F0 and Raised-F0 conditions. Figure 5.5 plots the median difference between these conditions, which was not identical for the unilateral and bilateral groups.

5.3.1.5 Spatial release from masking

The amount of SRM shown by the participants is plotted in Figure 5.4 (including data from children who used 4, 10, or 14 toys). With noise ipsilateral to the first device, the bilaterally-implanted children showed more SRM than the unilaterally-implanted children [$z = -2.84$, $p_{bf} < .01$, $r = .43$] but less SRM than the normally-hearing children [$z = -2.53$, $p_{bf} < .05$, $r = .31$]. With noise contralateral to the first device, the amount of SRM shown by the bilaterally-implanted children was similar to that shown by the unilaterally-implanted children [$z = -1.71$, $p_{bf} > .05$, $r = .26$] and the normally-hearing children [$z = -0.78$, $p_{bf} > .05$, $r = .10$].

Within-subjects comparisons SRM is significant if SRTs are significantly lower in the condition with noise from the side than the condition with noise from the front. On average, the bilaterally-implanted children showed significant SRM with noise ipsilateral to the first device [$z = -3.34$, $p_{bf} < .01$, $r = .45$] and with noise contralateral to the first device [$z = -3.99$, $p_{bf} < .01$, $r = .54$]. On average, the unilaterally-implanted children did not show significant SRM with noise ipsilateral to the first device [$z = -0.98$, $p_{bf} > .05$, $r = .17$]. On average, the unilaterally-implanted children did show significant SRM with noise contralateral to the first device [$z = -3.41$, $p_{bf} < .01$, $r = .62$].

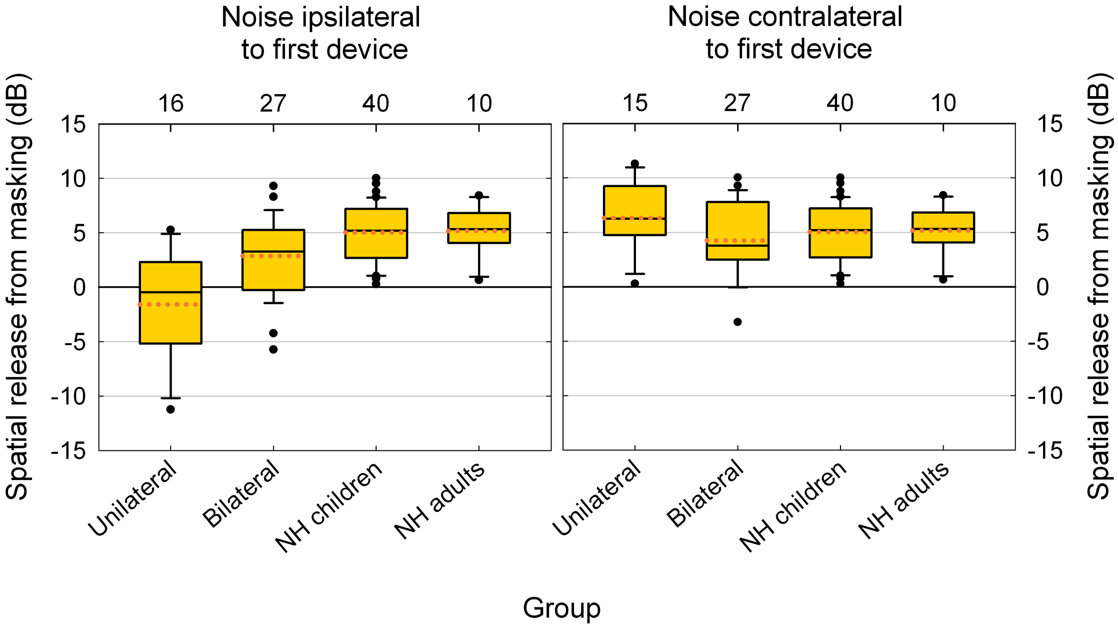

Figure 5.4. The amount of SRM shown by unilaterally-implanted children, bilaterally-implanted children, normally-hearing (NH) children, and normally-hearing adults. Left panel: with noise ipsilateral to the first device. Right panel: with noise contralateral to the first device. For participants with normal hearing, the mean SRM is plotted. The yellow boxes show the area between the 25th and 75th percentiles. The solid black horizontal lines within the boxes show the median; the dotted orange lines show the mean. The whiskers show the 10th and 90th percentiles, scores outside this range are plotted as black circles. The numbers above the upper horizontal axis indicate how many participants in each group provided data.

5.3.1.6 Toy Discrimination test in pulsatile noise

The results of the Toy Discrimination test in pulsatile noise are shown in Table 5.2 and are plotted in Figure 5.5 as the difference in SRT between the Same-F0 and Raised-F0 conditions. A positive score in Figure 5.5 indicates lower SRTs in the Raised-F0 condition than in the Same-F0 condition. On average, both groups of implanted children showed a positive difference score; the groups did not differ significantly [$z = -0.70$, $p_{bf} > .05$, $r = .14$]. The normally-hearing children had a greater difference score than the bilaterally-implanted children [$z = -2.37$, $p_{bf} < .05$, $r = .36$].

5.3.1.6.1 Within-subjects comparisons The bilaterally-implanted children showed significantly lower SRTs in the Raised-F0 condition than the Same-F0 condition [$z = -2.33$, $p_{bf} < .05$, $r = .43$]. The unilaterally-implanted children showed SRTs that did not differ significantly between the Raised-F0 condition and the Same-F0 condition [$z = -1.28$, $p_{bf} > .05$, $r = .29$].

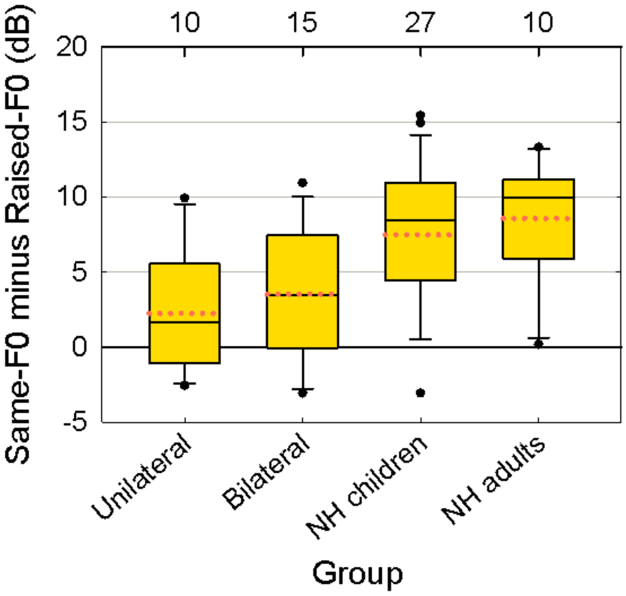

Figure 5.5. Results of the Toy Discrimination test in pulsatile noise for unilaterally-implanted children, bilaterally-implanted children, normally-hearing (NH) children, and normally-hearing adults. The difference in SRT between the Same-F0 and Raised-F0 conditions is plotted. The yellow boxes show the area between the 25th and 75th percentiles. The solid black horizontal lines within the boxes show the median; the dotted orange lines show the mean. The whiskers show the 10th and 90th percentiles, scores outside this range are plotted as black circles. The numbers above the upper horizontal axis indicate how many participants in each group provided data.

5.3.1.7 BKB Sentence test

The results of the BKB Sentence test are shown in Figure 5.6. When listening with the device(s) they used normally, the performance of the bilaterally- and unilaterally-implanted children did not differ significantly [$z = -1.40$, $p > .05$, $r = .28$]. There were insufficient data to make further between-subjects comparisons. For bilaterally-implanted children, scores obtained when listening with the first device were not significantly different to those obtained using both devices [$z = -1.99$, $p_{bf} > .05$, $r = .34$]. For bilaterally-implanted children, scores obtained when listening with the first device were higher than those obtained when listening with the second device [$z = -2.55$, $p_{bf} < .01$, $r = .45$].

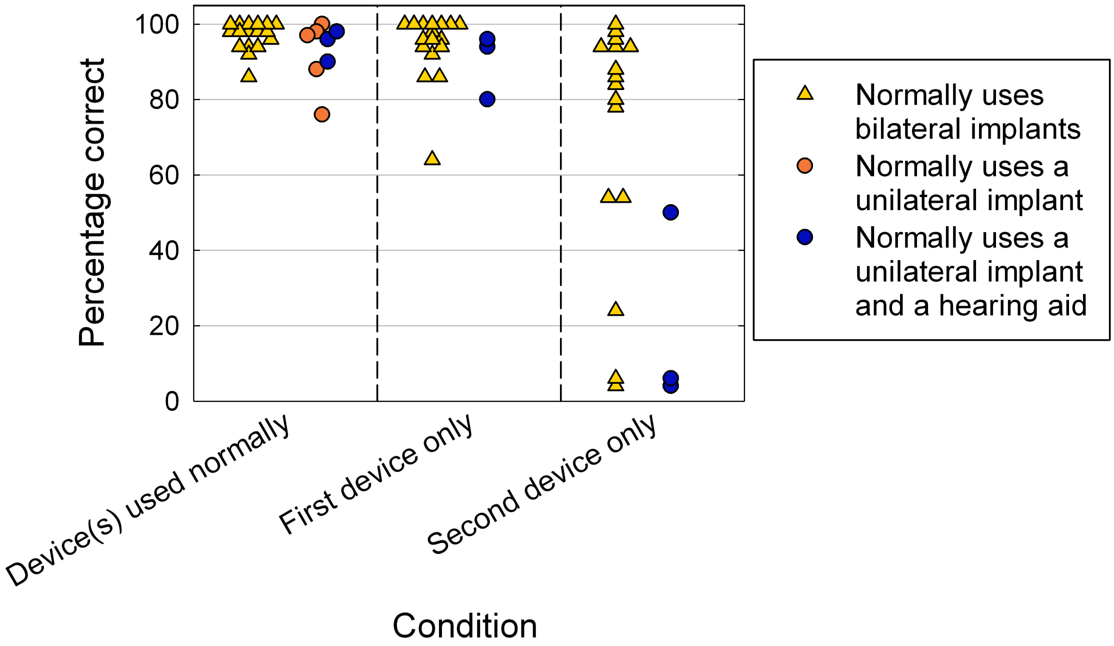

Figure 5.6. Scatterplot of the results of the BKB Sentence test. The percentage of keywords correct is plotted for three conditions: listening with the child's normal device(s) (left panel), listening with the first device only (centre panel), and listening with the second device only (right panel). The yellow triangles show scores from bilaterally-implanted children. The circles show scores from unilaterally-implanted children: those who normally use a hearing aid are shaded in blue, those who do not are shaded in orange. Within each panel, symbols are offset horizontally so that each child's score is visible.

5.3.2 Controlling for missing data and confounding variables

Forty deaf children were above the age limit for the composite localisation score: data were imputed for four children on one of the tests used to form the composite, and for one child on three of the tests. Accurate performance on the Left-Right Discrimination, Localisation, and Movement Tracking tests is represented by a high composite localisation score. The mean composite localisation score was 75.0% (95% confidence interval 66.9 to 83.1) for the bilateral group and 53.1% (95% confidence interval 44.7 to 61.6) for the unilateral group. Fifty deaf children were above the age limit for the measure of SRM with noise ipsilateral to the first device: data were imputed for seven children. The mean was +2.44 dB (95% confidence interval +1.20 to +3.69) for the bilateral group and −0.82 dB (95% confidence interval −3.06 to +1.42) for the unilateral group.

When the influence of covariates was held constant, bilateral implantation was associated with a significant increase of 20.3% in composite localisation score and a significant increase of 3.5 dB in SRM with noise ipsilateral to the first device

(Tables 5.3 and 5.4). The only statistically-significant covariate was the age at diagnosis of deafness: an increase of one month in age at diagnosis was associated with an increase of 0.3% in composite localisation score.

Table 5.3. Results of multiple linear regression with composite localisation score as the dependent variable. The value of R^2 for the model was .44 ($p < .001$). The unstandardised regression coefficient, B (with 95% confidence interval, c.i., in parentheses), and the standardised regression coefficient, β, are listed for each variable in the model.

	B (95% c.i.)	β
Constant	+50.3 (+29.5 to +71.1)	
Group (unilateral or bilateral)	+20.3 (+7.77 to +32.8)	+0.46**
Number of additional disabilities[a]	−4.11 (−18.9 to +10.6)	−0.07
Age at diagnosis of deafness (months)	+0.32 (+0.13 to + 0.51)	+0.44**
Duration of deafness at time of first implantation (months)	+0.11 (−0.19 to +0.41)	+0.10

** $p < .01$; [a] Dichotomous: none or more than one.

Table 5.4. Results of multiple linear regression: the dependent variable was SRM with noise ipsilateral to the first device. The value of R^2 for the model was .23 ($p < .05$). The unstandardised regression coefficient, B (with 95% confidence interval, c.i., in parentheses), and the standardised regression coefficient, β, are listed for each variable in the model.

	B (95% c.i.)	β
Constant	+2.70 (−1.50 to +6.90)	
Group (unilateral or bilateral)	+3.47 (+0.82 to +6.11)	+0.39*
Number of additional disabilities[a]	−2.01 (−5.04 to +1.02)	−0.18
Age at diagnosis of deafness (months)	−0.04 (−0.08 to + 0.01)	−0.23
Duration of deafness at time of first implantation (months)	−0.03 (−0.09 to +0.03)	−0.14

* $p < .05$; [a] Dichotomous: none or more than one.

5.3.3 The relationship between biographical variables and outcome

The correlations between biographical variables and two measures of spatial listening skill for unilaterally-implanted children are shown in Table 5.5. The only significant correlation indicated that children with a longer duration of deafness at first implantation tended to show better performance on the Left-Right Discrimination test. This result was unexpected, given previous demonstrations that a shorter duration of deafness is associated with better listening skills (see sections 3.1.1 and 3.7). An examination of the data from the present study indicated that the correlation was strongly influenced by two outliers.

The correlations between biographical variables and spatial listening skills for bilaterally-implanted children are shown in Table 5.6. The only significant correlation indicated that children with an older chronological age tended to show better performance on the Left-Right Discrimination test.

Table 5.5. Correlations between biographical variables and performance for unilaterally-implanted children. For the ±30° condition of the Left-Right Discrimination test ($N = 17$) and SRM with noise ipsilateral to the first device ($N = 16$), the Kendall's tau correlation coefficient and *p* value are listed. The statistically-significant correlation is emboldened. A positive correlation with gender indicates that girls tended to show better performance.

	Left-Right Discrimination		SRM noise ipsilateral	
	τ	p	τ	p
Chronological age	+.29	.11	−.16	.39
Hearing age	+.11	.56	+.08	.65
Family income	−.36	.06	+.01	.96
Gender	+.14	.50	−.17	.43
Number of additional disabilities	−.03	.88	−.36	.10
Age at diagnosis of deafness	+.15	.43	−.08	.68
Duration of deafness at first implantation	**+.46**	**.01**	−.35	.06
Experience with current device(s)	+.11	.56	−.02	.93

Table 5.6. Correlations between biographical variables and performance for bilaterally-implanted children. For the ±30° condition of the Left-Right Discrimination test ($N = 34$) and SRM with noise ipsilateral to the first device ($N = 27$), the Kendall's tau correlation coefficient and *p* value are listed. The statistically-significant correlation is emboldened. A positive correlation with gender indicates that girls tended to show better performance.

	Left-Right Discrimination		SRM noise ipsilateral	
	τ	p	τ	p
Chronological age	**+.34**	**.01**	−.15	.29
Hearing age	+.14	.27	−.06	.65
Family income	+.13	.33	−.05	.74
Gender	−.10	.52	−.30	.07
Number of additional disabilities	+.06	.67	−.14	.37
Age at diagnosis of deafness	+.22	.08	−.12	.40
Duration of deafness at first implantation	−.03	.83	−.09	.50
Duration of deafness at second implantation	+.09	.45	−.01	.97
Experience with both devices	−.01	.99	−.13	.34

5.3.4 Analyses of subgroups

The results of the listening tests for the simultaneous and sequential bilaterally-implanted children are shown in Table 5.7, along with the results of statistical comparisons of these two subgroups. The subgroups did not differ significantly on any of the listening tests. Seven simultaneous bilaterally-implanted children completed some conditions of the Toy Discrimination test; five of these children used fewer than 14 toys. Consequently, the SRTs for the Toy Discrimination test are not shown.

The results of the listening tests for the two subgroups of unilaterally-implanted children are shown in Table 5.8, along with the results of statistical comparisons of these subgroups. The subgroups did not differ significantly on any of the listening tests. Tests were omitted from Tables 5.7 and 5.8 if fewer than five children in a subgroup provided data.

Table 5.7. Results of the listening tests for the simultaneous and sequential bilaterally-implanted children. The second column shows the lower age limit. The 25th percentile (25th), 50th percentile (Median), 75th percentile (75th), and the number of participants contributing data (*N*) are listed for each group, alongside the standardised test statistic (*z*), *p* value, and effect size (*r*) resulting from a Mann-Whitney comparison of the groups. SRM noise ipsi. and SRM noise contra. refer to SRM with noise ipsi- or contra-lateral to the first device, respectively.

	Age limit	Simultaneous				Sequential				Mann-Whitney		
	(months)	25th	Median	75th	*N*	25th	Median	75th	*N*	*z*	*p*	*r*
Left-Right ±60°, percent correct	24	73.0	100.0	100.0	14	80.0	100.0	100.0	20	−1.01	.32	.17
Left-Right ±30°, percent correct	24	52.2	77.0	100.0	15	77.5	85.0	95.0	20	−0.79	.44	.13
Localisation 60° separation, RMS error	48	0.0	11.1	82.0	5	24.5	36.3	50.9	17	−0.43	.69	.09
Movement Tracking, percent correct	24	25.0	75.0	100.0	20	25.0	50.0	93.8	20	−0.76	.48	.13
SRM noise ipsi., dB	36	+1.00	+4.78	+8.28	7	−0.44	+2.50	+5.18	20	−1.44	.16	.28
SRM noise contra., dB	36	+2.50	+3.25	+8.78	7	+2.40	+4.26	+7.65	20	−0.03	.99	.01

Table 5.8. Results of the listening tests for two groups of unilaterally-implanted children: those who did, and those who did not, use a hearing aid. The second column shows the lower age limit for each test. The 25th percentile (25th), 50th percentile (Median), 75th percentile (75th), and the number of participants contributing data (*N*) are listed for each group, alongside the standardised test statistic (*z*), *p* value, and effect size (*r*) resulting from a Mann-Whitney comparison of the groups. Noise ipsi. and noise contra. refer to noise being presented ipsi- or contra-lateral to the child's implant, respectively. SRTs are shown only for participants who used 14 toys. SRM, and the difference between the Same-F0 and Raised-F0 conditions of the Toy Discrimination test in pulsatile noise, are shown for all participants.

	Age limit	Used a hearing aid				Did not use a hearing aid				Mann-Whitney		
	(months)	25th	Median	75th	*N*	25th	Median	75th	*N*	*z*	*p*	*r*
Left-Right ±60°, percent correct	24	55.0	75.0	97.5	9	40.0	52.5	72.5	10	−1.72	.09	.39
Left-Right ±30°, percent correct	24	38.5	70.0	85.0	7	38.9	52.5	62.5	10	−0.88	.40	.21
Localisation 60° separation, RMS error	48	32.9	63.9	77.5	7	49.0	67.5	74.1	7	−0.58	.62	.15
Movement Tracking, percent correct	24	0.00	0.00	50.0	9	0.00	25.0	25.0	11	−0.53	.62	.12
Toy Discrimination noise front, SRT (dB)	36	−1.52	−0.15	+3.04	6	+0.10	+3.10	+4.73	5	−1.19	.27	.36
Toy Discrimination, noise ipsi., SRT (dB)	36	+2.36	+6.33	+12.1	6	+1.97	+3.33	+5.20	5	−1.19	.27	.36
Toy Discrimination, noise contra., SRT (dB)	36	−4.64	−3.14	+0.36	7	−6.14	−4.14	−2.72	5	−1.30	.22	.38
SRM noise ipsi. (dB)	36	−9.73	−5.26	+1.75	7	−1.60	+0.28	+3.62	9	−1.85	.07	.46
SRM noise contra. (dB)	36	+1.78	+5.00	+6.25	7	+5.75	+7.71	+9.27	8	−1.74	.09	.45
Same-F0 minus Raised-F0 (dB)	36	−1.00	−0.06	+7.69	5	−1.81	+3.44	+4.69	5	−0.42	.74	.13

5.3.5 Summary

Bilaterally-implanted children performed significantly better than unilaterally-implanted children on tests of left-right discrimination, localisation, movement tracking, speech perception with noise ipsilateral to the first device, and SRM with noise ipsilateral to the first device. Significant differences between the bilaterally- and unilaterally-implanted children were maintained following imputation of missing data and control for confounds. The performance of the bilaterally- and unilaterally-implanted children was similar on the following tests:

1. SRM with noise contralateral to the first device.
2. BKB sentences in quiet when listening with their normal device(s).
3. The Toy Discrimination test in quiet, with pink noise from the front, with pink noise contralateral to the first device, and with pulsatile noise.

The normally-hearing children performed significantly better than the bilaterally-implanted children on all tests except Left-Right Discrimination with loudspeakers at ±60° and SRM with noise contralateral to the first device. The relationship between biographical variables and performance was weak for both bilaterally- and unilaterally-implanted children. The performance of the simultaneous and sequential bilaterally-implanted children did not differ significantly. The performance of the unilaterally-implanted children who used a hearing aid did not differ significantly from those who did not use a hearing aid.

5.4 Discussion

5.4.1 Summary of main findings

The bilaterally-implanted children displayed four important listening skills. On average, they distinguished sounds on the left from sounds on the right, they discriminated among three and five possible sound-source locations, they tracked moving sounds, and they displayed improved speech perception when a masking noise was moved from the front to either side of their head. On average, the unilaterally-implanted children performed more poorly, at levels that were often close to chance. Previous comparisons of unilaterally- and bilaterally-implanted children have not shown consistent differences in sound-source localisation skills (Beijen et al., 2007; Litovsky, Johnstone, Godar, Agrawal, et al., 2006; Litovsky, Johnstone, & Godar, 2006), nor have they demonstrated that bilaterally-implanted children show lower SRTs and greater SRM than unilaterally-implanted children (Litovsky, Johnstone, & Godar, 2006; Mok et al., 2007, 2009; Peters et al., 2007; Schafer & Thibodeau, 2006). By recruiting a larger sample, this study found such differences.

The two groups of implanted children showed similar levels of performance on tests of speech perception in which the signal-to-noise ratio was the same at both ears (e.g. the Toy Discrimination test in quiet, the Toy Discrimination test with pink noise from the front, and the BKB Sentence test). Thus, in these situations, this sample of bilaterally-implanted children did not show a benefit from stimulation of the more-responsive auditory nerve and/or an electrical signal being delivered to both ears. Similar results were reported by Litovsky, Johnstone, and Godar (2006), Mok et al. (2009), and Schafer and Thibodeau (2006).

5.4.2 Risk of bias

The sources of bias that can affect nonrandomised studies were summarised in section 3.5. The present study is at risk of selection bias because it is nonrandomised. There were confounding differences between the groups: the bilateral group had an older age at diagnosis of deafness, a shorter duration of deafness, and a greater proportion of children with additional disabilities than the unilateral group. Following statistical control over these three confounding variables, significant differences in performance between the bilateral and unilateral groups were sustained on measures of sound-source localisation and SRM with noise ipsilateral to the first device. An additional confound was that the bilateral group had less experience with their current devices than the unilateral group. This confound was not controlled for, because the number of variables that could be included in the analysis was restricted by the sample size. However, less experience with the current device(s) is associated with poorer listening skills in both unilaterally- and bilaterally-implanted children (Litovsky, Johnstone, Godar, Agrawal, et al., 2006; Stacey et al., 2006; Steffens et al., 2007). Thus, the omission of the confound of experience from the analyses is likely to lead to an under-estimation, rather than an over-estimation, of the effectiveness of bilateral compared to unilateral implantation.

The median family income of both the unilateral and bilateral groups exceeded the national average of £30,000 (Office for National Statistics, 2008), which may limit the external validity of the study. Outcomes from implantation are positively associated with higher socioeconomic status (Stacey et al., 2006). Therefore, both groups of implanted children may have shown atypically positive outcomes. Nonetheless, the bilaterally-implanted children (and, by extension, the unilaterally-implanted children) performed worse than normally-hearing children with a similar average hearing age, showing that bilateral implantation had not restored normal listening skills in this sample of children.

The study is at risk of bias because some children did not complete all of the outcome measures. Following the imputation of missing data, significant differences in performance between the bilateral and unilateral groups were sustained on measures of sound-source localisation and SRM with noise ipsilateral to the first device. The method of imputation was deliberately conservative and may therefore underestimate the effectiveness of bilateral implantation.

The study is at risk of detection bias because the experimenter was not blind to whether the child had unilateral or bilateral implants. However, the tests were designed to reduce detection bias. During the Left-Right Discrimination test, the experimenter was blind to the correct answer and listened to music via headphones to mask the acoustical stimuli. For the remaining tests, the child made responses that could be scored relatively objectively (e.g. picking up a toy). To avoid reporting bias, this chapter reports all of the outcome measures that were attempted by the children. To summarise, the design, data analysis, and reporting of the study aimed to minimise bias.

5.4.3 Effectiveness compared to efficacy

This study assessed the effectiveness of bilateral implantation for children when care is provided by a number of programmes run by the UK National Health Service. The study did not aim to assess efficacy, meaning the benefit of an intervention under optimal conditions (Gartlehner et al., 2006). Children's devices were not adjusted prior to testing, despite demonstrations that fine-tuning the gain on both devices can improve the localisation performance of bilaterally-implanted adults and bimodally-aided children (Tyler, Noble, Dunn, & Witt, 2006 and Ching et al., 2001, respectively). Moreover, the unilateral group may have performed better if all children had been fitted with a contralateral acoustic hearing aid.

To assess the degree to which the participants of the present study showed sub-optimal performance, the results can be compared with published studies of efficacy. Unfortunately, previous studies of bilaterally-implanted children used outcome measures that were not comparable to those in the present study (see Chapter 3). Ching, Hill, et al. (2005) tested 18 bimodally-aided children using a five-alternative localisation task. The stimulus was pink noise. After the loudness and frequency response of the two devices had been adjusted, children's median RMS error was 49° (25th percentile 37°, 75th percentile 54°). The present study used a similar test and obtained data from nine unilaterally-implanted children, four of whom used a contralateral acoustic hearing aid. The group's median RMS error was 46° (25th percentile 38°, 75th percentile 59°). Thus, on average, the unilaterally-implanted children in the present study showed localisation skills that were similar to those of bimodally-aided children tested under optimal conditions.

5.4.4 The results of within-subjects comparisons

5.4.4.1 Spatial release from masking

Bilaterally-implanted children showed significant SRM with noise on either side of the head. This novel finding provides evidence that, when listening to speech in noise, bilaterally-implanted children can attend to whichever ear has a better signal-to-noise ratio. This skill may help children to understand speech in a noisy environment such as a classroom. In contrast, unilaterally-implanted children showed significant SRM only when noise was contralateral to their implant.

5.4.4.2 Speech in pulsatile noise

The Toy Discrimination test in pulsatile noise measured whether children could tolerate a more adverse signal-to-noise ratio when there was a difference in F0 between speech and masker than when both speech and masker had the same F0. It was thought that bimodally-aided children may have shown such a difference, because acoustic hearing aids deliver an accurate representation of F0. However, the group of unilaterally-implanted children showed no significant difference between the Raised-F0 and Same-F0 conditions. The subgroup analysis indicated that bimodally-aided children did not show a greater difference between conditions than the unilaterally-implanted children who did not use a hearing aid (Table 5.8). Furthermore, an examination of the data provided no evidence that the bimodally-aided children who performed well on the sound-source localisation tasks (and were therefore presumably gaining benefit from the hearing aid) were more likely to show a difference between the Raised-F0 and Same-F0 conditions than the bimodally-aided children who showed poorer localisation skills. Nonetheless, it is possible that a greater difference between conditions would be shown by a sample of bimodally-aided children with more residual hearing. A test of this prediction, using a simulation of bimodal devices, is reported in Chapter 6.

Contrary to expectations, the bilaterally-implanted children were able to tolerate a significantly more adverse signal-to-noise ratio in the Raised-F0 condition than the Same-F0 condition. It is not clear why bilaterally-implanted children showed this difference between conditions. It is possible that the two maskers differed in the number of harmonics that fell within the passband of the filters in the children's cochlear-implant processors (see Figure 3.2 on page 24). Consequently, some electrodes may have delivered a signal that was masked less in the Raised-F0 condition than the Same-F0 condition (this idea is discussed in more detail in section 6.4.5.4). However, it is not clear why a difference in masking between conditions, after the signal had been processed, would lead to a difference in SRT between conditions for the bilaterally- but not the unilaterally-implanted children.

5.4.4.3 BKB Sentences in quiet

On the BKB Sentence test, the performance of bilaterally-implanted children when listening with both implants was similar to their performance when listening with only the first implant. In contrast, previous studies showed a significant advantage of using both implants for similar tests (Gordon & Papsin, 2009; Kim et al., 2009; Kühn-Inacker et al., 2004; Scherf et al., 2009b). There appears to have been a ceiling effect in the present study: of the 17 bilaterally-implanted children who completed the test using only the first implant, 11 children correctly reported over 90% of the keywords. Thus, a more demanding test may reveal an advantage of using both implants rather than just one.

The bilaterally-implanted children could perceive speech more accurately when listening with the first implant than when listening with the second implant. This difference may have arisen because, for some children, the second implantation occurred after a sensitive period in the development of the auditory nervous system (see section 3.7 and Graham et al., 2009). Alternatively, the difference between conditions may have arisen because the children had less listening experience with the second implant than with the first implant. In support of the first theory, children's scores with the second implant correlated with their age at second implantation (Kendall's $\tau = -.43$, $p < .05$) but not with their experience with the second implant (Kendall's $\tau = +.06$, $p > .05$). The unilaterally-implanted children did not provide sufficient data on this test to enable within-subject comparisons.

5.4.5 The relationship between biographical variables and outcome

For both unilaterally- and bilaterally-implanted children, there were only weak correlations between biographical variables and spatial listening skills when listening with their usual device(s). It is possible that significant correlations were not observed because the sample size in each group was limited. Studies of greater numbers of bilaterally-implanted children found that better performance on tests of spatial listening correlates with a shorter duration of deafness in both ears (Zeitler et al., 2008), a younger age at the first and second implantation (Scherf et al., 2009b; Steffens et al., 2007; Van Deun et al., 2010), and greater experience with both implants (Steffens et al., 2007).

5.4.6 Simultaneous versus sequential bilateral implantation

There was no significant difference between the performance of children who received bilateral implants in a single surgery and children who received bilateral implants in sequential surgeries. However, the simultaneous group had a considerably younger chronological age and hearing age, and less experience of using both devices, than the sequential group. These differences probably arose because simultaneous bilateral implantation is a relatively new intervention in the UK. Future work could compare outcomes for simultaneous and sequential bilaterally-implanted children with similar audiological histories. A younger age at the second implantation, and a shorter duration of deafness, is associated with better listening skills with bilateral implants (Steffens et al., 2007; Zeitler et al., 2008) and markers of normal development of the auditory nervous system (see section 3.7; Bauer et al., 2006; Gordon et al., 2007; Sharma et al., 2005). Consequently, it seems likely that simultaneous bilateral implantation, or sequential bilateral implantation with a short interval between surgeries, will result in better outcomes than sequential bilateral implantation with a long interval between surgeries.

5.4.7 Unilaterally-implanted children: the benefit of a contralateral acoustic hearing aid

There was no significant difference between the performance of bimodally-aided children and unilaterally-implanted children who did not use a hearing aid. A difference between these groups was expected, because bimodally-aided children show better spatial listening skills when using both devices than when using just their implant (Beijen et al., 2009; Ching et al., 2000, 2001; Ching, Hill, et al., 2005). It is possible that the confound of unfamiliarity, or other sources of bias, caused the difference between conditions in the within-subjects studies (see section 3.5). On the other hand, the present study was underpowered to detect a difference between unilaterally-implanted and bimodally-aided children, and a difference may be revealed by a larger study.

5.4.8 Conclusion

The present study demonstrates, more rigorously than previous studies, that bilateral implantation of severely-profoundly deaf children is associated with an improved ability to localise sources of sound and to perceive speech in noise.

5.5 Summary

- On average, bilaterally-implanted children performed better than unilaterally-implanted children on tests of left-right discrimination, localisation, movement tracking, and SRM with noise ipsilateral to the first implant.
- On measures of sound-source localisation and SRM with noise ipsilateral to the first device, significant differences between the bilateral and unilateral groups

were sustained following imputation of missing data and statistical control of confounds.

- Bilaterally-implanted children showed significant SRM with noise on either side of the head, whereas unilaterally-implanted children showed significant SRM only when noise was contralateral to their implant.
- The bilaterally- and unilaterally-implanted children showed similar levels of performance on speech-perception tests in which the signal-to-noise ratio was the same at both ears.
- On most tests, bilaterally-implanted children did not perform as well as normally-hearing children.
- There were no significant differences in listening skill between simultaneous and sequential bilaterally-implanted children. However, these groups differed in their audiological histories.

Chapter 6

Spatial Listening with Simulated Unilateral or Bilateral Cochlear Implants

This chapter reports a study in which normally-hearing adults attempted tests of spatial listening using simulations of a unilateral implant, a unilateral implant with contralateral acoustic hearing (bimodal devices), or bilateral implants. The simulation of bilateral implants yielded better performance than the other simulations on tests of sound-source localisation and SRM with noise ipsilateral to the simulated first device. These results mirror the superior performance of bilaterally- compared to unilaterally-implanted children on similar tests (Chapter 5). The concordance of the two studies provides evidence that the differences in listening skill observed between groups of children were primarily caused by a difference in the number of implants the children used, rather than by confounds. In simulation, bimodal devices resulted in better speech perception in noise than bilateral implants, but only when the former condition provided a greater degree of acoustic hearing than is likely to be observed in most cochlear-implant users.

6.1 Introduction

In Chapter 5, and in previous studies (see Chapter 3), it was inferred that differences in performance between unilaterally- and bilaterally-implanted children were caused by a difference in the number of implants the children used. This inference was supported by the statistical analyses reported in section 5.3.2, which controlled for some confounds. Nonetheless, it is possible that other confounds may have caused, or contributed to, the observed differences in performance. The current study measured the spatial listening skills of normally-hearing adults who listened to simulations of unilateral or bilateral cochlear implants. If the adults showed differences in performance between simulations that were similar to those observed between groups of implanted children, it would provide further evidence that the children's performance was primarily influenced by the number of implants they used rather than by confounds. A within-subjects design ensured that differences between the adult participants did not bias the results.

A second question of interest is whether some patients would be likely to show better outcomes with bimodal devices rather than bilateral implants. A simulation study allows one to parametrically vary the amount of acoustic hearing the participant can use, and removes the need to control for differences between participants. Furthermore, one can simulate bimodal listening with considerable hearing in the nonimplanted ear, to the extent that patients who heard so well using hearing aids may not have been eligible for implantation. Accordingly, the current study assessed whether simulations of bimodal devices with varying degrees of acoustic hearing yielded better performance than a simulation of bilateral implants.

A further aim was to compare absolute levels of performance between adults listening to simulated implants and the implanted children whose results were reported in Chapter 5. Interpreting the results of this comparison is not straightforward, because there are multiple differences between the participants and the simulations encompass only some aspects of listening with an implant. These issues are discussed in section 6.4.3. The following sections describe the signal processing that can be used to simulate a cochlear implant, and the additional processing required to simulate spatially-separated sources of sound.

6.1.1 Vocoder simulations

The signal processing carried out by a cochlear-implant system can be simulated using a noise vocoder (Figure 6.1; Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). The input signal is filtered into a limited number of channels and the amplitude envelope is extracted from those channels. The amplitude envelope is used to modulate a carrier signal (white noise in Figure 6.1). The signal is bandpass filtered a second time to restrict it to the original channel bandwidth, then the channels are combined. Thus, the temporal fine structure of the input signal is replaced by a carrier signal whose temporal fine structure is unrelated to the input signal. The extent to which a vocoder removes spectral detail depends upon the number of channels and their bandwidth, an issue that is discussed in the following section. Normally-hearing listeners report that noise-vocoded speech sounds like a harsh whisper. Vocoders simulate the signal processing carried out by a cochlear-implant system, but they do not replicate the effects of presenting stimuli via electrodes (such as the spread of current within the cochlea), partial survival of spiral ganglion cells, or abnormal processing in the auditory nervous system.

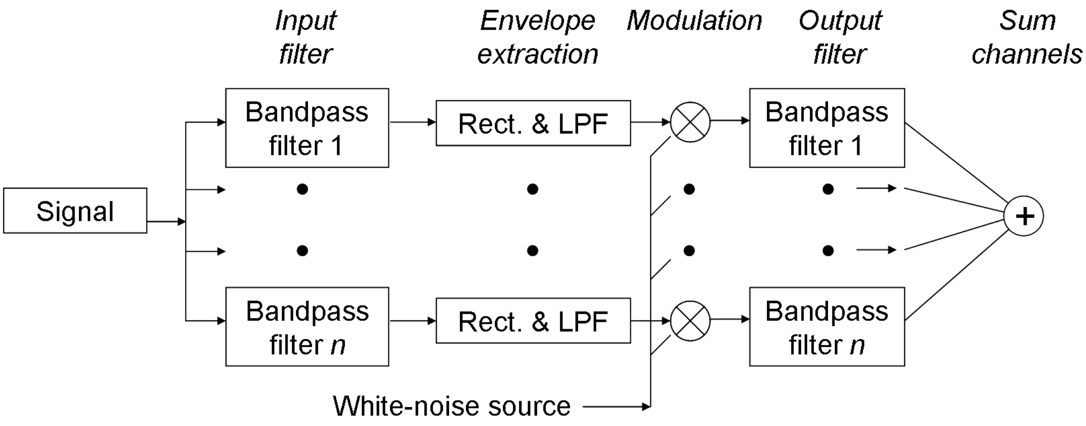

Figure 6.1. Stages of processing in a noise vocoder with *n* channels. The input signal is processed by *n* contiguous bandpass filters. The amplitude envelope is extracted using half-wave rectification and low-pass filtering (Rect. & LPF) and then used to modulate a source of white noise. The signal is bandpass filtered a second time to restrict it to the original channel bandwidth, then the channels are combined. Image adapted from Wilson et al. (2005).

6.1.1.1 The number of channels within a vocoder

A noise vocoder with only four channels allows normally-hearing adults to report 90% of the words in sentences presented in quiet (Shannon et al., 1995). However, a greater number of channels provides a higher degree of spectral resolution. Consequently, when listening to vocoded speech in noise, performance improves with an increasing number of channels (at least up to 20 channels; Dorman, Loizou, Fitzke, & Tu, 1998; Friesen et al., 2001). Modern cochlear implants have between 12 and 22 processing channels. The ability of implanted adults to perceive speech in noise improves as the number of channels is increased up to around seven, but the addition of further channels does not yield further improvements in performance (Fishman, Shannon, & Slattery, 1997; Friesen et al.). It is possible that patients do not benefit from additional channels because of the spread of current within the cochlea. Furthermore, the ability to use additional spectral information may be limited if there is a mismatch between the frequency range conveyed by a channel and the characteristic frequency of the cochlear location stimulated by that electrode (known as a frequency-to-place mismatch; Friesen et al.). With an eight-channel vocoder, the average performance of normally-hearing adults on a test of sentence perception in noise is similar to the performance of the best cochlear-implant users (Friesen et al.).

6.1.1.2 Noise versus tone vocoders

With a noise vocoder, fluctuations in the amplitude envelope of the noise source can introduce extraneous fluctuations in the amplitude envelope of the vocoded signal, which may create misleading phonetic cues (Whitmal, Poissant, Freyman, & Helfer, 2007). Accordingly, the present study used a tone vocoder in which the amplitude envelope from each channel was used to modulate a sine wave at the centre frequency of the channel (Dorman et al., 1998; Hopkins et al., 2008; Stone, Füllgrabe, & Moore, 2008).

6.1.1.3 Practice effects with vocoded stimuli

In order to simulate a frequency-to-place mismatch in the cochlea, a vocoder can be modified by setting the passbands of the output bandpass filters to a higher frequency range than the passbands of the input bandpass filters (see Figure 6.1; Rosen, Faulkner, & Wilkinson, 1999; Stacey & Summerfield, 2008). With this type of simulation, the ability of normally-hearing listeners to understand speech continues to improve after several hours of practice (Rosen et al.; Stacey and Summerfield). If the vocoder does not simulate a frequency-to-place mismatch (as was the case in the present study), normally-hearing listeners show high levels of performance after a short practice session, at least on tests of speech perception in quiet (M. H. Davis, Johnsrude, Hervais-Adelman, Taylor, & McGettigan, 2005; Friesen et al., 2001). Although M. H. Davis et al. and Friesen et al. did not specify the duration of the practice sessions, the descriptions imply that they were shorter than an hour.

To reduce the influence of short-term practice effects on the results of the present study, participants completed a familiarisation phase in each condition prior to data collection. M. H. Davis et al. (2005) compared two training procedures in which participants heard a sentence three times. In one condition, the order of presentation was vocoded, unprocessed, vocoded; in the other it was vocoded, vocoded, unprocessed. The first condition yielded higher levels of performance with novel sentences, and was therefore used in the current study.

6.1.2 Assessments of spatial listening skills with simulated cochlear implants

To measure spatial listening skills with simulated bilateral implants, one could present vocoded stimuli from an array of loudspeakers (Arbogast, Mason, & Kidd, 2002). This simulation preserves ITDs, whereas the signals delivered by bilateral implants do not represent ITDs in the temporal fine structure. An alternative is to use headphones to present stimuli that have been convolved with a head-related transfer function (HRTF). An HRTF can be derived from recordings made with microphones in the ears of a participant or a manikin. The function specifies the frequency- and direction-dependent effects of the pinna, head, and torso on the level and spectrum of a sound on arrival at each ear. When nonvocoded stimuli are convolved with an HRTF and presented binaurally over headphones, normally-hearing listeners typically perceive a source of sound located outside the head (Plenge, 1974; Wenzel, Arruda, Kistler, & Wightman, 1993). Following processing with an HRTF, stimuli can be vocoded and presented either monaurally or binaurally to create simulations of unilateral or bilateral implants, respectively. To create a simulation of bimodal devices, stimuli are convolved with an HRTF, then the signal to one ear is vocoded and the signal to the other ear is low-pass filtered (to simulate low-frequency residual hearing). The following sections review studies that measured the spatial listening skills of normally-hearing adults using simulations of bilateral implants or bimodal devices. A search of the literature did not reveal studies of spatial listening that used a simulation of a unilateral implant without contralateral acoustic hearing.

6.1.2.1 Spatial listening skills with simulated bilateral implants

6.1.2.1.1 Sound-source localisation A thesis by Moy (2004) described a study in which stimuli were processed using an HRTF followed by an eight-channel noise vocoder. Three listeners attempted a seven-alternative localisation task with virtual locations between −90° and +90°. The stimulus was a sentence presented at a constant level. The mean RMS error was 23° for the vocoded stimuli, compared to 12° for nonvocoded stimuli. A cross-correlation analysis confirmed that the vocoded stimuli did not convey ITDs in the temporal fine structure, which may explain the deficit in performance relative to nonvocoded stimuli.

6.1.2.1.2 Spatial release from masking Garadat, Litovsky, Yu, and Zeng (2009) processed stimuli using an HRTF followed by a tone vocoder with 4, 8, or 16 channels. Participants completed a closed-set word-identification task in which target speech and masking speech were spoken by different male talkers. SRM was calculated as the difference in performance between two conditions: 1) both target and masker were presented from a virtual location of 0°; 2) the target was presented from a virtual location of 0° and the masker from a virtual location 90° to one side. The greatest benefit of spatial separation was observed in the eight-channel condition, in which participants showed 8 dB of SRM, on average. Moy (2004) reported 3 to 5 dB of SRM, using a sentence-perception task in steady-state noise. These studies demonstrate a benefit of SRM when vocoded stimuli are presented binaurally, even when the percept of spatial separation is created by an HRTF rather than the listener's own head and torso.

6.1.2.2 Spatial listening skills with simulated bimodal devices

6.1.2.2.1 Sound-source localisation Francart, Bogaert, Moonen, and Wouters (2009) processed stimuli using an HRTF, then created a simulation of bimodal devices. The signal presented to the left ear was processed using an eight-channel noise vocoder, and the signal to the right ear was low-pass filtered at 500 Hz. Participants attempted a 13-alternative localisation task with virtual locations between −90° and

+90°. The stimulus was white noise and the presentation level was roved by ±6 dB. The average RMS error was 48°, a score which decreased to 34° when the ILDs were artificially increased. A cross-correlation analysis confirmed that the processed stimuli did not convey ITDs in the temporal fine structure. Accordingly, the limited localisation skills with simulated bimodal devices must have been based on ITDs in the envelope, ILDs (although these were reduced by the low-pass filter), and/or monaural level or spectral cues.

6.1.2.2.2 Speech perception in noise A search of the literature did not reveal any assessments of SRM with simulated bimodal devices, but several studies have measured the ability to perceive speech in the presence of noise from the same spatial location. The aim of many studies was to identify the acoustic or phonetic cues that enable unilaterally-implanted patients to benefit from using a contralateral acoustic hearing aid, even when the patient is unable to understand speech using just the hearing aid (see section 3.3.2 and Kong et al., 2005). The difference in performance between using both devices and using just the implant will be referred to as the bimodal benefit, both for studies of patients and studies using simulated bimodal devices.

It has been suggested that the bimodal benefit occurs because listeners combine the representation of F0 in the acoustic signal with the relatively poor representation of F0 in the signal from the implant, and then use F0 to segregate concurrent talkers (Kong et al., 2005; Qin & Oxenham, 2006). Kong and Carlyon (2007) presented two lines of evidence against this theory. First, there was a significant benefit of adding low-pass filtered speech to vocoded speech, even when cues to F0 were removed from the amplitude envelope of the vocoded speech. Second, a low-frequency harmonic complex that reproduced variation in the F0 and amplitude envelope of the target speech did not yield a bimodal benefit (except for a small benefit at the lowest signal-to-noise ratio). The authors concluded that most of the bimodal benefit is due to an improved perception of low-frequency phonetic cues (such as the first formant, formant transitions, and voicing) and an enhanced ability to 'glimpse' the target speech. Li and Loizou (2008) defined glimpsing as the ability to identify regions in time and frequency that have a relatively beneficial signal-to-noise ratio. Li and Loizou proposed that glimpsing allows listeners to detect the presence of target speech and then to access phonetic cues, such as a formant peak.

The role of voicing cues and glimpsing is supported by data from Brown and Bacon (2009). Vocoded speech was combined with a low-frequency tone that was either: 1) modulated in frequency to represent changes in the F0 of the target speech (T_{F0}); 2) modulated in amplitude to represent the amplitude envelope of the target speech (T_{env}); or 3) unmodulated except for onsets and offsets that indicated when the target speech was voiced. The task was to report the words in sentences, and a range of maskers were used. There was a significant benefit of adding any one of the tones to the vocoded speech. The authors proposed that the T_{F0} and T_{env} tones helped listeners to identify moments with a relatively beneficial signal-to-noise ratio. In addition, all three tones provided a cue to voicing. Two observations suggest that the benefit of the T_{F0} tone was unlikely to be due to enhanced segregation. First, the benefit of the T_{F0} tone was smallest when the difference in F0 between target and masker was greatest. Second, a subsequent experiment demonstrated no benefit of a tone that conveyed the F0 of the masking speech. Brown and Bacon acknowledge that the significant benefit of the T_{F0} and T_{env} tones contradicts the results of Kong and Carlyon (2007), and state that further research is being conducted to find the cause of the difference.

The phonetic cues that underlie the bimodal benefit for implant users may depend upon the bandwidth of their residual hearing. One study of unilaterally-implanted adults found that an acoustic signal that had been low-pass filtered at 125 Hz provided almost as much bimodal benefit as a wideband acoustic signal, on tests of speech perception in quiet and in noise (Zhang, Dorman, & Spahr, 2010). The authors suggested that the low-frequency representation of F0 and the amplitude envelope helped listeners to perceive the manner and voicing of consonants, to glimpse the target in noise, and to identify syllable structure and word boundaries. A case study by Cullington and Zeng (2010) found that there was an additional benefit of an acoustic signal with energy above 125 Hz, for a patient who had more residual hearing than the participants in the study of Zhang and colleagues. Presumably, the patient with more residual hearing used the wideband acoustic signal to improve the perception of phonetic cues, such as the first formant, that are conveyed by sounds over 125 Hz.

6.1.2.3 Comparisons of simulated bilateral implants with simulated bimodal devices

A search of the literature revealed a single study that compared simulated bilateral implants with simulated bimodal devices (Chang, Bai, & Zeng, 2006). In one condition, tone-vocoded stimuli were presented diotically. In a sense, this condition simulates two implant systems that convey identical signals (in contrast, current processors use independent AGC and present signals that may not be aligned in time). A simulation of bimodal devices was created by presenting a vocoded signal to one ear and a signal that had been low-pass filtered at 500 Hz to the other ear. The participants completed a speech-perception task in which there was no spatial separation between target and masker (spoken by a male and a female talker, respectively). The participants' SRTs were 7 dB lower in the bimodal simulation than in the condition with diotic vocoded stimuli.

Interim summary

Sound-source localisation with either simulated bilateral implants or simulated bimodal devices is above the level expected by chance, but poorer than for unprocessed stimuli. Normally-hearing adults show between 3 and 8 dB of SRM when listening to simulations of bilateral implants. The bimodal benefit for speech perception in noise appears to be due to an improved ability to glimpse the target speech, and an improved representation of voicing and the lower formants. Differences in methods, and a scarcity of published studies, make it difficult to compare spatial listening skills with simulated bilateral implants or simulated bimodal devices. One study reported that speech perception in noise was better with simulated bimodal devices than with simulated bilateral implants.

6.1.3 Aims and hypotheses

This study measured the spatial listening skills of normally-hearing adults when listening to simulations of cochlear implants presented over headphones. A repeated-measures design was used in which five conditions simulated bilateral implants, a unilateral implant with no contralateral acoustic hearing, and bimodal devices with an increasing bandwidth of contralateral acoustic hearing. The tests of spatial listening were similar to those attempted by implanted children in the study reported in Chapter 5. The first aim was to assess whether the differences in performance between conditions were similar to the differences in performance between the groups of implanted children. The second aim was to measure whether simulations of bimodal devices resulted in higher levels of performance than a simulation of bilateral implants. The third aim was to compare absolute levels of performance between adults in the present study and the implanted children in Chapter 5.

Based on the results from implanted children, it was predicted that performance would be higher with simulated bilateral implants than with a simulated unilateral implant (without contralateral acoustic hearing) on tests of left-right discrimination, localisation, movement tracking, and SRM with noise ipsilateral to the simulated first device. It was predicted that all of the simulations would result in similar levels of performance on tests of sentence perception in quiet and SRM with noise contralateral to the simulated first device. It was not known whether any of the simulations of bimodal devices would yield better performance than the simulation of bilateral implants. Regarding the absolute levels of performance, it was predicted that adults listening to simulations of implants would, on average, perform better than implanted children on tests of speech perception in noise (Friesen et al., 2001).

6.2 Method

6.2.1 Participants

Ten adults aged between 18 and 31 years (mean age 22.9 years, standard deviation 4.3 years) were recruited from the University of York participant pool. Two of the participants were male. The participants had pure-tone thresholds equal to or better than 20 dB HL at octave frequencies between 0.25 and 8 kHz, inclusive, measured using the British Society of Audiology guidelines (1981). Approval was obtained from the Research Ethics Committee of the Department of Psychology of the University of York. Participants gave written informed consent and were paid for their time.

6.2.2 Creation of stimuli

6.2.2.1 Recording of stimuli

Recordings were made in the booth containing the ring of loudspeakers described in section 4.2.2 (Figure 6.2). A head and torso simulator (Brüel & Kjaer Type 4128C) was positioned in the centre of the ring facing the same direction as participants during testing in Chapter 5. A HiRes Auria™ sound processor (Advanced Bionics, Sylmar, USA) was placed behind each ear of the manikin with a T-Mic™ omnidirectional microphone (Advanced Bionics) positioned over the concha. Each sound processor was attached to a clinical programming interface (Advanced Bionics) that was controlled by a personal computer. The clinical programming interface was set to output the signal from the sound processor after the AGC circuitry but before further processing. The signal from each clinical programming interface was digitised at 44.1 kHz with 16-bit amplitude quantization. The signals from the processor on the left and right ear formed the left and right channels of the resulting stereo file, respectively. The stimuli for the tests of spatial listening were presented from the loudspeakers and recordings were made using this apparatus. Thus, the recordings incorporated the effects of the microphones employed by cochlear implants and of AGC in two independent devices (cf. Chang et al., 2006; Francart, Bogaert, et al., 2009; Moy, 2004).

The stimuli for the tests of spatial listening were presented from the loudspeaker locations that were used with children (see section 4.2.2). For the Left-Right Discrimination and Localisation tests, stimuli were presented at the average level used with children (70 dB (A) SPL) and the level was not roved. The stimuli for the Movement Tracking and BKB Sentence tests were presented at the levels used with children: 71 and 70 dB (A) SPL, respectively. There were five versions of the Toy Discrimination test: three with pink noise (presented from the left, front, or right) and two with pulsatile noise (either Same-F0 or Raised-F0, both presented from the front). The speech stimuli were presented at the levels used with implanted children:

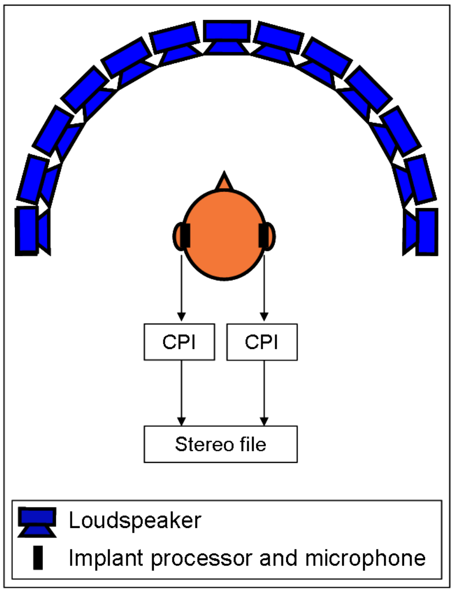

Figure 6.2. Apparatus used to record the stimuli. The orange figure depicts a head and torso simulator placed in the centre of a ring of loudspeakers (only the front 13 loudspeakers are shown). A cochlear-implant sound processor and microphone were placed on each ear. A clinical programming interface (CPI) was used to output the signal from each sound processor and the signals were digitised into a stereo file.

50 and 51 dB (A) SPL for the versions in pink and pulsatile noise, respectively. For each version of the Toy Discrimination test, the level of the noise was manipulated so that recordings of each toy name were made at signal-to-noise ratios at 3 dB intervals between −21 and +33 dB, inclusive. The signal-to-noise ratio was calculated from separate measurements of the level of the speech and noise, made using a free-field microphone in the centre of the ring (see section 4.2.2 for further details of how levels were measured). For the versions in pink noise, the noise token was selected at random for each recording. To record stimuli for the familiarisation task, 40 of the IEEE sentences (IEEE, 1969) were presented from each of seven loudspeakers (located at −90°, −60°, −30°, 0°, +30°, +60°, and +90°). One sentence was presented from one loudspeaker at a time, at an average level of 61 dB (A) SPL.

6.2.2.2 Processing of stimuli

Stimuli for individual trials were extracted from the recording and periods of silence before and after each stimulus were deleted using CoolEdit 2000 (Syntrillium Software Corporation, Phoenix, USA). The subsequent stages of processing were implemented in MATLAB (The MathWorks Inc., Natick, USA) and are summarised in Figure 6.3. Each stimulus was processed in four different ways: using a tone vocoder or a low-pass filter (zero-phase twelfth-order Butterworth) with a cut-off at either 1320, 880, or 440 Hz.

The vocoder used a series of zero-phase sixth-order elliptic bandpass filters to create eight channels (Table 6.1) whose centre frequencies were spaced at equal intervals along the basilar membrane according to Greenwood's formula (Greenwood, 1990). The range of centre frequencies matched the typical range used in a HiRes Auria™ sound processor (P. Boyle, personal communication, May 22, 2009). The amplitude envelope in each channel was extracted by half-wave rectification and low-pass filtering at 160 Hz (zero-phase second-order elliptic filter). The amplitude envelope was used to modulate a sine wave at the centre frequency of the channel. Each channel was bandpass filtered using the same filter as in the initial stage of processing, then the channels were summed.

The stereo files containing the processed stimuli were split into left and right signals, and then combined to form five conditions: both left and right signal vocoded (CI-CI); one signal vocoded and one signal silent (CI-0000); one signal vocoded and one signal low-pass filtered at 1320, 880, or 440 Hz (CI-1320, CI-0880 or CI-0440, respectively). Cosine onset and offset ramps of 25 ms duration were applied to all stimuli. For each participant, a vocoded signal was presented to the same ear throughout the experiment (the left ear for half of the listeners, the right ear for the other half).

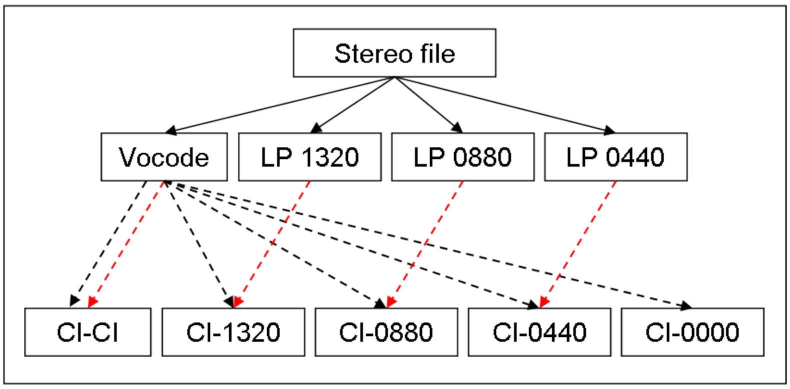

Figure 6.3. The principal stages of stimulus processing. Each stereo file was processed in four different ways: using a tone vocoder or a low-pass filter (LP) with a cut-off at either 1320, 880, or 440 Hz. Each file was split into left and right signals (black and red dotted lines, respectively). Stimuli for five conditions were formed by combining one left and one right signal: CI-CI, CI-1320, CI-0880, CI-0440, and CI-0000 (in which one channel was silent). Half of the participants were presented with a vocoded signal to the left ear in every condition (as illustrated here) and half to the right ear.

6.2.3 Procedure

Testing took place in a double-walled booth (Industrial Acoustics Company). Stimuli were generated by a PC soundcard (Lynx One), processed by a 24-bit MOTU digital to analogue converter and Tucker-Davis Technologies PA4 attenuator, and presented using Sennheiser HD580 headphones. The five conditions were presented in an order counterbalanced across participants, and one condition was completed per testing

Table 6.1. The centre frequency and frequency range (2.5-dB down-points) for the eight channels in the tone vocoder.

Channel	Centre frequency (Hz)	Frequency range (Hz)
1	350	269–446
2	561	446–696
3	857	696–1048
4	1275	1048–1544
5	1863	1544–2241
6	2691	2241–3224
7	3857	3224–4609
8	5500	4609–6558

session. The sessions lasted up to 2.5 hours and were completed on different days. At the start of the study, participants were shown a diagram of the ring of loudspeakers. They were told that the stimuli had been recorded using a manikin in the centre of the ring, in order to create an illusion of sound sources at different locations. Participants were informed that the stimuli had been processed to sound like cochlear implants and/or hearing aids, but they were not told which condition they were attempting in each session.

The following sections describe how the tests of spatial listening for children were modified for this study (details of the original tests are in section 4.2.2). Due to time constraints, only a subset of the tests for children was used. Each session began with the familiarisation task, then participants completed half of the trials of each test in the order in which the tests are described below. The remaining trials were then completed, with the tests presented in the reverse order. Participants took breaks between tests. Unless stated otherwise, a personal computer was used to record participants' responses. For the remainder of this chapter, 'source location' refers to the location of the loudspeaker that presented the stimulus during recording.

6.2.3.1 Familiarisation task

A trial began with the presentation of a sentence from one of seven source locations. The sentence had undergone the signal processing for the condition the participant was attempting that day. Participants were asked to indicate the source location using a response screen that showed a diagram of the possible locations. Feedback was provided by illuminating the actual source location. The same sentence was then repeated twice from the same location: once unprocessed (i.e. before vocoding or low-pass filtering) and once processed. There were 168 trials, which took approximately 45 minutes to complete.[1]

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[1] In this and subsequent descriptions, the number of trials is the total completed per condition.

6.2.3.2 Left-right discrimination

Participants completed 80 trials of the ±60° condition. The stimulus was presented once and the participant responded by pressing one of two buttons (labelled ‘Left’ and ‘Right’). For children, the presence or absence of a reward video provided feedback. To replicate this, the button pressed by the participant was illuminated green or red to indicate a correct or incorrect response, respectively. The percentage of correct responses was measured.

6.2.3.3 Localisation

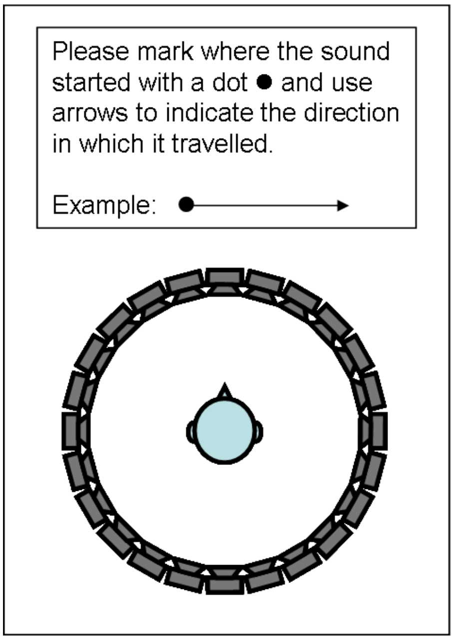
Participants completed 120 trials of the three-alternative task with sources at −60°, 0°, and +60°. The stimulus was presented once and the participant responded by pressing one of three buttons (labelled ‘Left’, ‘Centre’, and ‘Right’). No feedback was provided. The RMS error was measured.

6.2.3.4 Movement tracking

Each of the four trajectories was presented once, in an order counterbalanced across conditions, then the four trajectories were presented again in the reverse order. The stimuli were the sound of either footsteps or hoof beats, with four trials of each type. After each trial, participants were asked to draw the location of the source of sound onto a diagram of the ring of loudspeakers (Figure 6.4). Participants were informed that the source was going to move. No feedback was provided. An independent observer attempted to deduce which of the four trajectories had been presented on each trial, based on the participant’s drawing. The percentage of correct deductions was measured.

6.2.3.5 Toy Discrimination test in pink noise

The signal-to-noise ratio was varied adaptively. The test began at a signal-to-noise ratio selected at random from +21, +24, and +27 dB. A one-down one-up adaptive routine with a step size of 6 dB was used for the first three reversals. A two-down one-up routine with a step size of 3 dB was used for the following 10 reversals. The average of the final eight reversals was taken to estimate the 70.7% correct threshold (Levitt, 1971). This signal-to-noise ratio will be referred to as the SRT. One estimate of the SRT was obtained for each noise location in an order counterbalanced across conditions, then a second estimate was obtained for each noise location in the reverse order. Participants responded by pressing one of 14 buttons labelled with the toy names. No feedback was provided. The mean SRT was calculated for each noise location.



Please mark where the sound started with a dot ● and use arrows to indicate the direction in which it travelled.

Example: ●⟶

Figure 6.4. Response sheet for the Movement Tracking test.

6.2.3.6 Toy Discrimination test in pulsatile noise

One estimate of SRT was obtained for each type of masker (Same-F0 and Raised-F0) in an order counterbalanced across conditions, then a second estimate was obtained for each type of masker in the reverse order. The adaptive routine and response interface were the same as for the Toy Discrimination test in pink noise. The mean SRT was calculated for each type of masker.

6.2.3.7 BKB Sentence test

In every condition, two lists (each of which contained 16 sentences) were presented binaurally. In the CI-1320, CI-0880, and CI-0440 conditions, participants completed two additional lists using monaural stimuli that had been low-pass filtered at 1320, 880 and 440 Hz, respectively. The monaural lists were presented after the first binaural list. Participants were asked to repeat the sentence aloud and to guess any words they were unsure of. Responses were scored by the experimenter, who listened to the signal from a microphone inside the testing booth. The percentage of keywords correct was measured using a loose keyword scoring method. A list was not repeated with the same participant.

The aim of the monaural presentation was to set the bimodal simulations in context. In the UK, adults are eligible for unilateral cochlear implantation if, whilst using acoustic hearing aids, they report correctly under 50% of the keywords in BKB sentences presented in quiet (NICE, 2009). If the results of the present study showed a monaural score that was greater than 50% on average, it would indicate that the corresponding bimodal simulation created a higher level of functional hearing in the nonimplanted ear than is likely to be observed in implanted adults. This conclusion may not extrapolate to the amount of residual hearing shown by implanted children, because the criteria of candidacy for children do not refer to the BKB sentences (NICE, 2009). However, the way in which the present study interprets the monaural BKB sentences is supported by the study of implanted children, in which the three children who completed the BKB Sentence test using only their hearing aid scored 4, 6, and 50% correct (see Figure 5.6 on page 125).

6.2.3.8 Presentation levels

In the CI-CI condition equal gain was applied to the left and right channels. In each of the CI-1320, CI-0880 and CI-0440 conditions, the level of the low-pass filtered stimulus was adjusted so that, for two pilot listeners, a stimulus from a source location at 0° created a percept that was approximately centred. The presentation levels were measured using a Brüel & Kjaer Investigator sound-level meter (Type 2260) with a Brüel & Kjaer artificial ear (Type 4153) and 1/2” microphone (Type 4134). The metering software displayed the peak value in dB(A) SPL in one-second intervals; the maximum value was recorded for each stimulus. The average presentation levels are shown in Table 6.2. The level of the stimuli for the Left-Right Discrimination and Localisation tests was randomly roved by ±5 dB in 1 dB steps.

Table 6.2. The presentation levels of the stimuli. For the low-pass filtered stimuli (0440, 0880, and 1320) and vocoded stimuli (CI), the average level at one headphone in dB (A) SPL is listed for each test. For the Toy Discrimination test, the level varied according to the signal-to-noise ratio and noise location or type of masker. Accordingly, the range of levels is stated for this test.

Test	0440	0880	1320	CI
Familiarisation task	62.6	63.8	63.4	66.7
BKB Sentences	67.3	72.4	71.7	75.4
Left-Right Discrimination[a]	60.0	65.8	65.3	69.8
Localisation[a]	61.1	68.0	67.9	67.3
Movement Tracking[a]	66.8	70.2	70.2	79.7
Toy Discrimination, pink noise	54.8–61.3	54.8–63.7	58.1–66.7	61.0–79.3
Toy Discrimination, pulsatile noise	44.8–59.7	56.8–63.4	56.4–63.3	63.2–78.6

[a] The average level for all source locations is stated.

6.2.4 Analyses

6.2.4.1 Presentation of results

The results are presented using bar charts showing means and 95% confidence intervals, overlaid with the scores of individual participants. The score for each adult is shown by a symbol that is the same throughout this chapter. For consistency, the results from implanted children are presented using bar charts even though these data were not distributed normally. In all conditions except CI-CI, participants were presented with a vocoded stimulus to one ear only. To enable an informative analysis of the Toy Discrimination test, the participant's left and right ears will be referred to as either the first or second device, as defined in Figure 6.5.

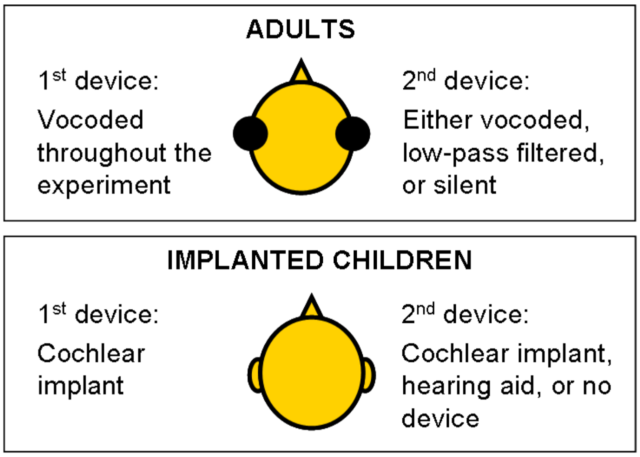


Figure 6.5. Upper panel: the definition of the first and second device for adults in the present study. Headphones are denoted by black circles. Lower panel: the definition of the first and second device for implanted children (see section 5.2.4.1). In both panels, the first device is illustrated in the left ear, although this was not always the case.

6.2.4.2 Statistical analyses

The aim of the statistical analyses was to assess:

1. For each test, whether the condition had an effect on performance.
2. For the Toy Discrimination test in pink noise, whether the condition and noise location had an effect on performance and whether there was an interaction between condition and noise location.
3. For the Toy Discrimination test in pulsatile noise, whether the condition and masker type had an effect on performance and whether there was an interaction between condition and masker type.
4. For each test, whether adults' performance in the CI-CI condition differed from the performance of children who used CI-CI.
5. For each test, whether adults' performance in the CI-0440 condition differed from the performance of children who used CI-HA.
6. For each test, whether adults' performance in the CI-0000 condition differed from the performance of children who used CI-only.

6.2.4.2.1 Statistical analyses of the results from adults The results from the binaural BKB Sentence test did not have a normal distribution. A Friedman's ANOVA was used to assess whether there was an effect of condition on performance, and Wilcoxon tests with a Bonferroni correction were used to assess which conditions differed. Effect sizes for Wilcoxon tests were calculated using the formula in section 5.2.4.4.2.

The remaining outcome measures had a normal distribution (confirmed by the Kolmogorov-Smirnov test). For each of the monaural BKB Sentence, Left-Right Discrimination, Localisation, and Movement Tracking tests, a one-way repeated-measures ANOVA was used to assess whether condition had an effect on performance. There was an *a priori* prediction that performance would be higher in the CI-CI condition than the CI-0000 condition, but there were no predictions regarding differences between the other conditions. Accordingly, within-subjects t tests with a Bonferroni correction were used to compare all of the conditions with each other. Effect sizes for t tests were calculated using the formula $r = \sqrt{t^2/(t^2+df)}$ where t is the test statistic and df are the degrees of freedom (Field, 2005).

To assess whether there was an effect of condition and/or noise location on SRTs in pink noise, a two-way repeated-measures ANOVA was carried out with the factors of condition (five levels) and noise location (three levels). Within-subjects t tests with a Bonferroni correction were used to analyse the differences between conditions. There was an *a priori* prediction regarding the effect of noise location, so planned comparisons with a Bonferroni correction were used to assess whether SRTs were lower in the noise-side conditions than in the noise-front condition (i.e. whether the participants showed SRM). Planned comparisons with a Bonferroni correction were used to interpret the interaction.

To assess whether there was an effect of condition and/or masker type on SRTs in pulsatile noise, a two-way repeated-measures ANOVA was carried out with the factors of condition (five levels) and masker type (two levels). Within-subjects t tests with a Bonferroni correction were used to assess which conditions differed. Planned comparisons with a Bonferroni correction were used to interpret the interaction.

6.2.4.2.2 Statistical comparisons of adults and children Mann-Whitney tests were used to compare adults' performance in the CI-CI, CI-0440, and CI-0000 conditions with the performance of children who used CI-CI, CI-HA, and CI-only, respectively. These analyses were explorative so a Bonferroni correction was not used, although there have been multiple comparisons of these data in this and previous chapters. The BKB Sentence test was not analysed in this way because only small numbers of children completed the test. For the Toy Discrimination test, the graphs and statistical analyses only included children who used 14 toys. Effect sizes for Mann-Whitney tests were calculated using the formula in section 4.2.5.2.

6.3 Results

6.3.1 BKB Sentence test

The results of the BKB Sentence test are shown in Figure 6.6. For the sentences presented binaurally, there was a significant effect of condition on performance [$\chi^2(4) = 10.5$, $p < .05$]. Based on inspection of the ranked data, the CI-1320 condition was compared to every other condition. None of the comparisons were statistically significant [all $p_{bf} > .05$]. For the sentences presented monaurally, there was a significant effect of condition on performance [$F(2{,}18) = 314$, $p < .001$]. Performance was higher in the 1320 condition than the 0880 condition [$t(9) = 4.51$, $p_{bf} < .01$, $r = .83$]. Performance was higher in the 0880 condition than the 0440 condition [$t(9) = 20.0$, $p_{bf} < .001$, $r = .99$].

With monaural stimuli low-pass filtered at 880 or 1320 Hz, the majority of participants correctly reported over 50% of the target words. Thus, when interpreting the results of this study, it should be borne in mind that the CI-0880 and CI-1320 conditions simulate a higher level of functional hearing in the nonimplanted ear than is likely to be observed in implanted adults in the UK. Accordingly, subsequent analyses compared the performance of children who used CI-HA with that of adults in the CI-0440 condition (rather than the CI-0880 or CI-1320 condition).

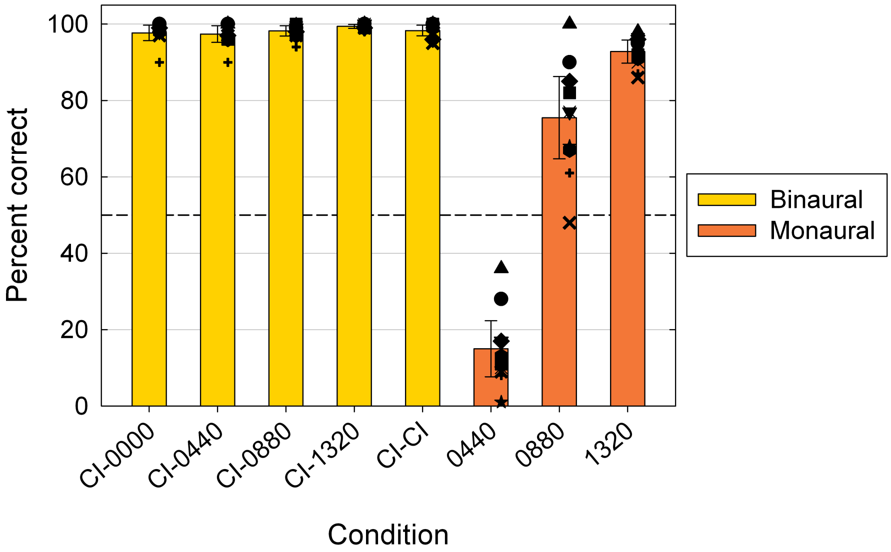


Figure 6.6. Results of the BKB Sentence test using binaural presentation (yellow bars) or monaural presentation (orange bars). The bars show mean scores, error bars show 95% confidence intervals, and black symbols show individual scores. The horizontal dashed line shows the current criterion of candidacy for adult unilateral cochlear implantation in the UK (NICE, 2009).

6.3.2 Left-Right Discrimination test

6.3.2.1 Results from adults

The results of the Left-Right Discrimination test are shown in Figure 6.7. Mauchly's test indicated that the assumption of sphericity had been violated, so the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (Field, 2005). There was a significant effect of condition on performance [$F(2.56,23.0) = 23.6$, $p < .001$]. Post-hoc tests revealed that performance was higher in the CI-CI condition than in all other conditions (Table 6.3). There were no other significant differences between conditions.

6.3.2.2 Comparison of adults and children

Adults' scores in the CI-CI condition were significantly lower than those of children who used CI-CI [$z = -2.25$, $p < .05$, $r = .33$] (although the difference in the ranked scores is not apparent in Figure 6.7, which shows mean scores). Adults' scores in the CI-0440 condition did not differ significantly from those of children who used CI-HA [$z = -1.88$, $p > .05$, $r = .43$]. Adults' scores in the CI-0000 condition did not differ significantly from those of children who used CI-only [$z = -1.67$, $p > .05$, $r = .37$].

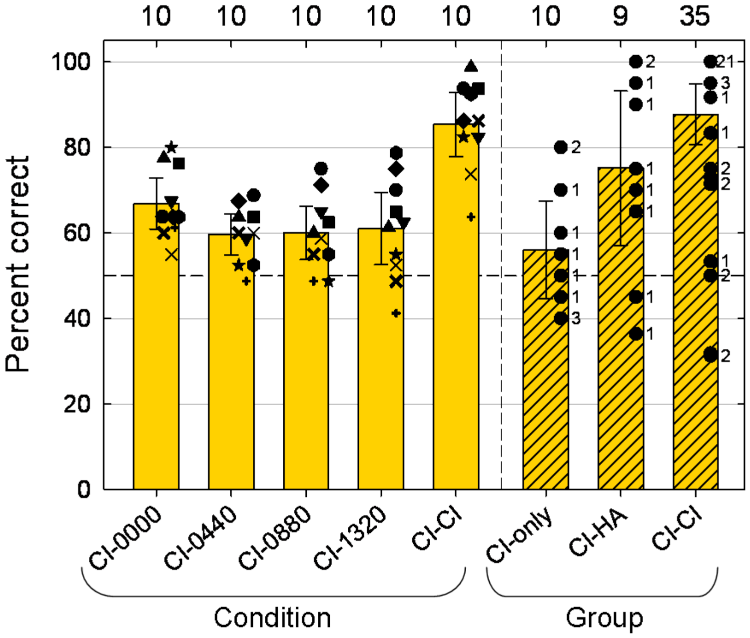


Figure 6.7. Results of the Left-Right Discrimination test. The left part of the graph shows results from the present study of adults (yellow bars), the right part shows results from the study of implanted children (striped bars). The bars show mean scores, error bars show 95% confidence intervals, and black symbols show individual scores. For children, the number to the right of each circle indicates how many children in that group showed that score. The horizontal dashed line shows the level of performance expected by chance. The numbers above the upper horizontal axis indicate how many participants in each condition or group provided data.

Table 6.3. The results of post-hoc comparisons of adults' scores in the Left-Right Discrimination test. The test statistic (t), Bonferroni-adjusted p value (p_{bf}), and effect size (r) are listed. A positive test statistic indicates that the first condition in the comparison had a higher mean score than the second condition. Degrees of freedom were 9 for all comparisons. Statistically-significant comparisons are emboldened.

Comparison	t	p_{bf}	r
CI-CI vs. CI-1320	+**8.79**	**< .01**	**.95**
CI-CI vs. CI-0880	+**8.05**	**< .01**	**.94**
CI-CI vs. CI-0440	+**9.67**	**< .01**	**.96**
CI-CI vs. CI-0000	+**6.03**	**< .01**	**.90**
CI-1320 vs. CI-0880	+0.34	.99	.11
CI-1320 vs. CI-0440	+0.41	.99	.14
CI-1320 vs. CI-0000	−1.39	.99	.42
CI-0880 vs. CI-0440	+0.29	.99	.10
CI-0880 vs. CI-0000	−1.71	.99	.49
CI-0440 vs. CI-0000	−2.18	.58	.59

6.3.3 Localisation test

6.3.3.1 Results from adults

The results of the Localisation test are shown in Figure 6.8. Mauchly's test indicated that the assumption of sphericity had been violated, so the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. There was a significant effect of condition on performance [$F(1.73,15.5) = 17.7$, $p < .001$]. Post-hoc tests revealed that error scores were lower in the CI-CI condition than in all other conditions, and that error scores were lower in the CI-0000 condition than in the CI-0440 condition (Table 6.4). There were no other significant differences between conditions.

6.3.3.2 Comparison of adults and children

Adults' scores in the CI-CI condition did not differ significantly from those of children who used CI-CI [$z = -0.41$, $p > .05$, $r = .07$]. Adults' scores in the CI-0440 condition did not differ significantly from those of children who used CI-HA [$z = -0.49$, $p > .05$, $r = .12$]. Adults' scores in the CI-0000 condition did not differ significantly from those of children who used CI-only [$z = -0.88$, $p > .05$, $r = .21$].

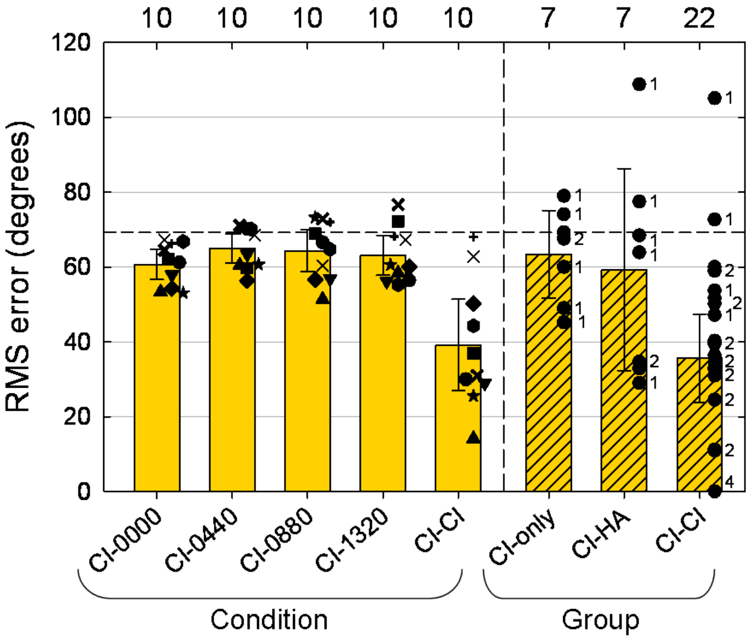


Figure 6.8. Results of the Localisation test. The left part of the graph shows results from the present study of adults (yellow bars), the right part shows results from the study of implanted children (striped bars). The bars show mean scores, error bars show 95% confidence intervals, and black symbols show individual scores. For children, the number to the right of each circle indicates how many children in that group showed that score. The horizontal dashed line shows the level of performance expected by chance. The numbers above the upper horizontal axis indicate how many participants in each condition or group provided data.

Table 6.4. The results of post-hoc comparisons of adults' scores in the Localisation test. The test statistic (t), Bonferroni-adjusted p value (p_{bf}), and effect size (r) are listed. A negative test statistic indicates that the first condition in the comparison had a lower mean score than the second condition. Degrees of freedom were 9 for all comparisons. Statistically-significant comparisons are emboldened.

Comparison	t	p_{bf}	r
CI-CI vs. CI-1320	**−4.56**	**.01**	**.84**
CI-CI vs. CI-0880	**−4.58**	**.01**	**.84**
CI-CI vs. CI-0440	**−5.02**	**< .01**	**.86**
CI-CI vs. CI-0000	**−4.80**	**.01**	**.85**
CI-1320 vs. CI-0880	−0.53	.99	.17
CI-1320 vs. CI-0440	−0.71	.99	.23
CI-1320 vs. CI-0000	+1.07	.99	.34
CI-0880 vs. CI-0440	−0.29	.99	.10
CI-0880 vs. CI-0000	+1.54	.99	.46
CI-0440 vs. CI-0000	+**3.94**	**.03**	**.80**

6.3.4 Movement Tracking test

6.3.4.1 Results from adults

The results of the Movement Tracking test are shown in Figure 6.9. There was no significant effect of condition on performance [$F(4,36) = 2.39$, $p > .05$].

6.3.4.2 Comparison of adults and children

Adults' scores in the CI-CI condition did not differ significantly from those of children who used CI-CI [$z = -0.27$, $p > .05$, $r = .04$]. Adults' scores in the CI-0440 condition did not differ significantly from those of children who used CI-HA [$z = -1.08$, $p > .05$, $r = .25$]. Adults' scores in the CI-0000 condition were significantly higher than those of children who used CI-only [$z = -2.11$, $p < .05$, $r = .46$].

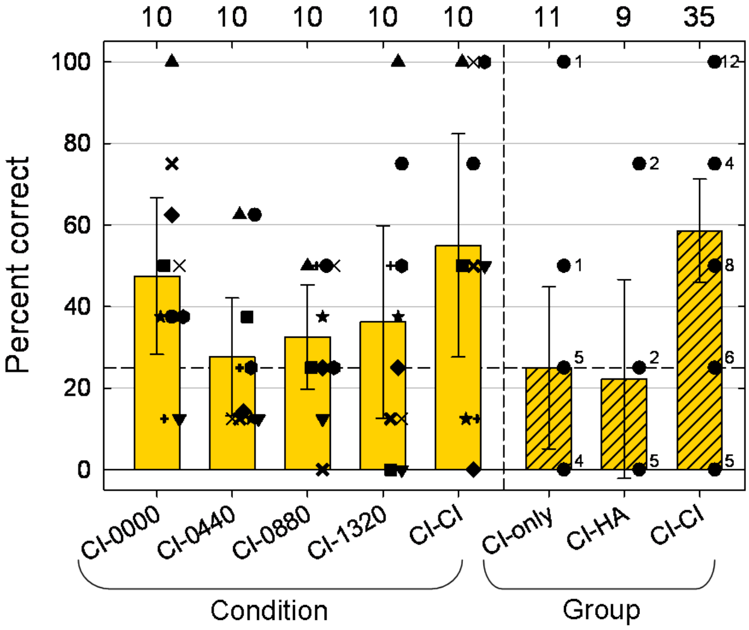


Figure 6.9. Results of the Movement Tracking test. The left part of the graph shows results from the present study of adults (yellow bars), the right part shows results from the study of implanted children (striped bars). The bars show mean scores, error bars show 95% confidence intervals, and black symbols show individual scores. For children, the number to the right of each circle indicates how many children in that group showed that score. The horizontal dashed line shows the level of performance expected by chance. The numbers above the upper horizontal axis indicate how many participants in each condition or group provided data.

6.3.5 Toy Discrimination test in pink noise

6.3.5.1 Results from adults

The results of the Toy Discrimination test in pink noise are shown in Figure 6.10. There was a significant effect of condition on SRTs [$F(4,36) = 17.3$, $p < .001$], a significant effect of noise location on SRTs [$F(2,18) = 59.6$, $p < .001$], and a significant interaction between condition and noise location [$F(8,72) = 6.49$, $p < .001$].

The results of post-hoc tests are listed in Table 6.5. Averaged across noise locations, the CI-1320 condition resulted in lower SRTs than the CI-CI, CI-0440, and CI-0000 conditions. The CI-0880 condition resulted in lower SRTs than the CI-0440 and CI-0000 conditions. The CI-CI condition resulted in lower SRTs than the CI-0000 condition. There were no other significant differences between conditions.

Planned contrasts revealed that, averaged across conditions, SRTs were lower with noise contralateral to the first device than with noise from the front [$F(1,9) = 84.0$, $p_{bf} < .001$, $r = .95$]. Averaged across conditions, there was no significant difference between SRTs with noise ipsilateral to the first device and SRTs with noise front [$F(1,9) = 1.28$, $p_{bf} > .05$, $r = .35$].

The interaction indicates that the effect of noise location differed according to the condition. Table 6.6 shows the results of contrasts that compared all conditions to CI-CI, and all noise locations to noise-front. Where a contrast is statistically significant, it indicates that the effect of presenting the noise from the side rather than from the front (i.e. SRM) was different for the comparator condition than the CI-CI condition. To aid interpretation, the data are re-plotted to show SRM in Figure 6.11. With noise ipsilateral to the first device, there was greater SRM in the CI-CI condition than in the CI-0000 and CI-1320 conditions. With noise ipsilateral to the first device, there was no significant difference between the CI-CI and CI-0440 conditions in the amount of SRM, nor was there a significant difference between the CI-CI and CI-0880 conditions. With noise contralateral to the first device, there was no significant difference between the CI-CI condition and the other conditions in the amount of SRM.

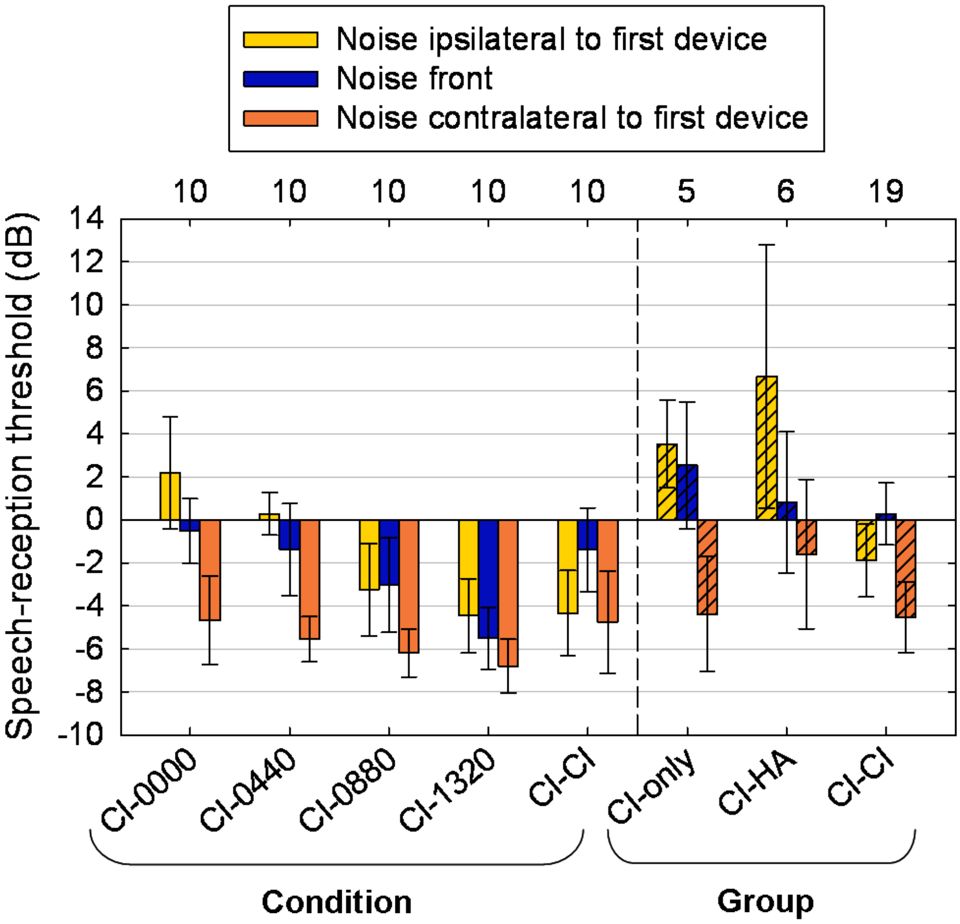


Figure 6.10. Results of the Toy Discrimination test in pink noise. The left part of the graph shows results from the present study of adults (non-striped bars), the right part shows results from the study of implanted children (striped bars). Yellow bars: noise ipsilateral to the first device. Blue bars: noise front. Orange bars: noise contralateral to the first device. The bars show mean scores and error bars show 95% confidence intervals. For clarity, individual data points are not plotted. The numbers above the upper horizontal axis indicate how many participants in each condition or group provided data.

Table 6.5. The results of post-hoc comparisons of adults' scores in the Toy Discrimination test in pink noise. The test statistic (t), Bonferroni-adjusted p value (p_{bf}), and effect size (r) are listed. A positive test statistic indicates that the first condition in the comparison had a higher mean SRT than the second condition. Degrees of freedom were 9 for all comparisons. Statistically-significant comparisons are emboldened.

Comparison	t	p_{bf}	r
CI-CI vs. CI-1320	+**3.86**	**.04**	**.79**
CI-CI vs. CI-0880	+0.85	.99	.27
CI-CI vs. CI-0440	−2.27	.50	.60
CI-CI vs. CI-0000	**−4.05**	**.03**	**.80**
CI-1320 vs. CI-0880	−2.75	.22	.68
CI-1320 vs. CI-0440	**−6.91**	**< .01**	**.92**
CI-1320 vs. CI-0000	**−5.79**	**< .01**	**.89**
CI-0880 vs. CI-0440	**−4.71**	**.01**	**.84**
CI-0880 vs. CI-0000	**−4.54**	**.01**	**.83**
CI-0440 vs. CI-0000	−2.74	.23	.67

Table 6.6. The results of contrasts for the interaction between condition and noise location for the Toy Discrimination test in pink noise. Only data from adults were included in the analysis. The test statistic (F), Bonferroni-adjusted p value (p_{bf}), and effect size (r) are listed. Degrees of freedom were 1,9 for all contrasts. Noise ipsi. and noise contra. refer to noise presented from ipsilateral and contralateral to the first device, respectively. Statistically-significant interactions are emboldened.

Condition comparison	Location comparison	F	p_{bf}	r
CI-CI vs. CI-1320	Noise front vs. noise ipsi.	**21.6**	**.02**	**.84**
CI-CI vs. CI-1320	Noise front vs. noise contra.	7.07	.37	.66
CI-CI vs. CI-0880	Noise front vs. noise ipsi.	4.07	.99	.56
CI-CI vs. CI-0880	Noise front vs. noise contra.	0.01	.99	.04
CI-CI vs. CI-0440	Noise front vs. noise ipsi.	12.4	.09	.76
CI-CI vs. CI-0440	Noise front vs. noise contra.	0.38	.99	.20
CI-CI vs. CI-0000	Noise front vs. noise ipsi.	**22.9**	**.01**	**.85**
CI-CI vs. CI-0000	Noise front vs. noise contra.	0.44	.99	.22

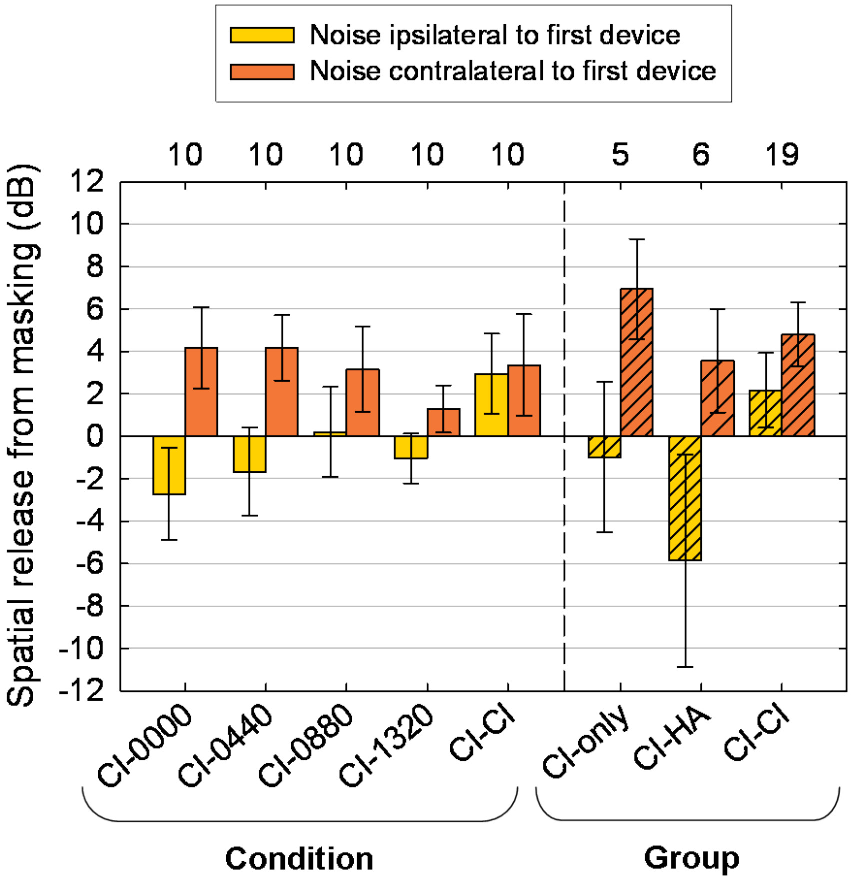


Figure 6.11. Spatial release from masking. The left part of the graph shows results from the present study of adults (non-striped bars), the right part shows results from the study of implanted children (striped bars). The yellow and orange bars show SRM with noise ipsilateral and contralateral to the first device, respectively. The bars show the mean and error bars show 95% confidence intervals. For clarity, individual data points are not plotted. The numbers above the upper horizontal axis indicate how many participants in each condition or group provided data.

6.3.5.2 Comparison of adults and children

The results of statistical comparisons of adults and children are shown in Table 6.7. With noise ipsilateral or contralateral to the first device, SRTs were lower for adults in the CI-0440 condition than for children who used CI-HA. With noise from the front, SRTs were lower for adults in the CI-0000 condition than for children who used CI-only. Mann-Whitney tests were also used to compare the amount of SRM shown by adults and children: there were no significant differences [all $p > .05$].

Table 6.7. The results of Mann-Whitney tests to compare the SRTs of adults and children on the Toy Discrimination test in pink noise. The standardised test statistic (z), p value, and effect size (r) are listed. Ipsi. and Contra. refer to noise presented from ipsilateral and contralateral to the first device, respectively. The upper section of the table lists comparisons of the adult CI-CI condition with children who use CI-CI. The middle section of the table lists comparisons of the adult CI-0440 condition with children who use CI-HA. The lower section of the table lists comparisons of the adult CI-0000 condition with children who use CI-only. Statistically-significant comparisons are emboldened.

Noise location	z	p	r
Adult CI-CI compared to children with CI-CI			
Front	−1.24	.22	.23
Ipsi.	−1.88	.06	.35
Contra.	−0.46	.66	.09
Adult CI-0440 compared to children with CI-HA			
Front	−1.30	.21	.33
Ipsi.	**−2.17**	**.03**	**.54**
Contra.	**−2.45**	**.03**	**.59**
Adult CI-0000 compared to children with CI-only			
Front	**−2.09**	**.04**	**.54**
Ipsi.	−1.10	.31	.28
Contra.	−0.74	.51	.19

6.3.6 Toy Discrimination test in pulsatile noise

6.3.6.1 Results from adults

A ceiling effect occurred for this test: some participants could identify the target word at the most adverse signal-to-noise ratio (−21 dB). If a participant responded correctly on five consecutive trials at a signal-to-noise ratio of −21 dB, the adaptive routine was stopped and the SRT was recorded as −21 dB. Across participants and conditions, 100 estimates of SRT were obtained for each masker. The adaptive routine was stopped on 34 estimates with the Raised-F0 masker and one estimate with the Same-F0 masker.

The results of the Toy Discrimination test in pulsatile noise are shown in Figure 6.12. There was a significant effect of condition on SRTs [$F(4,36) = 8.79$, $p < .001$], a significant effect of masker type on SRTs [$F(1,9) = 181$, $p < .001$], and a significant interaction between condition and masker type [$F(4,36) = 5.95$, $p < .01$].

The results of post-hoc tests are listed in Table 6.8. Averaged across maskers, the CI-1320 condition resulted in lower SRTs than the CI-CI and CI-0000 conditions. The CI-0880 condition resulted in lower SRTs than the CI-0000 condition. There were no other significant differences between conditions.

The main effect of masker type showed that, averaged across conditions, SRTs were lower with the Raised-F0 masker than the Same-F0 masker. The interaction indicates that the effect of masker type differed according to the condition. Table 6.9 shows the results of contrasts that compared all conditions to CI-CI, and compared the two maskers. Where a contrast is statistically significant, it indicates that the effect of masker type was different for the comparator condition than the CI-CI condition. To aid interpretation, the data are re-plotted to show the difference in SRT between the two maskers in Figure 6.13. There was a greater difference between the maskers in the CI-1320 condition than the CI-CI condition. The remaining contrasts were not statistically significant.

Table 6.8. The results of post-hoc comparisons of adults' scores in the Toy Discrimination test in pulsatile noise. The test statistic (t), Bonferroni-adjusted p value (p_{bf}), and effect size (r) are listed. A positive test statistic indicates that the first condition in the comparison had a higher mean SRT than the second condition. Degrees of freedom were 9 for all comparisons. Statistically-significant comparisons are emboldened.

Comparison	t	p_{bf}	r
CI-CI vs. CI-1320	**+4.11**	**.03**	**.81**
CI-CI vs. CI-0880	+2.51	.33	.64
CI-CI vs. CI-0440	−0.42	.99	.14
CI-CI vs. CI-0000	−3.41	.08	.75
CI-1320 vs. CI-0880	+0.73	.99	.24
CI-1320 vs. CI-0440	−1.85	.97	.53
CI-1320 vs. CI-0000	**−5.70**	**< .01**	**.89**
CI-0880 vs. CI-0440	−2.86	.19	.69
CI-0880 vs. CI-0000	**−5.39**	**< .01**	**.87**
CI-0440 vs. CI-0000	−2.00	.76	.56

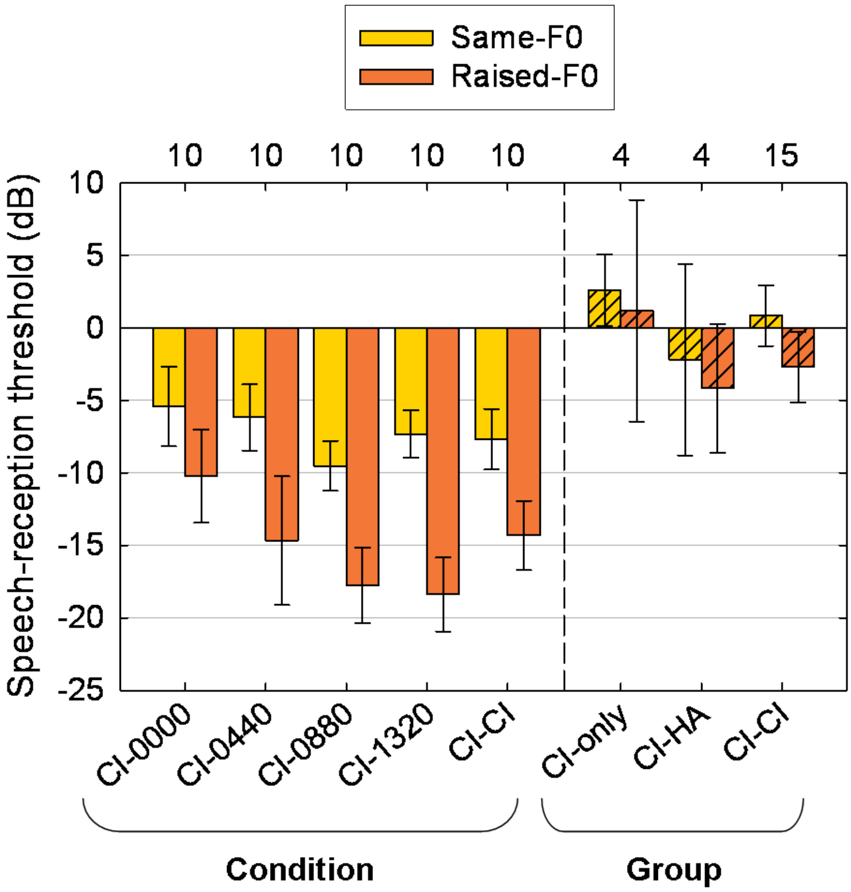


Figure 6.12. Results of the Toy Discrimination test in pulsatile noise. The left part of the graph shows results from the present study of adults (non-striped bars), the right part shows results from the study of implanted children (striped bars). The yellow and orange bars show results with the Same-F0 and Raised-F0 maskers, respectively. The bars show mean scores and error bars show 95% confidence intervals. For clarity, individual data points are not plotted.

Table 6.9. The results of contrasts for the interaction between condition and masker type for the Toy Discrimination test in pulsatile noise. The test statistic (*F*), Bonferroni-adjusted *p* value (p_{bf}), and effect size (*r*) are listed. Degrees of freedom were 1,9 for all contrasts. The statistically-significant interaction is emboldened.

Condition comparison	Masker comparison	*F*	p_{bf}	*r*
CI-CI vs. CI-1320	Same-F0 vs. Raised-F0	**14.9**	**.03**	**.79**
CI-CI vs. CI-0880	Same-F0 vs. Raised-F0	1.51	.99	.38
CI-CI vs. CI-0440	Same-F0 vs. Raised-F0	1.13	.99	.33
CI-CI vs. CI-0000	Same-F0 vs. Raised-F0	3.09	.99	.51

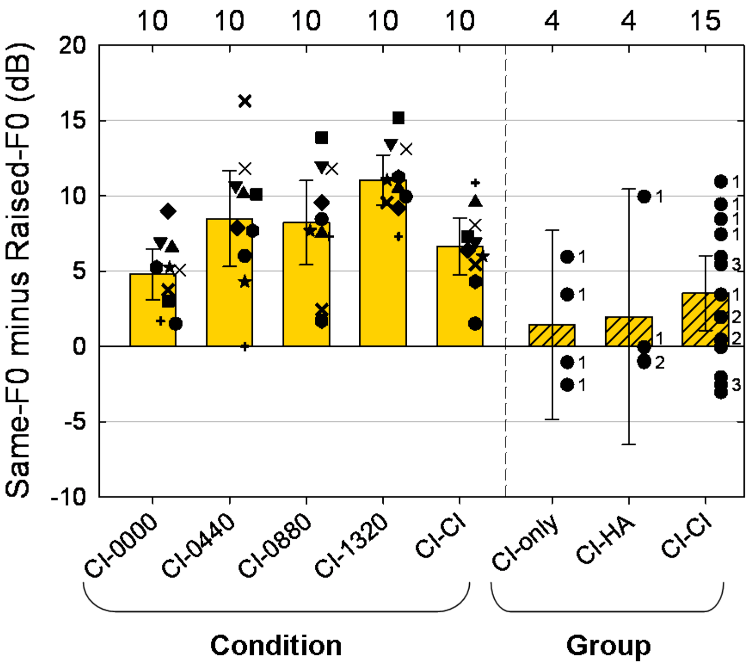


Figure 6.13. The difference in SRT between the Same-F0 and Raised-F0 maskers. A positive score indicates lower SRTs with the Raised-F0 masker. The left part of the graph shows results from the present study of adults (non-striped bars), the right part shows results from the study of implanted children (striped bars). The bars show mean scores, error bars show 95% confidence intervals, and black symbols show individual scores. For children, the number to the right of each circle indicates how many children in that group showed that score. The numbers above the upper horizontal axis indicate how many participants in each condition or group provided data.

6.3.6.2 Comparison of adults and children

The results of statistical comparisons of the SRTs of adults and children are shown in Table 6.10. For both types of masker, SRTs were lower for adults in the CI-CI condition than for children who used CI-CI. Similarly, for both types of masker, SRTs were lower for adults in the CI-0000 condition than for children who used CI-only. For the Raised-F0 masker, SRTs were lower for adults in the CI-0440 condition than for children who used CI-HA. However, the comparisons involving CI-only and CI-HA children should be interpreted with caution, as only four children in each group provided data.

Table 6.10. The results of Mann-Whitney tests to compare the SRTs of adults and children on the Toy Discrimination test in pulsatile noise. The standardised test statistic (*z*), *p* value, and effect size (*r*) are listed. The upper section of the table lists comparisons of the adult CI-CI simulation with CI-CI children. The middle section of the table lists comparisons of the adult CI-0440 simulation with CI-HA children. The lower section of the table lists comparisons of the adult CI-0000 simulation with CI-only children. Statistically-significant comparisons are emboldened.

Masker	*z*	*p*	*r*
Adult CI-CI compared to children with CI-CI			
Same-F0	**−3.89**	**< .01**	**.78**
Raised-F0	**−4.05**	**< .01**	**.81**
Adult CI-0440 compared to children with CI-HA			
Same-F0	−1.56	.14	.42
Raised-F0	**−2.27**	**.03**	**.61**
Adult CI-0000 compared to children with CI-only			
Same-F0	**−2.69**	**< .01**	**.72**
Raised-F0	**−2.55**	**.01**	**.68**

6.3.7 Summary

For the Left-Right Discrimination and Localisation tests, adults responded more accurately in the CI-CI condition than in the other conditions. For the Movement Tracking test, variability was high and there was no significant effect of condition on performance. For the Toy Discrimination test in pink noise and in pulsatile noise, the CI-1320 condition resulted in lower SRTs than the CI-CI and CI-0000 conditions. CI-CI was the only condition in which participants showed a benefit of SRM with noise both ipsilateral and contralateral to the first device. Figure 6.11 summarises the results of statistical comparisons between the CI-CI condition and each of the CI-0440, CI-0880, and CI-1320 conditions. The CI-CI condition resulted in the best sound-source localisation, whereas the CI-1320 condition resulted in the lowest SRTs.

On several of the outcome measures, adults' performance in the CI-CI, CI-0440, and CI-0000 conditions did not differ significantly from the performance of children who used CI-CI, CI-HA, and CI-only, respectively. The most marked exception was the Toy Discrimination test in pulsatile noise, for which adults had lower SRTs than all three groups of children. Compared to the children, the adults appeared to show a greater difference in SRT between the two types of pulsatile masker, but there were insufficient data to conduct statistical comparisons of the difference scores shown by children and adults.

Table 6.11. Summary of statistical comparisons between the CI-CI condition and each of the CI-0440, CI-0880, and CI-1320 conditions. The comparisons are shown in the three columns on the right: each column lists which of the two conditions yielded significantly better performance for each test ($p_{bf} < .05$). An equals sign indicates that there was no significant difference. SRM noise ipsi. and SRM noise contra. refer to SRM with noise ipsilateral and contralateral to the first device, respectively.

Test	CI-CI vs. CI-0440	CI-CI vs. CI-0880	CI-CI vs. CI-1320
BKB Sentences	=	=	=
Left-Right Discrimination	CI-CI	CI-CI	CI-CI
Localisation	CI-CI	CI-CI	CI-CI
Movement Tracking	=	=	=
SRTs in pink noise^a	=	=	CI-1320
SRM noise ipsi.	=	=	CI-CI
SRM noise contra.	=	=	=
SRTs in pulsatile noise^b	=	=	CI-1320
Same-F0 minus Raised-F0	=	=	CI-1320

^{a} Averaged across noise locations. ^{b} Averaged across masker type.

6.4 Discussion

The first parts of the discussion relate to the three aims of the study: 1) to compare the differences in performance between simulations with the differences in performance between groups of implanted children; 2) to compare simulated bimodal devices with simulated bilateral implants; and 3) to compare the absolute levels of performance shown by adults and children. Subsequent sections consider the strengths and limitations of the cochlear-implant simulations, and the causes of the observed differences between conditions.

6.4.1 Similarities in the patterns of performance shown by adults and children

Normally-hearing adults performed better with simulated bilateral implants than with a simulated unilateral implant (with or without simulated contralateral acoustic hearing) on tests of left-right discrimination, localisation, and SRM with noise ipsilateral to the first device. These results mirror the superior performance of bilaterally- compared to unilaterally-implanted children on similar tests. The adults did not show a difference in performance between simulations of bilateral and unilateral implants on tests of sentence perception in quiet and SRM with noise contralateral to the first device. The performance of bilaterally- and unilaterally-implanted children did not differ on similar tests. These data reinforce the conclusion that the differences in spatial listening skill observed between bilaterally- and unilaterally-implanted children were due to a difference in the number of implants the children used, rather than uncontrolled differences between the groups.

Nevertheless, the patterns of performance shown by adults and children were not identical. On the Movement Tracking test, adults showed similar levels of performance in all simulations, whereas bilaterally-implanted children performed better than unilaterally-implanted children. The cause of this difference between adults and children is not known. Anecdotally, some adults reported that the task was difficult and that the sounds did not form a coherent pattern of movement.[2]

The Toy Discrimination test revealed two additional differences between the patterns of performance shown by adults and children:

1. For adults, SRTs in pink noise and in pulsatile noise were lower for one of the simulations of bimodal devices (CI-1320) than for the simulation of bilateral implants. In contrast, the only significant difference in SRT between groups of children was that the bilateral group had a lower SRT than the unilateral group with pink noise ipsilateral to the first device.

2. For adults, the difference in SRT between the Raised-F0 and Same-F0 maskers was greater for one of the simulations of bimodal devices (CI-1320) than for the simulation of bilateral implants. In contrast, the difference in SRT between the Raised-F0 and Same-F0 maskers was similar for both unilaterally- and bilaterally-implanted children.

These two differences between adults and children probably arose because the CI-1320 condition simulated a greater degree of hearing in the nonimplanted ear than was enjoyed by the unilaterally-implanted children. Evidence for this interpretation comes from the monaural BKB Sentence test—adult patients who achieved the scores shown in the 1320 condition would not be eligible to receive an implant. The simulations of bimodal devices with a lesser degree of acoustic hearing (CI-0880 and CI-0440) resulted in SRTs, and a difference between maskers, that were similar to the

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[2] Normally-hearing adults showed high levels of performance on the Movement Tracking test when the stimuli were presented by the ring of loudspeakers (Figure 4.8). Thus, it is not the case that this test is problematic for adults in general, but rather that this test is problematic for adults after the stimuli have been processed to simulate cochlear implant(s).

results with simulated bilateral implants. This pattern of results for adults is similar to the pattern shown by unilaterally- and bilaterally-implanted children.

6.4.2 Comparison of simulated bimodal devices and simulated bilateral implants

Performance on the Left-Right Discrimination and Localisation tests was better with simulated bilateral implants than with any of the simulations of bimodal devices. On tests of speech perception in noise, the CI-1320 simulation of bimodal devices resulted in lower SRTs than the simulation of bilateral implants. The simulations of bimodal devices with less acoustic hearing (CI-0880 and CI-0440) resulted in SRTs that were similar to those with simulated bilateral implants. Only the simulation of bilateral implants resulted in significant SRM with noise on either side of the head. Thus, on this test battery, spatial listening skills with simulated bilateral implants were either superior, or equal, to skills with simulated bimodal devices, when the latter simulations created a level of functional acoustic hearing that is likely to be observed in implanted adults.

Chang et al. (2006) reported that speech perception in noise was poorer with simulated bilateral implants than with a simulation of bimodal devices in which the nonvocoded stimulus was low-pass filtered at 500 Hz. In contrast, the current study did not find a difference in SRTs between the simulation of bilateral implants and the simulations of bimodal devices that were similar to the simulation used by Chang and colleagues (CI-0880 or CI-0440). There are two possible reasons for the difference in results. First, the vocoded stimuli in the present study contained greater spectral detail than the four-channel vocoded stimuli used by Chang and colleagues. The additional detail may have reduced the benefit of combining low-pass filtered speech and vocoded speech. Second, the bimodal benefit is greater for tests of speech perception with a speech masker (as used by Chang et al.) than a steady-state noise masker, possibly because the latter reduces the opportunity to glimpse the target speech (Li & Loizou, 2008; Qin & Oxenham, 2006). A replication of the current study, using a test in which speech is masked by speech, may reveal greater advantages of simulated bimodal devices over simulated bilateral implants.

6.4.3 The absolute levels of performance shown by adults and children

To interpret the absolute levels of performance, it is helpful to consider factors that could lead implanted children to perform better than the adults in the present study. The children were experienced users of their devices, whereas the adults had only 45 minutes of training in each condition. The children listened to ITDs and ILDs generated by their own head and torso, and they could potentially turn their head and use the resulting changes in spectrum and level to help localise sources of sound. In contrast, the adults listened to interaural differences generated by a head and torso simulator, and they could not use head turns. These factors may explain why, on the Left-Right Discrimination test, bilaterally-implanted children performed better than adults listening to simulated bilateral implants.

On the other hand, the adults perceived stimuli via normal acoustic hearing rather than electrical stimulation, and they were unaffected by the perceptual consequences of hearing loss. Normally-hearing adults typically show lower SRTs than normally-hearing children, because adults have a fully-developed auditory nervous system and mature attentional and cognitive abilities (Chapter 4; Elliott et al., 1979; Garadat & Litovsky, 2007; Hall et al., 2002). These factors may explain why adults listening to simulations of implants showed lower SRTs than implanted children, in pulsatile noise and in some conditions in pink noise.

One factor that was shared by the children and adults was that the stimuli had been processed in a similar way, by either a cochlear-implant system or a vocoder. The performance of children and adults was remarkably similar on several of the outcome measures, which suggests that the signal processing limited the performance of both groups. It follows that the spatial listening skills of implanted children may improve if the signal processing is improved, either to provide greater spectral and temporal resolution (Rubinstein, 2004) or to coordinate the delivery of signals to the two electrode arrays. Bilaterally-implanted adults show increased sensitivity to ITDs when stimuli are delivered directly to their electrodes rather than via their sound processor (Grantham et al., 2008; Poon et al., 2009), which suggests that the sensitivity of implant users to interaural differences is not being fully utilised by current processors. However, it is also possible that the adults in the present study performed at a similar level to the implanted children because the factors discussed in the previous two paragraphs fortuitously cancelled each other out.

6.4.4 Strengths and limitations of the cochlear-implant simulations

The simulations used in the present study reflected several aspects of the listening environment that was experienced by implanted children during testing. The recordings encompassed the effects of the microphone used in one type of cochlear-implant system, and the location of that microphone over the concha. A head and torso simulator, situated in the testing booth used by children, was used to capture the interaural differences generated by the stimuli. Two independent devices applied AGC to the signals. Furthermore, the signals that were presented to the two ears had been processed in such a way that the temporal fine structure did not provide a cue to ITDs.

On the other hand, the simulations did not reflect some aspects of hearing via cochlear implant(s). The study did not simulate a frequency-to-place mismatch within the cochlea, although such a mismatch is common and is associated with impaired speech perception in implanted adults (Skinner et al., 2002). The simulations did not reflect the perceptual consequences of cochlear hearing loss, such as abnormal frequency selectivity, loudness growth, and a limited ability to benefit from temporal fine structure (B. C. J. Moore, 1996). The study employed the microphone, AGC, and frequency range used in cochlear-implant systems made by Advanced Bionics, and different results may be obtained using simulations of other systems. Furthermore, the simulations of bimodal devices did not incorporate the signal processing carried out by an acoustic hearing aid, and they created a rare situation of normal acoustic hearing within a certain frequency range and almost no hearing outside that range. Thus, although simulation studies are a useful way of comparing the potential benefits of different devices, it is necessary to consider results from studies of patients before making recommendations for clinical practice.

6.4.5 Causes of the differences between conditions

6.4.5.1 Tests of sound-source localisation

All of the conditions conveyed cues to source location that were somewhat distorted, because of the way the stimuli were recorded and processed. The HiRes Auria™ processor applies AGC to signals above 63 dB SPL (P. Boyle, personal communication, April 4, 2007). Consequently, the stimuli may have generated attenuated ILDs if the AGC was active in one processor but not the other (although undistorted ILDs may have been present at the onset of the stimulus, before the AGC was fully active). The vocoder processing meant that none of the simulations conveyed ITDs in the temporal fine structure (Francart, 2008; Moy, 2004). Despite the distorted cues, performance with simulated bilateral implants was above chance levels on tests of sound-source localisation. Presumably, participants responded on the basis of ITDs conveyed by the amplitude envelope, ILDs, and/or monaural level and spectral cues.

Performance was poorer with simulated bimodal devices than with simulated bilateral implants on tests of left-right discrimination and localisation. In the bimodal simulations, the low-pass filtering removed the frequencies at which ILDs are greatest (above 2 kHz, Fedderson et al., 1957). Moreover, it may have been difficult to detect ILDs in the bimodal simulations, because the signals at the two ears only partly overlapped in frequency (Francart & Wouters, 2007). For example, in the CI-0440 condition, the listener had to compare the gross energy in the lowest vocoder channel (centred on 350 Hz) with the nonvocoded energy in the range 0–440 Hz. Accordingly, it is likely that participants were less able to use ILD as a cue to source location in the bimodal simulations than in the simulation of bilateral implants.

Performance with a simulated unilateral implant (CI-0000) was above chance levels on tests of left-right discrimination, localisation, and movement tracking. This indicates that, following training, monaural cues can be used to perform the Localisation test, despite the processing described in Appendix A. It is not clear why performance on the Localisation test was better with a simulated unilateral implant (CI-0000) than with simulated bimodal devices (CI-0440). Possibly, presenting a low-pass filtered stimulus to one ear disrupted the ability of participants to attend to monaural cues at the other ear.

6.4.5.2 Tests of speech perception in pink noise

Two of the simulations of bimodal devices (CI-1320 and CI-0880) resulted in lower SRTs in pink noise than a simulation of bimodal devices with less acoustic hearing (CI-0440) or a simulation of a unilateral implant (CI-0000). For this female target talker, the signals that were low-pass filtered at 1320 or 880 Hz conveyed the first formant and sometimes the second formant (Peterson & Barney, 1952). The low-pass filtered signals also conveyed information about voicing. Presumably, this additional phonetic information enabled participants to tolerate a more adverse signal-to-noise ratio in the CI-1320 and CI-0880 conditions than the CI-0440 and CI-0000 conditions. The phonetic information conveyed by the low-pass filtered signal also explains why participants could tolerate a more adverse signal-to-noise ratio in the CI-1320 condition than in the CI-CI condition.

The simulation of bilateral implants resulted in lower SRTs in pink noise than the simulation of a unilateral implant (CI-0000). This difference was mostly due to the head shadow effect: with noise ipsilateral to the first device, SRTs were 6.5 dB lower with simulated bilateral implants than with a simulated unilateral implant.

6.4.5.3 Spatial release from masking

The simulation of bilateral implants was the only condition in which participants showed significant SRM with noise on either side of the head. In this condition, the wideband vocoded signals allowed listeners to take advantage of the beneficial signal-to-noise ratio that was created at a microphone when noise was presented from the far side of the head. The same physical effect was present in the recordings for the simulations of bimodal devices, but the low-pass filter removed the frequencies at which the head shadow is greatest (Fedderson et al., 1957). Thus, the difference in signal-to-noise ratio between the noise-front condition and the noise-ipsilateral condition was smaller for the simulations of bimodal devices than the simulation of bilateral implants, meaning that SRM was smaller in the conditions with simulated bimodal devices.

6.4.5.4 Tests of speech perception in pulsatile noise

In all conditions, SRTs in the Toy Discrimination test in pulsatile noise were lower for the Raised-F0 masker than the Same-F0 masker. The following sections discuss possible causes of the difference between maskers, first for the vocoded stimuli and second for the simulations of bimodal devices.

6.4.5.4.1 Speech perception in pulsatile noise with vocoded stimuli The frequency spectra of the vocoded stimuli are shown in Figure 6.14. A number of factors may have contributed to the difference in SRT between maskers:

1) After vocoding, the total RMS power of the Raised-F0 masker was 1 dB less than the Same-F0 masker. However, this difference is too small to account for all of the observed difference in SRT, which was 5–7 dB on average.

2) The two maskers differed in the number of harmonics that fell within the passband of the channel filters in the vocoder. Consequently, the sine waves at the centre frequency of channels 5, 7, and 8 were of a lower amplitude for the Raised-F0 masker than the Same-F0 masker. It is likely that, for this female target talker, the frequency region conveyed by channel 5 (centred on 1.9 kHz) carried information about the second formant (Peterson & Barney, 1952). This phonetic information may have been masked less by the Raised-F0 masker than the Same-F0 masker. However, the opposite argument could be applied to channels 1, 3, and 4, where evidence of the first formant would have been conveyed.

3) The amplitude modulation of the carrier sine waves created sidebands, meaning components whose frequency was above or below that of the carriers (Figure 6.14). Prior to vocoding, the amplitude of each stimulus was modulated at a rate equal to the F0 (which was 200 Hz for the speech and the Same-F0 masker, and 360 Hz for the Raised-F0 masker). The vocoder used a low-pass filter at 160 Hz to extract the amplitude envelope, so one might expect amplitude modulations above this frequency to have been removed. However, the second-order filter had a shallow roll-off, so amplitude modulations at 200 Hz and 360 Hz were preserved (with some attenuation of the modulations at 360 Hz). Consequently, for the Same-F0 masker and the speech, sidebands occurred at integer multiples of 200 Hz above and below the centre frequency of each channel. For the Raised-F0 masker, sidebands occurred at integer multiples of 360 Hz above and below the centre frequency. Thus, the sidebands of the speech were masked less by the Raised-F0 masker than the Same-F0 masker. If the sidebands conveyed phonetic information and listeners could resolve the sidebands (Stone et al., 2008), the difference in masking may have contributed to the difference in SRT. To investigate this possibility, the vocoded stimuli for the CI-CI condition were processed to remove the components at and around the centre frequency of each channel in the vocoder while leaving the sidebands intact. An FFT filter was used to apply eight inverse Hanning windows, each centred on a

centre frequency and approximately 200 Hz wide. Two normally-hearing listeners completed the Toy Discrimination test in pulsatile noise using the filtered stimuli. Both listeners had SRTs that were 9 to 10 dB lower with the Raised-F0 masker than the Same-F0 masker. Thus, the difference between maskers persisted when only the sidebands were present. This result is compatible with the idea that: (i) fluctuations in the levels of the sidebands in the speech conveyed phonetic information, and (ii) the fluctuations were masked more effectively by the sidebands of the Same-F0 masker than by the sidebands of the Raised-F0 masker.

4) A percept of pitch, based on periodicity in the amplitude envelope, may have helped listeners to segregate the speech from the Raised-F0 masker. Souza and Rosen (2009) demonstrated that normally-hearing listeners can accurately report changes in the F0 of sine-vocoded speech, if the low-pass filter used to extract the amplitude envelope has a cut-off above the F0 of the speech. Although the present study used a filter with a cut-off below the F0 of the speech, the filter had a shallow roll-off. As a result, participants may have been able to segregate the speech from the Raised-F0 masker, but not the Same-F0 masker, on the basis of F0.

To summarise, sidebands in the vocoded speech signal were masked to a lesser degree by the Raised-F0 masker than the Same-F0 masker, which appears to have contributed to the difference in SRT between maskers. The difference in the amplitude of the vocoded maskers probably added to the difference in SRT. Further research is required to assess whether reduced masking of the second formant, and/or segregation on the basis of F0, also contributed to the better performance with the Raised-F0 masker.

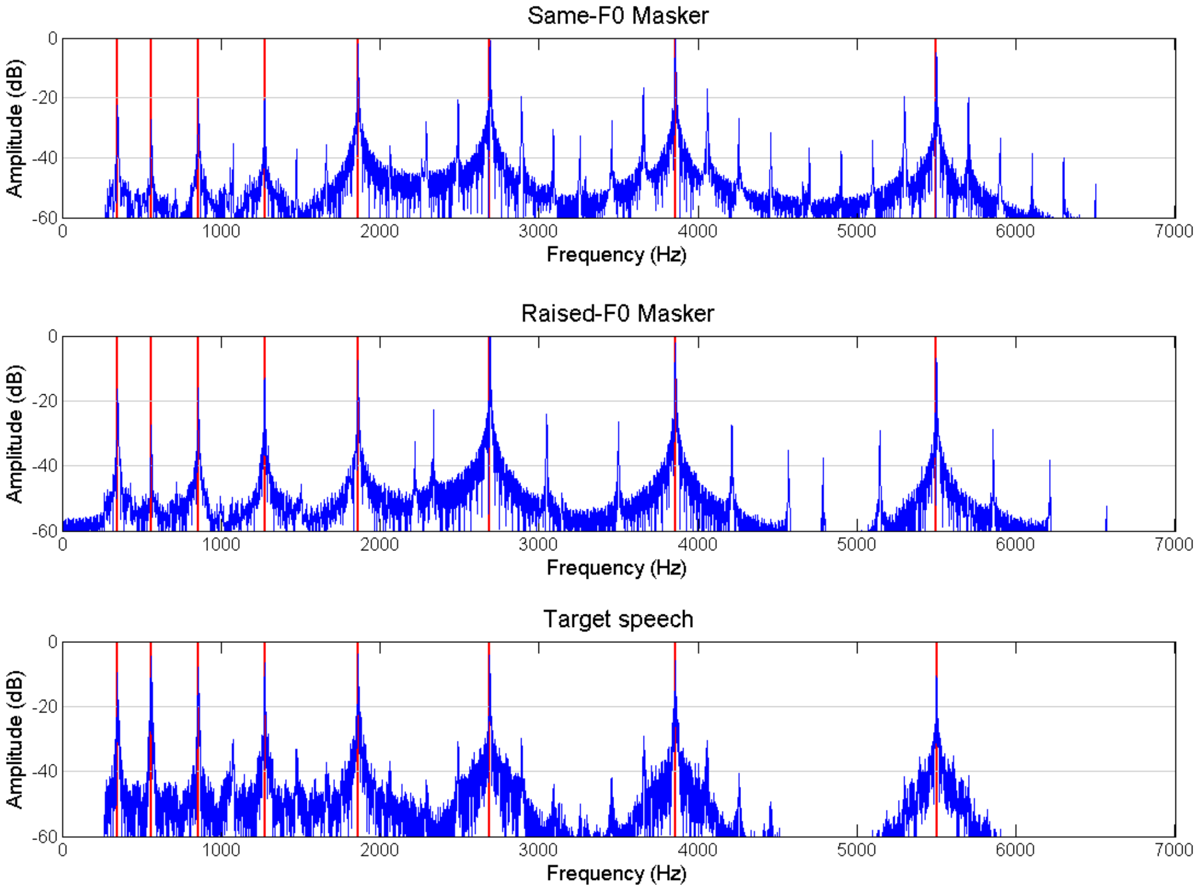

Figure 6.14. The frequency spectra of the vocoded stimuli for the Toy Discrimination test in pulsatile noise. Upper panel: Same-F0 masker. Centre panel: Raised-F0 masker. Lower panel: a speech phrase (“Point to the cup”). The blue trace shows the frequency spectra. The vertical red lines indicate the centre frequencies of the channels in the vocoder. The peaks between those centre frequencies indicate sidebands created by the amplitude modulation of the carrier sine waves. Sidebands around the low-frequency carriers were removed by the second stage of bandpass filtering in the vocoder. The scale of the vertical axis is the same for each graph.

6.4.5.4.2 Speech perception in pulsatile noise with simulated bimodal devices

Listeners showed a greater difference between the Raised-F0 and Same-F0 maskers with the CI-1320 simulation of bimodal devices than with the simulation of bilateral implants. In the CI-1320 condition, listeners may have been able to segregate the speech from the Raised-F0 masker on the basis of a difference in F0 (Assmann & Summerfield, 1990). Relevant data come from Culling and Darwin (1993), who presented normally-hearing adults with two concurrent vowels that had either: 1) the same F0 throughout the frequency spectrum, or 2) a difference in F0 around the region of the first formant and the same F0 in higher-frequency regions. The vowels were identified more accurately in the latter condition. In the CI-1320 condition of the present study, the first formant was represented by the nonvocoded signal. Based on the findings of Culling and Darwin it is plausible that, in the CI-1320 condition, listeners segregated the first formant from the Raised-F0 masker, allowing them to tolerate a more adverse signal-to-noise ratio than with the Same-F0 masker.

Although both maskers were presented at an equal level in the ring of loudspeakers, the Same-F0 masker contained energy above 200 Hz whereas the Raised-F0 masker only contained energy above 356 Hz. Consequently, in the nonvocoded signals in the bimodal simulations, low-frequency phonetic information (such as the F0, which provides a cue to voicing) will have been distorted to a lesser degree by the Raised-F0 masker than the Same-F0 masker. The reduced masking at low frequencies may have contributed to the difference between maskers shown in all of the bimodal simulations.

6.4.6 Conclusion

Normally-hearing adults showed differences in performance between simulations of unilateral and bilateral implants that were similar to the differences observed between unilaterally- and bilaterally-implanted children. This study provides further evidence that the children's performance was primarily influenced by the number of implants they used, rather than by confounds. Spatial listening skills with simulated bilateral implants were either superior, or equal, to skills with simulated bimodal devices, if the latter simulations created a level of functional acoustic hearing that is likely to be observed in implanted adults. The levels of performance shown by the adults were remarkably similar to the levels of performance shown by implanted children, which suggests that the signal processing carried out by the implant system (or a simulation of that processing) limits the performance of both normally-hearing adults and implanted children.

6.5 Summary

- Normally-hearing adults attempted tests of spatial listening using stimuli presented over headphones. The tests were designed to be similar to those used in the study of implanted children.
- Five conditions simulated the signal processing carried out by a unilateral implant, a unilateral implant with varying degrees of contralateral acoustic hearing, and bilateral implants.
- Performance was better with simulated bilateral implants than with the other simulations on tests of left-right discrimination, localisation, and SRM with noise ipsilateral to the first device.
- Performance was better with simulated bimodal devices than with simulated bilateral implants on tests of speech perception in steady-state noise. This difference was not shown when the simulation of bimodal devices included a lesser degree of contralateral acoustic hearing.
- All conditions yielded similar levels of performance on tests of sentence perception in quiet, movement tracking, and SRM with noise contralateral to the first device.
- The differences in performance between simulations reflect the differences in performance between groups of implanted children, indicating that the children's performance was primarily influenced by their devices rather than by confounds.

Chapter 7

Quality of Life of Children with Unilateral or Bilateral Cochlear Implants

Measurements of quality of life contribute to the effectiveness component of cost-effectiveness analysis, which is used by policy-makers in the UK and elsewhere to prioritise spending within the healthcare system. Consequently, the question of whether bilateral implantation improves quality of life compared with unilateral implantation has implications for healthcare policy. This chapter reports two studies that compared the quality of life of children with unilateral or bilateral cochlear implants. The first study obtained estimates from the parents of unilaterally- and bilaterally-implanted children, and found that the groups did not differ significantly in quality of life. However, the estimate of the difference between the groups had a confidence interval that embraced the minimum difference required for bilateral implantation to be considered cost-effective. The second study obtained estimates from informants who read descriptions of an implanted child. Bilateral implantation was associated with a significant gain in quality of life relative to unilateral implantation. These studies indicate that implanting both ears rather than one may increase the quality of life of severely-profoundly deaf children, but the exact extent of any increase remains uncertain.

7.1 Introduction

Healthcare systems around the world are faced with rising medical costs due to a growing population, increasing longevity, demand for new treatments, and rising expectations for healthy life. Healthcare systems whose resources are finite cannot provide every possible intervention: they have to decide which interventions should be funded and which should not. In England and Wales, the National Institute for Health and Clinical Excellence (NICE) is responsible for making such decisions on behalf of the National Health Service. Decisions are based on safety, clinical effectiveness, and cost-effectiveness (NICE, 2008b).

Cost-effectiveness analysis, which is also used outside the UK, enables one to describe any healthcare intervention in terms of the costs it incurs relative to its effectiveness (Drummond, Sculpher, Torrance, O'Brien, & Stoddart, 2005). To enable comparisons between a range of different interventions, effectiveness can be measured as the degree to which an intervention extends life *and* the degree to which it improves health-related quality of life.[1] The cost-effectiveness of an intervention is assessed relative to the next-best alternative. Thus, for bilateral cochlear implantation, the incremental costs and incremental gain in quality of life are measured relative to unilateral cochlear implantation.

The studies reported in this chapter assessed the health-related quality of life of children with either unilateral or bilateral implants, in order to estimate the incremental gain in health-related quality of life associated with bilateral implantation. To set the studies in context, the following sections describe how costs and effectiveness can be measured and how these measurements are combined to assess cost-effectiveness. The subsequent sections review previous assessments of the quality of life of bilaterally-implanted patients and the cost-effectiveness of bilateral implantation.

7.1.1 Measuring costs

The cost of an intervention can be calculated from a number of perspectives: costs may be incurred or averted by the health service, by other government services, by the patient and their family, or as a result of changes in productivity. For NICE, the primary perspective is that of the National Health Service in England and Wales (NICE, 2008b). Costs are estimated as the total incremental cost of providing the treatment, compared to the next-best alternative, over the expected remaining lifetime of a cohort of patients. In some cases, NICE also considers a secondary perspective that includes costs that are incurred or averted by government services in addition to the National Health Service (NICE, 2008b). For example, in an analysis of paediatric unilateral implantation commissioned by NICE, the estimated costs incorporated savings in the cost of education that are associated with unilateral implantation, compared to the provision of bilateral acoustic hearing aids (Barton et al., 2006a; Bond et al., 2007).

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[1] Other authors use the term 'cost-utility analysis' to refer to analyses in which effectiveness is measured by the extension of life and the change in health-related quality of life (Drummond et al., 2005). This thesis follows NICE in using the more general term of cost-effectiveness analysis.

7.1.2 Measuring effectiveness

7.1.2.1 Measuring health-related quality of life

The first step in measuring effectiveness is to measure the incremental gain in health-related quality of life associated with an intervention. The incremental gain can be calculated as the difference in health-related quality of life between two groups of patients: those who received the intervention of interest and those who received the next-best alternative. The estimates of quality of life can be obtained from the patients themselves, from the patients' parents or carers, or from other members of the public who have read a description of the health state. There are several methods for measuring health-related quality of life, all of which can be thought of as obtaining a person's preference for a state of health (Drummond et al., 2005).

7.1.2.1.1 Formal measures of preference The term utility refers to a person's preference for a state of health, obtained under conditions of uncertainty, and expressed using an interval scale on which perfect health takes the value one and dead takes the value zero (Drummond et al., 2005). Utility is measured using the standard gamble, in which the participant is presented with two alternatives (Drummond et al.; Torrance, 1986). The first alternative is to opt for a treatment with two possible outcomes: the participant may be healthy for their remaining years of life (with probability p) or they may die immediately (with probability 1-p). The second alternative is to continue living in the health-state *i* for the remaining years of life. The participant is asked to vary p until they are indifferent between the two alternatives. Their preference for the health-state *i* is equal to p. The advantage of the standard gamble is that preference is measured under conditions of uncertainty, which reflects the uncertain outcome of many healthcare interventions. However, the standard gamble is time-consuming and conceptually complicated.

An alternative method for measuring a person's preference for a state of health is the time trade-off technique (TTO; Drummond et al., 2005; Torrance, Thomas, & Sackett, 1972). The participant is again presented with two alternatives. The first alternative is to live in the health-state *i* for their remaining expected years of life (t). The second alternative is to live in a state of perfect health for x years. The participant is asked to adjust the value of x until they are indifferent between the two alternatives. Their preference for the health-state *i* is x / t. The results are expressed on an interval scale on which perfect health takes the value one and dead takes the value zero. Although the TTO incorporates an opportunity cost (the years given up), it does not measure preference under conditions of uncertainty, so the results are referred to as values rather than utilities (Drummond et al.). The TTO can be adapted for use with parents whose children have the health-state *i*: the parent is asked to trade-off years from the end of their own life in order for their child to have perfect health for the remainder of the child's life. However, parents occasionally find this technique difficult to understand or upsetting.

7.1.2.1.2 Visual-analogue scales A person's preference for a state of health can be measured using a visual-analogue scale (VAS; Drummond et al., 2005). Typically, the scale is a line ranging from 0 (labelled dead) to 100 (labelled perfect health) and the participant is asked to make a mark to indicate the quality of life associated with a health state. VASs can be completed quickly and are easy to understand. VASs may not give a measure of preference on an interval scale, because they are subject to two types of bias (Torrance, Feeny, & Furlong, 2001). First, participants tend not to make marks at the extreme ends of the scale. Second, VASs are affected by context: when given a group of health states, participants tend to space out their answers on the scale even if they assign similar utilities to those health states using the standard gamble. Ratings from VASs are typically lower than preferences obtained using the standard gamble or TTO, because of participants' aversion to risk and unwillingness to trade-off years of life (Torrance et al., 2001). To approximate the standard gamble or TTO, VAS ratings can be compressed using a power formula of the form $1-(1-\mathrm{VAS})^b$. Studies which used both VAS and TTO found that an exponent, b, of 1.6 resulted in VAS values that were similar to values measured using TTO (e.g. Cheng et al., 2000; Torrance, 1976).

7.1.2.1.3 Health-status questionnaires One can also measure health-related quality of life using a questionnaire that generates a description of health status. For example, the Health Utilities Index Mark 3 (HUI) contains 15 questions relating to eight dimensions of health: vision, hearing, speech, ambulation, dexterity, emotion, cognition, and pain (Horsman, Furlong, Feeny, & Torrance, 2003). A high score on each dimension is assumed to represent good health. A sample of the Canadian public used the standard gamble to assign utilities to descriptions of health status generated by the questionnaire (Feeny et al., 2002). These data were used to define a function to convert questionnaire responses into utilities. Thus, a participant's response on the HUI can be converted to a utility which reflects the preferences of the Canadian population. It is possible to obtain a negative utility, which indicates a health state that the public considered to be worse than death. A parent-proxy version of the HUI is suitable for the parents of children aged 5 years and above (Horsman et al.).

A different questionnaire, the EuroQol EQ-5D, contains five questions relating to mobility, self-care, usual activity, pain/discomfort, and anxiety/depression (EuroQol Group, 1990). A function to convert EuroQol EQ-5D scores to TTO values was derived from a study in which members of the public in the UK used the TTO to value health states defined by the EuroQol EQ-5D (Dolan, 1997). The EuroQol EQ-5D does not contain questions about the ability to hear or the ability to speak. Consequently, compared to the HUI, this questionnaire is insensitive to impairments in quality of life caused by impaired hearing (Barton et al., 2005) and to improvements in quality of life caused by interventions to improve hearing (Grutters et al., 2007; Sach & Barton, 2007). Moreover, the EuroQol EQ-5D was not designed for use with children under the age of 12 years (EuroQol Group, 2010), nor is there a parent-proxy version for the parents of children under the age of 12 years (NICE, 2008b).

7.1.2.1.4 The impact of deafness on health-related quality of life There is evidence that the parents of some deaf children do not consider that deafness is associated with a loss of health-related quality of life, but rather a loss of general quality of life. Sach and Barton (2007) asked the parents of 160 unilaterally-implanted children to complete two VASs, on which the endpoints were labelled either 'best and worst imaginable health state' or 'best and worst imaginable quality of life'. The parents completed the scales for their child's current health state and quality of life, and also retrospectively based on their memories of their child prior to implantation. The average increment associated with unilateral implantation was +0.14 (95% confidence interval +0.10 to +0.18) on the scale labelled 'health state', and +0.35 (95% confidence interval +0.32 to +0.39) on the scale labelled 'quality of life'. The authors concluded that the benefits of cochlear implantation may be underestimated if outcomes are measured only by the change in health-related quality of life.

7.1.2.1.5 Interim summary There are several techniques for measuring a person's preference for a state of health, and the results vary depending on which method is used (Drummond et al., 2005). Guidance from NICE states that their preferred measure of preference is the EuroQol EQ-5D, because the values reflect the preferences of the UK population (NICE, 2008b). However, other measures of preference are considered by NICE if data from the EuroQol EQ-5D are unavailable or inappropriate for a certain condition. The EuroQol EQ-5D, and VASs that refer to health-related quality of life, are less sensitive to the benefits of unilateral cochlear implantation than the HUI and VASs that refer to general quality of life.

7.1.2.2 Calculating quality-adjusted life years

Some interventions extend life whereas others, such as cochlear implantation, improve quality of life. To enable comparisons between these interventions, effectiveness can be summarised by the gain in quality-adjusted life years (QALYs): the gain in quality of life integrated over the predicted lifetime of the patient (Drummond et al., 2005). Any of the measures of quality of life described in section 7.1.2.1 can be used to calculate QALYs, provided they use an interval scale from one (perfect health) to zero (dead). Consequently, a single year at perfect quality of life is one QALY. Figure 7.1 shows a simple example of how QALYs are calculated.

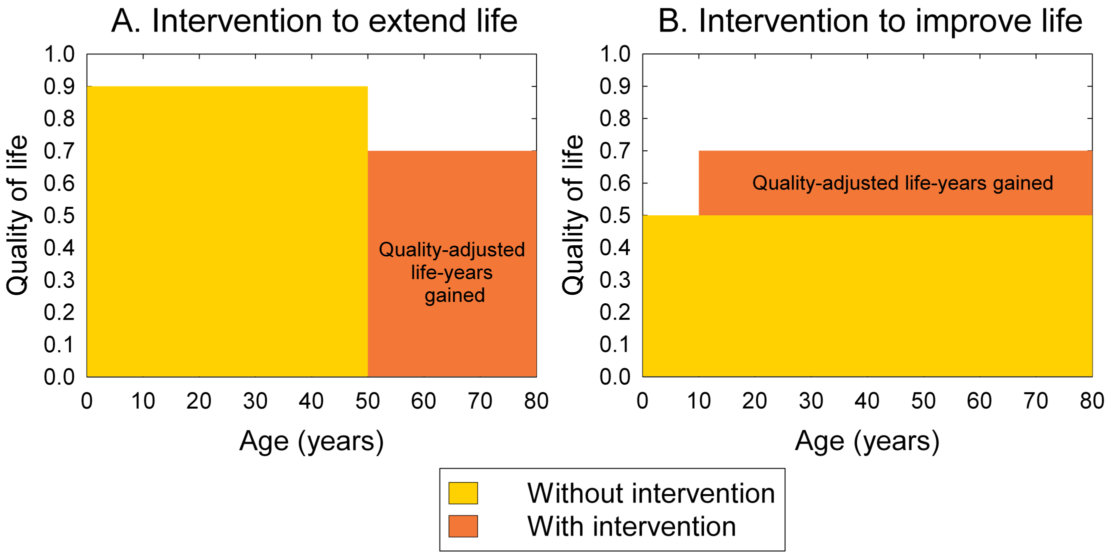

Figure 7.1. Calculating quality-adjusted life years. Each figure plots the quality of life of a hypothetical patient over 80 years of life. Plot A shows an intervention that extends life and Plot B shows an intervention that improves life. Plot A: the patient had a quality of life of 0.9 for 50 years (yellow area), at which point they would have died without the intervention. Having received the intervention, they lived for a further 30 years with a quality of life of 0.7 (orange area). The gain in QALYs was 0.7*30 = 21. Plot B: without the intervention, the patient would have had a quality of life of 0.5 for 80 years (yellow area), at which point they die. Having received the intervention at the age of 10 years, their quality of life increased to 0.7 (orange area) for the remaining 70 years of life. The gain in QALYs was 0.2*70 = 14.

7.1.3 The cost-effectiveness ratio and incremental net benefit

The ratio of incremental costs to incremental QALYs is known as the cost-effectiveness ratio. For an intervention with an average incremental cost (ΔC) of £50,000 per patient and an average incremental gain (ΔQ) of 2 QALYs per patient, the incremental cost-effectiveness ratio ($\Delta C/\Delta Q$) is £25,000 per QALY.[2] It is difficult to perform informative statistical analyses on ratios of incremental costs and QALYs, particularly given that the increments can be negative. Therefore, the ratios can be converted (linearised) by expressing them as values of *incremental net benefit*, calculated as $r\Delta Q - \Delta C$ where r is the amount that society is willing to pay to gain a QALY. For a given value of r, an intervention is cost-effective if the incremental net benefit is positive. For the example at the beginning of the paragraph, the incremental net benefit is +£10,000 for a value

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[2] In practice, both costs and QALYS are discounted, meaning they are reduced by a certain percentage per annum. Discounting reflects people's preference to incur benefits sooner rather than later, but to incur expenditure later rather than sooner. This is known as the principle of time preference (Drummond et al., 2005).

of r of £30,000, but the incremental net benefit is −£10,000 if society is willing to pay only £20,000 to gain a QALY.

For the majority of interventions, the costs and QALYs vary from one patient to another. To reflect this variability, one can construct a decision-analytic model which defines the possible outcomes, the probability of each outcome, and the costs and QALYs associated with each outcome (Briggs, Sculpher, & Claxton, 2006; Drummond et al., 2005). Such a model provides a framework to calculate the incremental net benefit. However, there is often uncertainty regarding the parameters in a model (meaning the probability of different outcomes, the costs, and the QALYs), because of random variation, lack of knowledge, and measurement error. To reflect uncertainty, a probabilistic sensitivity analysis can be conducted by calculating the incremental costs and QALYs many times (Briggs et al.). For every calculation, each parameter in the model is sampled from the observed distribution of that parameter. This process yields a distribution of incremental costs and QALYs, which can be summarised by calculating the incremental net benefit and a confidence interval around that estimate. In addition, one can calculate the probability that the incremental net benefit is positive, for a given value of r.

Cost-effectiveness analysis can be used by policy-makers to prioritise interventions that gain QALYs at an acceptable cost. Typically, NICE only recommends an intervention if the incremental net benefit is positive for a maximum value of r of £30,000 (NICE, 2008b; Rawlins & Culyer, 2004). In other words, NICE recommends interventions with an incremental cost-effectiveness ratio less than £30,000. If the cost-effectiveness ratio is higher than this threshold, it is necessary to make "an increasingly stronger case for supporting the technology as an effective use of National Health Service resources" (NICE, 2008b).

7.1.4 The quality of life of children with bilateral cochlear implants

There have been only two assessments of the quality of life of bilaterally-implanted children. Beijen et al. (2007) asked the parents of five bilaterally- and five unilaterally-implanted children to complete the Pediatric Quality of Life Inventory, a questionnaire that assesses physical, emotional, and social functioning. There was no significant difference between the groups: the bilateral mean was 90.2%, the unilateral mean was 89.4%, and the 95% confidence interval (c.i.) for the difference was −11.0 to +12.6 (a positive difference indicates higher ratings for the bilateral group). The descriptions of health status generated by the Pediatric Quality of Life Inventory have not been valued by members of the public using the standard gamble or TTO, and therefore this questionnaire does not yield a formal measure of health-related quality of life. Despite finding no difference in quality of life, Beijen et al. did find that there was a significant difference between the groups in parental ratings of listening skill: the bilateral group had higher scores than the unilateral group on the spatial subscale of the Speech, Spatial, and Qualities of Hearing Scale (see section 7.2.2.2.1 for further details of the questionnaire).

Bichey and Miyamoto (2008) obtained utility estimates from 23 participants (both adults and children) who had received bilateral implants in sequential surgeries. The participants completed the HUI three times: based on their memory of life with no implant, based on their memory of life with one implant, and based on their current state of health. The average utilities were 0.33, 0.69, and 0.81, respectively. Thus, the increment in utility associated with unilateral implantation was +0.36 and the increment associated with bilateral implantation was +0.12; both increments were statistically significant (c.i. were not reported). The estimates from Bichey and Miyamoto for utility with no implant and with a unilateral implant were similar to those reported by Cheng et al. (2000), who obtained HUI utilities from the parents of 22 unilaterally-implanted children. The average utility based on their memory of the child's life with no implant was 0.25 and the average utility for the child's current health was 0.64, giving a significant increment of +0.39 (95% c.i. +0.31 to +0.46). Retrospective judgements may reveal disability, because sometimes patients (or parents) realise how debilitating a condition is only after it has improved. On the other hand, retrospective judgements are confounded with maturation: the individual's quality of life may have improved with time regardless of the intervention they received. Moreover, retrospective judgements are at risk of recall bias (meaning patients incorrectly recall their health status), and at risk of bias caused by gratitude for healthcare received (or paid for) and by expectations of that healthcare.

To assess the degree to which the results of Bichey and Miyamoto (2008) may be affected by bias, the results can be compared with studies that obtained contemporary, rather than retrospective, estimates of health-related quality of life using the HUI. Using the parent-proxy version of the HUI, Barton et al. (2006b) found that the utility of 403 unilaterally-implanted children was 0.58 and the utility of 290 unimplanted children with a similar hearing loss was 0.35. After controlling for confounds, the greatest increment in utility shown by any of the subgroups of implanted children was +0.23 (95% c.i. +0.18 to +0.28). Just over half of the participants in the study of Bichey and Miyamoto were adults, so comparisons with studies of adults are also informative. The UK Cochlear Implant Study Group (2004a) administered the HUI to 311 adults prior to, and 9 months after, unilateral implantation. The greatest increment in utility shown by any of the subgroups was +0.23 (95% c.i. +0.20 to +0.27). Thus, Bichey and Miyamoto reported an increment in utility associated with unilateral implantation that was greater than the maximum increments shown by studies using contemporary estimates. Consequently, the results of Bichey and Miyamoto appear to be at risk of bias, which casts doubt on the validity of the reported increase in utility associated with bilateral implantation.

7.1.5 The quality of life of adults with bilateral cochlear implants

Given the scarcity of data relating to the quality of life of bilaterally-implanted children, it is helpful to review assessments of the quality of life of bilaterally-implanted adults. Summerfield et al. (2006) reported a randomised controlled trial that compared the HUI utilities of 12 unilaterally- and 12 bilaterally-implanted adults. The utility of the unilateral group did not differ significantly from that of the bilateral group, when the latter group was assessed 9 months after the second implantation (mean +0.1 higher for bilateral, 95% c.i. −0.1 to +2.9). The unilateral group then received a second implant. Accordingly, Summerfield et al. (2006) presented data from a within-subjects comparison of the entire sample of 24 patients who completed the HUI prior to, and 9 months after, receiving a second implant. The mean change in utility following bilateral implantation was −0.02 (95% c.i. −0.11 to +0.08). The decrease in utility was attributed to two of the patients who reported increased annoyance from tinnitus following the second implantation (typically, a smaller proportion of patients report this complication; Pan et al., 2009). When the effect of worsening tinnitus was controlled statistically, the change in HUI associated with bilateral implantation was +0.03 (95% c.i. −0.05 to +0.10). However, the within-subjects comparison was confounded with gratitude for healthcare received and with the passage of time (the patients' quality of life may have improved over time, regardless of the intervention).

A further study asked researchers and clinicians, who worked with hearing-impaired people, to read descriptions of hypothetical adults with unilateral or bilateral implants (Summerfield, Marshall, Barton, & Bloor, 2002). The participants completed the TTO for each description. Their estimate of the incremental gain in health-related quality of life associated with bilateral implantation was +0.03 (95% c.i. +0.02 to +0.04), which is congruent with the adjusted estimate reported by Summerfield et al. (2006).

7.1.6 The cost-effectiveness of bilateral implantation for children

Cochlear implantation was evaluated by NICE between 2006 and 2009. One of the most contentious issues was paediatric bilateral implantation: there was uncertainty about whether this intervention resulted in improved quality of life and whether any gain in quality of life was large enough to justify the additional cost compared with unilateral implantation. The uncertainty was reflected in the decision-making process: draft guidance recommended bilateral implantation for children (NICE, 2007), then revised draft guidance stated that unilateral implantation should be the standard intervention (NICE, 2008a). The proposal was reversed again in the final guidance, which recommends bilateral implantation for children (NICE, 2009).

The health economists commissioned by NICE used estimates of utility obtained from bilaterally-implanted adults as the basis of cost-effectiveness analyses of bilateral implantation for children (Bond et al., 2007). The gain in utility of +0.03 from Summerfield et al. (2006) was used for the initial analysis, which found that the average incremental cost-effectiveness ratio for paediatric bilateral implantation was £36,040 per QALY. This is above the usual threshold of £30,000 per QALY. Subsequent analyses reported that, if the increment in utility was as great as +0.04 or +0.05, the average incremental cost-effectiveness ratio would be £27,886 per QALY or £22,740 per QALY, respectively (p. 20, NICE, 2009). Thus, the increment in health-related quality of life associated with bilateral implantation would have to be at least +0.04 for the intervention to be considered cost-effective. Based on advice from clinical experts, the committee appointed by NICE decided that a gain of +0.04 was plausible, and therefore recommended bilateral implantation for children as a cost-effective use of resources (pp. 28–9, NICE, 2009).

The aim of the two studies described in this chapter was to measure the gain in health-related quality of life, and general quality of life, associated with bilateral compared to unilateral implantation in children. The first experiment obtained estimates of quality of life from the parents of implanted children; the second experiment obtained estimates from informants who read descriptions of a hearing-impaired child. The findings of the second study were incorporated into a probabilistic decision-analytic model by Summerfield, Lovett, Batten, and Bellenger (in press.).

7.2 Experiment 1: Parental estimates of the quality of life of children with cochlear implants

7.2.1 Introduction, aims and hypotheses

This study obtained estimates of the quality of life of the unilaterally- and bilaterally-implanted children whose listening skills were described in Chapter 5. Estimates of quality of life were obtained from a parent rather than from the child, because of the young age of some of the children. The HUI was used to measure health-related quality of life, because it is easier to understand than the standard gamble or TTO and more sensitive to hearing impairment than the EuroQol EQ-5D. A VAS was used to measure general quality of life. The Speech, Spatial, and Qualities of Hearing Scale was used to obtain parental ratings of children's listening skills (Galvin, Mok, & Dowell, 2007; Gatehouse & Noble, 2004).

The first objective was to compare the quality of life of unilaterally- and bilaterally-implanted children. The second objective was to compare parental ratings of the listening skills of unilaterally- and bilaterally-implanted children, in order to assess whether the benefits of bilateral implantation demonstrated in laboratory tests were also evident in listening skills in everyday life. The third objective was to obtain retrospective estimates of children's general quality of life before and after receiving bilateral implants, to allow comparisons with the study of Bichey and Miyamoto (2008). The fourth objective was to compare parental estimates of quality of life and listening skills for simultaneous and sequential bilaterally-implanted children. The fifth objective was to assess whether parental estimates of quality of life correlated with either parental ratings of listening skills or laboratory assessments of spatial listening skills.

It was not known whether the unilateral and bilateral groups would differ in parental estimates of general or health-related quality of life. It was predicted that the parents of bilaterally-implanted children would rate their child's listening skills more highly than the parents of unilaterally-implanted children. It was predicted that the parents of bilaterally-implanted children would rate their child's current quality of life more highly than their quality of life if they had received only one implant. Based on the results of Chapter 5, it was predicted that the simultaneous and sequential bilaterally-implanted children would have similar parental ratings of listening skills and similar parental estimates of quality of life.

7.2.2 Method

7.2.2.1 Participants

One parent of each child who participated in the experiment reported in Chapter 5 took part. For the unilateral group, 16 of the 20 respondents (80%) were female and their average age was 41.1 years (standard deviation 5.6 years). For the bilateral group, 27 of the 35 respondents (77%) were female and their average age was 41.1 years (standard deviation 6.1 years). The study was approved by the North West Research Ethics Committee of the National Research Ethics Service. Parents gave written informed consent.

7.2.2.2 Procedure

The questionnaires were usually completed after the child had finished the listening tests; occasionally they were returned by post. Parents were asked to complete questionnaires in the following order.

7.2.2.2.1 The Speech, Spatial, and Qualities of Hearing Scale for Teachers of the Deaf The Speech, Spatial, and Qualities of Hearing Scale was developed as a self-report measure for hearing-impaired adults (Gatehouse & Noble, 2004). Galvin, Mok, and Dowell (2007) modified the scale to create a version for parents and a version for teachers: the Speech, Spatial and Qualities of Hearing Scale for Teachers of the Deaf (SSQ). The teachers' version was given to parents in the current study, because the question phrases are simpler than in the parents' version. The question content is similar in both versions. The SSQ is included in Appendix B; it contains three subscales that measure hearing for speech (this subscale contains eight questions), spatial hearing (five questions), and qualities of hearing (eight questions). An example question from the speech subscale is, "You are talking to your child in a room in which there are many other people talking. Can your child follow what you say?" Parents responded using a horizontal VAS with endpoints marked 0 and 10 (labelled "Not at all" and "Perfectly", respectively). The responses on the VAS were converted to a number with an accuracy of one decimal place, then averaged for each subscale. This yielded a score from 0 to 10 for each subscale, with higher scores representing greater ability.

7.2.2.2.2 The Health Utilities Index Mark 3 The parent-proxy version of the HUI was completed by parents of children aged 5 years and above (the questionnaire is not suitable for the parents of younger children). The format is multiple-choice with between four and six alternative responses for each question (see Appendix C). The HUI responses were converted to utilities using the function defined by Feeny et al. (2002).

7.2.2.2.3 Visual-analogue scales Parents valued their child's general quality of life using a horizontal VAS with endpoints labelled "Worst" and "Best" imaginable quality of life (see Appendix D). The scale was labelled numerically in 10-point intervals from 0 to 100, with 100 representing the best quality of life. All parents were given a VAS that asked about the child's current quality of life ('current VAS'). The parents of bilaterally-implanted children were given a VAS that asked them to imagine their child's quality of life if the child had received only one implant ('one-implant VAS'). All parents were given a VAS that asked them to imagine their child's quality of life if the child had not received an implant ('no-implant VAS'). The VAS ratings were compressed (Cheng et al., 2000; Torrance, 1976)[3] using the formula $1-(1-\mathrm{VAS}/100)^{1.6}$.

7.2.2.3 Analyses

The outcome measures did not distribute normally, so medians were used to summarise the results. To enable comparisons with the analyses of cost-effectiveness commissioned by NICE (Bond et al., 2007), mean increments and 95% confidence intervals are also reported in the text. The aim of the statistical analyses was to assess:

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[3] Lovett et al. (2010) presented the results of this experiment without compressing the VAS scores. Consequently, this chapter and the published paper report different data. The results of statistical comparisons were the same for both compressed and noncompressed data.

1. Whether there was a difference between the bilateral and unilateral groups in parental responses on the SSQ, the HUI and the current VAS.

2. For the unilateral group, whether parental responses on the current VAS were higher than on the no-implant VAS.

3. For the bilateral group, whether parental responses on the current VAS were higher than on the one-implant VAS. Also for the bilateral group, whether parental responses on the one-implant VAS were higher than on the no-implant VAS.

4. Whether there was a difference between the simultaneous and sequential bilaterally-implanted children in parental responses on the SSQ, the HUI and the current VAS.

5. Whether parents' responses on the SSQ, the HUI, and the current VAS were correlated with each other.

6. Whether parents' responses on the SSQ, the HUI, and the current VAS were correlated with their child's performance on the listening tests reported in Chapter 5.

Mann-Whitney tests were used to compare the bilateral and unilateral groups and to compare the simultaneous- and sequential-bilateral groups. Wilcoxon signed-rank tests were used to assess whether VAS responses differed according to the question that was asked. Throughout this chapter, effect sizes for Mann-Whitney and Wilcoxon tests were calculated according to the formulae in sections 4.2.5.2 and 5.2.4.4.2, respectively. No data were missing for the SSQ, current VAS, HUI, or one-implant VAS. Two parents (one with a unilaterally-implanted child and one with a bilaterally-implanted child) had missing data for the no-implant VAS. These two parents were excluded from the analysis of the no-implant VAS questionnaire.

Kendall's rank-order correlation coefficients (tau) were used for all correlational analyses. One set of correlations assessed whether parents' questionnaire responses covaried with their child's performance on the listening tests. If each questionnaire had been correlated with every listening test, the likelihood of detecting statistically-significant correlations after a Bonferroni correction was very small. Accordingly, only two measures of listening skill were analysed: the ±30° condition of the Left-Right Discrimination test and SRM with noise ipsilateral to the first device. These measures were chosen because they led to a range of performance and few children had missing data. A parent-child pair was excluded from a correlational analysis if either one of the pair had missing data.

7.2.3 Results

7.2.3.1 Comparisons of children with unilateral or bilateral cochlear implants

The results of the SSQ, HUI and VAS are shown in Table 7.1. The bilateral group had higher ratings than the unilateral group on the spatial-hearing subscale of the SSQ. The two groups did not differ significantly in parental ratings on the speech-hearing and qualities-of-hearing subscales of the SSQ, nor did they differ significantly in parental estimates of quality of life using HUI or current VAS. The mean difference in HUI was −0.01 (95% c.i. −0.11 to +0.09); the mean difference in current VAS was +0.02 (95% c.i. −0.03 to +0.07). Positive values indicate a higher quality of life for the bilateral group. The no-implant VAS for the unilateral group was higher than the no-implant VAS for the bilateral group. The current VAS for the unilateral group was higher than the one-implant VAS for the bilateral group [$z = -4.90$, $p_{bf} < .01$, $r = .66$].

7.2.3.2 Within-subjects analyses of visual-analogue scales

For the unilateral group, the current VAS was higher than the no-implant VAS [$z = -3.82$, $p < .001$, $r = .62$]. For the bilateral group, the current VAS was higher than the one-implant VAS [$z = -5.16$, $p_{bf} < .001$, $r = .62$]; the mean difference was +0.22 (95% c.i. +0.16 to +0.29). For the bilateral group, the one-implant VAS was higher than the no-implant VAS [$z = -5.01$, $p_{bf} < .001$, $r = .61$].

7.2.3.3 Comparison of children with simultaneous or sequential bilateral implants

The results of the SSQ, HUI and VAS for the simultaneous and sequential bilaterally-implanted children are shown in Table 7.2, along with the results of statistical comparisons of the two groups. The two groups did not differ significantly on any of the questionnaires.

Table 7.1. Results of the parental questionnaires. The 25th percentile (25th), 50th percentile (Median, in emboldened text), 75th percentile (75th) and the number of participants contributing data (*N*) are listed for each group alongside the standardised test statistic (*z*), *p* value, and effect size (*r*) resulting from a Mann-Whitney comparison of the groups. N/A: not applicable.

	Unilateral				Bilateral				Mann-Whitney		
	25th	**Median**	75th	*N*	25th	**Median**	75th	*N*	*z*	*p*	*r*
SSQ speech	4.65	**5.88**	7.68	20	5.71	**7.53**	8.25	35	−1.93	.05	.26
SSQ spatial	2.43	**4.85**	5.88	20	6.20	**7.46**	8.82	35	−3.61	.01	.49
SSQ qualities	6.44	**7.16**	8.15	20	6.99	**7.60**	8.43	35	−1.42	.16	.19
HUI	0.69	**0.78**	0.85	14	0.65	**0.83**	0.85	22	−0.03	.98	.01
Current VAS	0.90	**0.97**	0.99	20	0.95	**0.98**	0.99	35	−1.40	.33	.19
One-implant VAS	N/A	N/A	N/A	N/A	0.71	**0.78**	0.86	35	N/A	N/A	N/A
No-implant VAS	0.26	**0.43**	0.63	19	0.15	**0.30**	0.46	34	−2.14	.03	.29

Table 7.2. Results of the parental questionnaires for the simultaneous and sequential bilaterally-implanted children. The 25th percentile (25th), 50th percentile (Median, in emboldened text), 75th percentile (75th) and the number of participants contributing data (*N*) are listed for each group alongside the standardised test statistic (*z*), *p* value, and effect size (*r*) resulting from a Mann-Whitney comparison of the groups.

	Simultaneous				Sequential				Mann-Whitney		
	25th	**Median**	75th	*N*	25th	**Median**	75th	*N*	*z*	*p*	*r*
SSQ speech	4.75	**7.14**	8.16	15	6.34	**7.78**	8.40	20	−1.32	.19	.22
SSQ spatial	6.50	**7.56**	9.00	15	4.22	**7.43**	8.28	20	−1.08	.29	.18
SSQ qualities	6.66	**7.28**	7.92	15	7.49	**7.84**	8.72	20	−1.85	.07	.31
HUI	0.20	**0.52**	0.81	4	0.70	**0.84**	0.85	18	[a]	[a]	[a]
Current VAS	0.95	**0.98**	0.99	15	0.97	**0.98**	1.00	20	−0.30	.77	.05
One-implant VAS	0.67	**0.81**	0.87	15	0.72	**0.77**	0.86	20	−0.50	.63	.08
No-implant VAS	0.03	**0.41**	0.56	14	0.16	**0.30**	0.37	20	−1.11	.28	.19

[a] There were insufficient data to perform a statistical comparison.

7.2.3.4 The relationship between questionnaires

The correlation matrix for the parental questionnaires is shown in Table 7.3. The matrix includes data from parents of unilaterally- and bilaterally-implanted children. The subscales of the SSQ all correlated with each other. The HUI utilities were correlated with the scores for the speech-hearing and qualities-of-hearing subscales of the SSQ; the current VAS scores were correlated with scores for the speech-hearing subscale. The HUI utilites and current VAS scores were not correlated with each other (although this correlation was statistically significant before the Bonferroni correction was applied, $p = .01$).

Table 7.3. Correlation matrix for parental questionnaires. The Kendall's tau correlation coefficient and the number of participants (in parentheses) are listed.

	SSQ speech	SSQ spatial	SSQ qualities	HUI	Current VAS
SSQ speech	—	.41*** (55)	.50*** (55)	.36* (36)	.27* (55)
SSQ spatial	—	—	.45*** (55)	.19 (36)	.14 (55)
SSQ qualities	—	—	—	.34* (36)	.11 (55)
HUI	—	—	—	—	.31 (36)
Current VAS	—	—	—	—	—

* $p_{bf} < .05$; ** $p_{bf} < .01$; *** $p_{bf} < .001$

7.2.3.5 The relationship between parental questionnaires and tests of spatial listening skill

The correlations between scores for the parental questionnaires and two laboratory tests of spatial listening skill are shown in Table 7.4, including data from both unilaterally- and bilaterally-implanted children. The only significant correlations were between scores for the ±30° condition of the Left-Right Discrimination test and scores for the speech-hearing and spatial-hearing subscales of the SSQ.

Table 7.4. Correlations between parental questionnaires and laboratory tests of spatial listening skill. The second column shows the lower age limit for each questionnaire. The Kendall's tau correlation coefficient and the number of participants (in parentheses) are listed for two measures of spatial listening skill: the ±30° condition of the Left-Right Discrimination test and SRM with noise ipsilateral to the first device.

	Age limit (months)	Left-Right Discrimination	SRM noise ipsilateral [a]
SSQ speech	24	+.36* (51)	−.08 (43)
SSQ spatial	24	+.32* (51)	−.02 (43)
SSQ qualities	24	+.24 (51)	−.05 (43)
HUI	60	+.20 (35)	−.17 (35)
Current VAS	24	+.10 (51)	−.07 (43)

[a] Lower age limit: 36 months. * $p_{bf} < .05$.

7.2.3.6 Summary of Experiment 1

The bilateral and unilateral groups did not differ in parental estimates of health-related quality of life using the HUI or in parental estimates of general quality of life using the VAS. The bilateral group had higher ratings than the unilateral group on the spatial-hearing subscale of the SSQ. When asked to provide retrospective estimates using a VAS, parents reported significant increments in general quality of life associated with both unilateral and bilateral implantation. For all questionnaires, the responses for the simultaneous and sequential bilaterally-implanted children did not differ significantly. The parental estimates of general and health-related quality of life were correlated with scores for some subscales of the SSQ. The parental estimates of general and health-related quality of life did not correlate with the child's performance on tests of spatial listening.

7.2.4 Discussion of Experiment 1

7.2.4.1 Results of between-subjects comparisons

Parental judgements indicated that, compared with unilaterally-implanted children, bilaterally-implanted children displayed better skills in spatial listening. This result mirrors the superior performance of the bilateral group on laboratory tests of sound-source localisation and speech perception (see section 5.3). However, questionnaire responses by the same parents did not reveal a difference between unilaterally- and bilaterally-implanted children in either general or health-related quality of life. Significant differences in questionnaire reports of everyday listening but not of quality of life were also found in an observational comparison of five unilaterally- and five bilaterally-implanted children (Beijen et al., 2007) and in a randomised trial comparing 12 unilaterally- and 12 bilaterally-implanted adults (Summerfield et al., 2006).

There are a number of possible reasons why this study, and previous studies, have not found a significant gain in quality of life associated with bilateral implantation (Beijen et al., 2007; Summerfield et al., 2006). First, the improvement in listening skill associated with bilateral implantation, and the potential reduction in anxiety regarding device failure, may not be sufficient to improve quality of life. In support of this theory, children's performance on laboratory tests of spatial listening did not correlate with parental estimates of general or health-related quality of life (see section 7.2.4.4 for further details). Second, advantages in quality of life may take longer to emerge than the 19 months post-second implantation that was the average in this sample, or the 9- and 22-month follow-ups of the previous studies (Summerfield et al., 2006 and Beijen et al., respectively). Spatial listening skills are positively associated with experience with both implants (Litovsky, Johnstone, Godar, Agrawal, et al., 2006; Steffens et al., 2007), so it is plausible that the same relationship applies to improvements in quality of life. Third, in the current study and in a previous study (Cheng et al., 2000), parents of unilaterally-implanted children gave high estimates of their child's quality of life, leaving little headroom for any advantage associated with bilateral implantation to be shown.

It is possible that a gain in quality of life associated with bilateral implantation has not yet been demonstrated because of a lack of statistical power. The increment may be as small as +0.03 (Summerfield et al., 2002, 2006). Neither the present study, nor previous studies (Beijen et al., 2007; Summerfield et al., 2006), were designed to detect a difference of this size. Indeed, the present study was designed to detect differences of one standard deviation: in the current sample, this was 0.18 for the HUI and 0.09 for the VAS. For bilateral implantation to be considered a cost-effective intervention, the increment must be at least +0.04. To detect a difference of this size between the HUI utilities of bilaterally- and unilaterally-implanted children with 80% power at $p < .05$, one would need a sample of 250 children in each group.

7.2.4.1.1 Simultaneous and sequential bilaterally-implanted children There was no significant difference between the simultaneous and sequential bilaterally-implanted children in parental reports of listening skill, health-related quality of life, or general quality of life. This finding was expected, because these groups did not differ in performance on tests of spatial listening (see section 5.3.4).

7.2.4.2 Hypothetical or retrospective judgements of quality of life

Parents of bilaterally-implanted children reported that the incremental gain in general quality of life associated with bilateral implantation was +0.22, measured using VASs. This value is greater than the increment of +0.12 obtained from adults and children who completed a self-report version of the HUI (Bichey & Miyamoto, 2008). One could argue that the present results demonstrate an association between bilateral implantation and enhanced quality of life. However, the judgements were retrospective (or, in the case of simultaneous bilateral implantation, hypothetical). Retrospective judgements are confounded with maturation and are at risk of recall bias (see section 7.1.4). Both retrospective and hypothetical judgements can be biased by gratitude for healthcare and by expectations of that healthcare. These sources of bias may explain two findings of the present study using VAS: 1) parents of bilaterally-implanted children gave lower ratings for quality of life with one implant than did parents of children who actually have one implant; 2) parents of bilaterally-implanted children gave lower ratings for quality of life with no implant than did parents of unilaterally-implanted children (see section 7.2.3.1).

The retrospective judgements do, however, show that this sample of parents of bilaterally-implanted children perceived an association between bilateral implantation and improved general quality of life. Thus, the null results of the between-subjects comparisons of general and health-related quality of life (see section 7.2.4.1) cannot be attributed to parents' insensitivity to the benefits of bilateral implantation. Also, the null results cannot to be attributed to atypically poor outcomes for this sample of bilaterally-implanted children, for two reasons. First, the bilaterally-implanted children performed better on tests of spatial listening than the unilaterally-implanted children. Second, the median HUI utility for the bilateral group in the current study was 0.83, similar to the median of 0.85 reported by Bichey and Miyamoto (2008).

7.2.4.3 The relationships between questionnaires

Parents' ratings of listening skill were correlated with their estimates of utility using the HUI. This relationship may have arisen because children's listening skills influenced their parents' responses on both questionnaires. To investigate this possibility, the scores on the hearing subscale of the HUI were examined. It was found that 91% of the entire sample of children were at level three on the hearing subscale, according to their parents (the scale is shown in Table 7.5). Thus, much of the variation in HUI utilities resulted from the other subscales. Therefore, the correlation between SSQ and HUI utility is not likely to be caused by the child's listening skill, but rather by another factor such as the number of additional disabilities. The lack of variation in the hearing subscale occurred because only levels three and five are applicable to implanted children: the other levels apply either to children who do not use a cochlear implant or to children who cannot hear at all. Consequently, although the HUI is sensitive to improvements in listening skill following unilateral implantation, the HUI may not have the resolution to distinguish fine-grained differences in listening skill between children who use cochlear implants.

Table 7.5. The levels of the hearing subscale of the HUI. Adapted from Drummond et al. (2005).

Level	Description
1	Able to hear what is said in a group conversation with at least three other people, without using a hearing aid or cochlear implant.
2	Able to hear what is said in a conversation with one other person in a quiet room, without using a hearing aid or cochlear implant, but requires a hearing aid or cochlear implant to hear what is said in a group conversation with at least three other people.
3	Requires a hearing aid or cochlear implant to be able to hear what is said in a group conversation with at least three other people or a conversation with one other person in a quiet room.
4	Able to hear what is said in a conversation with one other person in a quiet room without a hearing aid or cochlear implant, but unable to hear what is said in a group conversation with at least three other people when using a hearing aid or cochlear implant.
5	Able to hear what is said in a conversation with one other person in a quiet room when using a hearing aid or cochlear implant, but unable to hear what is said in a group conversation with at least three other people when using a hearing aid or cochlear implant.
6	Unable to hear at all.

The two measures of quality of life (HUI and VAS) showed only a weak correlation with each other (r = .31). The weak relationship probably arose because the end-points of the VAS referred to quality of life, rather than health or health-related quality of life. A stronger correlation between VAS and HUI (Pearsons's $r = 0.58$) was reported in a study that labelled the end-points of the VAS best and worst ‘health state’ (Rashidi, Anis, & Marra, 2006).

7.2.4.4 The relationships between parental questionnaires and tests of spatial listening

There was no significant correlation between HUI utilities and tests of spatial listening, probably because much of the variation in HUI utilities was not caused by variation in the hearing subscale. The absence of a correlation between VAS ratings and tests of spatial listening perhaps indicates that, when asked to estimate their child’s general quality of life, parents do not place much weight on spatial listening skills. Children’s performance on a test of the ability to discriminate sound sources on the left from those on the right correlated with their parent’s rating on the spatial subscale of the SSQ. A similar correlation has been reported previously (Van Deun et al., 2010), and is evidence for the validity of the parent-proxy version of the SSQ.

7.2.4.5 Conclusion

In this sample of children, bilateral implantation was associated with a nonsignificant average increment in health-related quality of life of −0.01 (as measured by HUI) and a nonsignificant average increment in general quality of life of +0.02 (as measured by VAS). The 95% confidence intervals for both estimates embraced +0.04, the minimum increment required for paediatric bilateral implantation to be considered cost-effective in the UK. Thus, considerable uncertainty surrounds the issue of whether there is an increment in either health-related quality of life or general quality of life associated with bilateral implantation. Accordingly, Experiment 2 was conducted to gather additional data on the quality of life of children with unilateral or bilateral implants.

7.3 Experiment 2: Informants' estimates of the quality of life of children with cochlear implants

7.3.1 Introduction, aims and hypotheses

The study of parents did not have sufficient statistical power to detect small differences in quality of life between unilaterally- and bilaterally-implanted children. If the standard deviation of the increment is 0.18 and the mean value is 0.04, then two groups of 250 children would be required to detect the difference with 80% power at $p < .05$. There are two reasons why such a study could not be conducted in the UK at the time of writing (February 2010). First, children in the UK have routinely received bilateral implantation since January 2009 (NICE, 2009), so a between-subjects comparison of contemporary groups of unilaterally- and bilaterally-implanted children is not possible. Second, only 270 children receive a cochlear implant every year in England and Wales (Bond et al., 2007). In general, research studies successfully recruit only a small proportion of the potential participants (Watson & Torgerson, 2006), so a study of 500 children would take a substantial amount of time to complete.

Even if a larger study of parents could be conducted, it is possible that parents are not the most objective judges: having done everything they can to maximise the quality of life of their child, parents of implanted children might give uniformly high estimates of quality of life, irrespective of the child's listening skills. It is also possible that some parents are not fully informed about the differences in listening skill between unilaterally- and bilaterally-implanted children. The design of Experiment 2 took these issues into consideration. Adults, who were not the parents of hearing-impaired children, acted as informants. The informants were asked to estimate the quality of life of a hypothetical profoundly-deaf child who had either no implant, a unilateral implant, a unilateral implant and a contralateral acoustic hearing aid, or bilateral implants. The experiment was designed to test whether estimates of quality of life would be higher for the scenario with bilateral implants than for either of the scenarios with a unilateral implant, and whether estimates would be higher for the scenarios with a unilateral implant than for the scenario with no implant. The data were gathered by Georgina Batten and Hannah Bellenger, as part of an undergraduate project that was co-supervised by the author.

7.3.2 Method

The informants read a document that asked them to imagine they were 33 years old and had a daughter who was born profoundly deaf and was now 6 years old (see Appendix E). The age of 6 years was chosen because it was old enough to allow for a tangible description of the child's listening skills and their impact on everyday life. In addition, Barton et al. (2006b) found that children's health-related quality of life improved over the first 4 years of implant use, so the age of 6 years allowed time for the hypothetical child to show an increment in quality of life associated with implantation. The age of 33 years was chosen to reflect the average age of mothers of 6-year-old children in the UK (Office for National Statistics, 2003). The child was described as being free from health problems other than impaired hearing. The informants read descriptions of four scenarios in which their hypothetical daughter: 1) had no implant (No-CI); 2) benefited from a unilateral implant (CI-only); 3) benefited from a unilateral implant and an acoustic hearing aid (CI-HA); and 4) benefited from bilateral implants (CI-CI). The descriptions encompassed the child's everyday functioning and future prospects, and were based on:

1. The results of studies that assessed the listening skills, educational achievements, and health-related quality of life of hearing-impaired children who used either bilateral acoustic hearing aids or a unilateral implant (Barton et al., 2006a; Stacey et al., 2006).

2. Preliminary results from the study of spatial listening skills reported in Chapter 5.

3. A review of the literature regarding the spatial listening skills of children with unilateral or bilateral cochlear implants (see Chapter 3).

4. A published report of interviews with the parents of unilaterally-implanted children, in which the quality of life of the child was discussed (Sach & Barton, 2007).

5. Discussion boards on the websites of charities that support hearing-impaired children and their families (Cochlear Implanted Children's Support Group,

2008; National Deaf Children's Society, 2008; Royal National Institute for Deaf People, 2008).

After they had read all four descriptions, the informants valued the general quality of life of the child in each scenario using the VAS from Experiment 1 (see section 7.2.2.2.3). The VAS ratings were compressed using the formula $1-(1-\mathrm{VAS}/100)^{1.6}$. The informants also valued the health-related quality of life of the child in each scenario using the TTO. The informants were told to imagine that they had a further life expectancy of 50 years (this figure was based on population averages for 33-year-olds in the UK; Office for National Statistics, 2009). The informants estimated the number of years of life (y) that they would give up from the end of their life in order for their hypothetical child to hear normally for the rest of her life. The number of years given up (y) was converted to a value of preference using the formula (50-y)/50.

7.3.2.1 Participants

The participants were a convenience sample of adults who were not the parents of hearing-impaired children. The aim was to recruit adults who varied widely in their age, experience of disability, and knowledge of the consequences of impaired hearing. The sample could be divided into three subgroups: researchers/clinicians, undergraduate students, and parents of normally-hearing children. The researchers/clinicians worked in child health and/or with hearing-impaired individuals. This subgroup attended lectures about cochlear implantation at which questionnaires were distributed and, if the individual elected to participate, returned by post. The students were contacted by email and attended an appointment to complete the questionnaire. The parents were recruited via a charity that supports disabled children and their families; questionnaires were distributed and returned by post. Participants were not offered any incentive to take part.

Of those invited to participate, the following proportions responded: 36/142 clinicians/researchers (25%), 83/108 students (77%), and 72/106 parents (68%). Data were missing from the questionnaires returned by two clinicians/researchers, one student, and six parents. These respondents were excluded. One clinician/researcher and one parent were excluded because they had a hearing-impaired child.[4] Biographical data for the remaining 180 participants are shown in Table 7.6. Twenty-six of the 65 parents had a disabled child. The study was designed to detect a difference between VAS ratings of 0.03 with 99% power at $p < .05$ (based on the variability observed in Experiment 1). The study was approved by the Research Ethics Committee of the Department of Psychology of the University of York.

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[4] The exclusion of these two participants, and the inclusion of two replacement participants, means that the participants in this study are not identical to those in the paper by Summerfield et al. (in press.).

Table 7.6. Biographical data for the participants in Experiment 2. For each subgroup and the entire group of participants, the number of participants (*N*), their mean age in years (with the standard deviation, *SD*, in years in parentheses), and the number of women (with the percentage of the group in parentheses) are listed.

	N	Mean age (*SD*)	Number of women (percentage of group)
Researcher/clinician	33	43.5 (8.7)	24 (73%)
Student	82	21.3 (0.7)	54 (66%)
Parent	65	46.0 (8.2)	49 (75%)
ALL	180	34.3 (13.4)	127 (71%)

7.3.2.2 Analyses

The outcome measures did not distribute normally, so medians were used to summarise the results. Mean increments in quality of life (with 95% c.i.) are stated in the text. The aim of the statistical analyses was to assess, for both VAS and TTO:

- For the group of participants as a whole and for each subgroup, whether the values for No-CI differed from CI-only, whether the values for CI-only differed from CI-HA, and whether the values for CI-HA differed from CI-CI.
- Whether the values for each scenario differed among the subgroups.

Wilcoxon tests with a Bonferroni correction were used to assess whether the values differed according to the scenario. Kruskal-Wallis tests were used to assess whether the values for each scenario differed among the subgroups. If a Kruskal-Wallis test was statistically significant, post-hoc Mann-Whitney tests with a Bonferroni correction were used to assess which subgroups differed.

7.3.3 Results

The informants' estimates of quality of life using VAS and TTO are shown for each scenario in Table 7.7. For the group as a whole, estimates using VAS were higher for CI-only than for No-CI [$z = -10.68$, $p_{bf} < .001$, $r = .80$], for CI-HA than for CI-only [$z = -10.79$, $p_{bf} < .001$, $r = .80$], and for CI-CI than for CI-HA [$z = -11.15$, $p_{bf} < .001$, $r = .83$]. These comparisons were also statistically significant for each of the subgroups of participants [all $p_{bf} < .01$].

Similarly, for the group as a whole, estimates using TTO were higher for CI-only than for No-CI [$z = -9.68$, $p_{bf} < .001$, $r = .72$], for CI-HA than for CI-only [$z = -8.98$, $p_{bf} < .001$, $r = .67$], and for CI-CI than for CI-HA [$z = -9.08$, $p_{bf} < .001$, $r = .68$]. These comparisons were also statistically significant for each of the subgroups [all $p_{bf} < .01$].

There were no significant differences between the subgroups in their estimates using VAS for No-CI, CI-HA, or CI-CI [all $p > .05$]. The subgroups differed significantly in their estimates using VAS for CI-only [H(2) = 6.76, $p < .05$]. Post-hoc tests revealed that, for this scenario, the researchers/clinicians gave higher estimates than the parents [$z = -2.56$, $p < .01$, $r = .26$]. The other post-hoc comparisons were not statistically significant [$p > .05$]. There were no significant differences between the subgroups in their estimates using TTO for any of the scenarios [all $p > .05$].

The results from the entire group of participants are summarised in Figure 7.2. The mean increment in quality of life from CI-only to CI-CI was +0.13 (95% c.i. +0.12 to +0.15) when estimated using VAS and +0.11 (95% c.i. +0.09 to +0.12) when estimated using TTO. The mean increment in quality of life from CI-HA to CI-CI was +0.06 (95% c.i. +0.05 to +0.07) when estimated using VAS and +0.05 (95% c.i. +0.04 to +0.06) when estimated using TTO.

Table 7.7. Informants' estimates of the quality of life of deaf children. For each scenario, the results are listed as the 25th percentile (25), 50th percentile (median, in emboldened text), and 75th percentile (75). The upper section of the table lists estimates using VAS, the lower section lists estimates using TTO.

	No-CI			CI-only			CI-HA			CI-CI		
	25	**Median**	75	25	**Median**	75	25	**Median**	75	25	**Median**	75
VAS												
Researcher/clinician	0.56	**0.67**	0.81	0.82	**0.89**	0.92	0.87	**0.94**	0.96	0.95	**0.97**	0.99
Student	0.50	**0.72**	0.83	0.74	**0.85**	0.93	0.85	**0.92**	0.97	0.94	**0.97**	0.99
Parent	0.43	**0.62**	0.77	0.68	**0.80**	0.90	0.82	**0.89**	0.95	0.92	**0.97**	0.99
ALL	0.49	**0.67**	0.81	0.74	**0.85**	0.92	0.85	**0.92**	0.96	0.93	**0.97**	0.99
TTO												
Researcher/clinician	0.50	**0.70**	0.80	0.70	**0.80**	0.90	0.77	**0.90**	0.99	0.80	**0.90**	1.00
Student	0.60	**0.70**	0.80	0.70	**0.84**	0.90	0.80	**0.90**	0.94	0.90	**0.94**	0.96
Parent	0.50	**0.74**	0.80	0.62	**0.80**	0.84	0.70	**0.80**	0.91	0.80	**0.90**	0.96
ALL	0.60	**0.70**	0.80	0.70	**0.80**	0.90	0.80	**0.88**	0.94	0.80	**0.90**	0.98

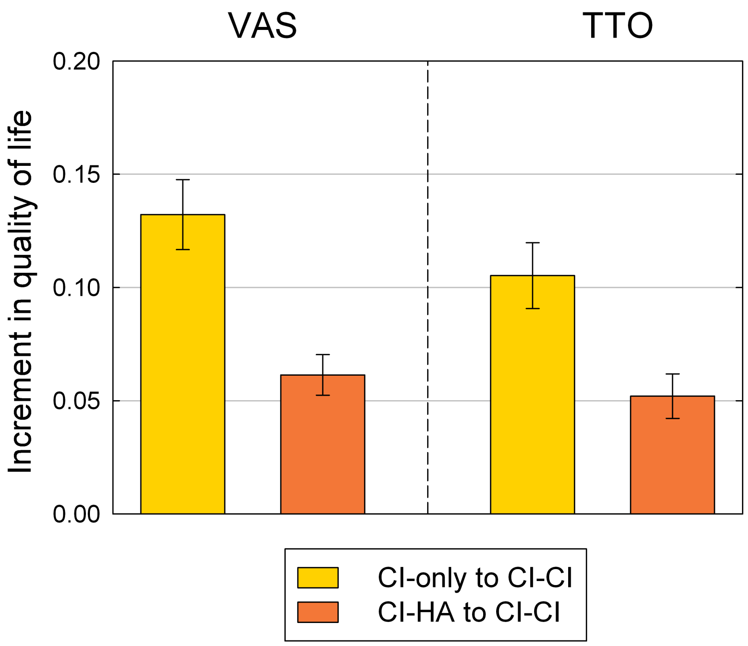

Figure 7.2. Summary of the results from the entire group of informants (*N* = 180). The left part of the graph plots estimates using VAS, the right part plots estimates using TTO. The yellow bars show the mean increment in quality of life from CI-only to CI-CI. The orange bars show the mean increment in quality of life from CI-HA to CI-CI. Error bars show 95% confidence intervals.

7.3.4 Discussion of Experiment 2

Participants who varied in their age, knowledge of hearing impairment, and experience of disability judged that bilateral implantation for children was associated with higher general and health-related quality of life than unilateral implantation. Although the subgroups of participants differed slightly in their estimates of the quality of life for the child in each scenario, the increment in quality of life associated with bilateral implantation was consistently positive and statistically significant. Furthermore, the increment in quality of life from unilateral to bilateral implantation was greater than +0.04 when measured using either VAS or TTO. An increment of this magnitude would mean that bilateral implantation gained QALYs for less than £30,000, and would therefore be viewed as a cost-effective intervention in England and Wales (Bond et al., 2007; NICE, 2009).

A number of criticisms can be levelled at the methods used in this study. First, the description of each scenario may not be representative of the functioning of hearing-impaired children in real life. To assess whether the descriptions were accurate, the increments in quality of life associated with unilateral implantation can be compared with the increments reported by Barton et al. (2006b). In the present study, the increment in VAS from No-CI to CI-only was +0.18 (95% c.i. +0.16 to +0.20) and from No-CI to CI-HA was +0.25 (95% c.i. +0.23 to +0.28). The corresponding increments in TTO were +0.11 (95% c.i. +0.09 to +0.12) and +0.16 (95% c.i. +0.14 to +0.18), respectively. The most comparable subgroup in the study of Barton et al. contained children who had been implanted before the age of 5 years and who had used their implant for at least 4 years. For this group of children, the mean increment in HUI utility associated with unilateral implantation was +0.23 (95% c.i. +0.18 to +0.28). It was not clear whether these children used a contralateral acoustic hearing aid. Thus, when the informants used VAS, but not when the informants used TTO, the descriptions in the present study yielded increments in quality of life associated with unilateral implantation that were within the 95% confidence interval of the increment reported by Barton et al.

A further criticism is that the description of the CI-HA scenario did not include any potential advantages of using bimodal stimulation rather than bilateral implants. Adult listeners show a better ability to understand speech and to recognise melody when using bimodal stimulation than when using an implant alone (Kong et al., 2005). It is possible that, for patients with residual hearing, bimodal stimulation could also be superior to bilateral implantation for the perception of speech in noise and for the enjoyment of music. Such potential benefits were not described because they have not yet been demonstrated (Litovsky, Johnstone, & Godar, 2006; Mok et al., 2009; Schafer & Thibodeau, 2006).

7.4 Summary of results

The two studies reported in this chapter generated estimates of the gain in quality of life associated with paediatric bilateral implantation that ranged from −0.01 to +0.22, on a scale from one (perfect quality of life) to zero (dead). Table 7.8 summarises the results of both studies.

Table 7.8. Summary of estimates of the mean increment in quality of life associated with bilateral implantation.

Increment (95% c.i.)	Method	Respondent
−0.01 (−0.11 to +0.09)	HUI	Parents of bilaterally- or unilaterally-implanted children
+0.02 (−0.03 to +0.07)	VAS	Parents of bilaterally- or unilaterally-implanted children
+0.22 (+0.16 to +0.29)	VAS	Parents of bilaterally-implanted children, retrospective/hypothetical estimates
+0.13 (+0.12 to +0.15)	VAS	Informant, CI-only to CI-CI
+0.11 (+0.09 to +0.12)	TTO	Informant, CI-only to CI-CI
+0.06 (+0.05 to +0.07)	VAS	Informant, CI-HA to CI-CI
+0.05 (+0.04 to +0.06)	TTO	Informant, CI-HA to CI-CI

7.5 Discussion

The studies reported in this chapter obtained estimates of the incremental gain in quality of life associated with bilateral implantation for children. The results from the study of parents of implanted children were equivocal. Bilateral implantation was associated with a nonsignificant decrement in health-related quality of life when measured using the HUI, and a nonsignificant increment in general quality of life when measured using the VAS. Both estimates had a confidence interval that embraced +0.04, a value that is large enough to bring the average incremental cost-effectiveness ratio below the criterion of £30,000/QALY. Thus, the study of parents is compatible with the idea that bilateral implantation for children is cost-effective, without providing unambiguous evidence that this is indeed the case. The study of informants indicated that the gain in quality of life associated with bilateral implantation was at least +0.04. Thus, individuals who were not the parents of hearing-impaired children perceived sufficient benefit from bilateral implantation for it to be considered cost-effective.

7.6 Conclusion

The studies reported in this chapter indicate that bilateral implantation may increase the quality of life of deaf children: uncertainty remains regarding the extent of any increase. To resolve the uncertainty, one would need to conduct a randomised controlled trial with sufficient statistical power to detect a difference in health-related quality of life of 0.04 between bilaterally- and unilaterally-implanted children. Given that the policy in England and Wales is to provide children with bilateral implants, such a trial would have to be conducted in another country.

7.7 Summary

- Parental estimates of health-related quality of life and general quality of life did not differ significantly between bilaterally- and unilaterally-implanted children. Both estimates had a confidence interval that embraced +0.04, a value that is large enough for bilateral implantation for children to be considered cost-effective.

- The same parents did report differences between the groups in spatial listening skill, reflecting the association between bilateral implantation and improved listening skill that was demonstrated in Chapter 5.

- Retrospective estimates by the parents of bilaterally-implanted children indicated an improvement in general quality of life following bilateral implantation.

However, such estimates may be biased.

- Simultaneous and sequential bilaterally-implanted children did not differ in parental ratings of quality of life or listening skill.
- Informants, who were not the parents of hearing impaired children, reported that bilateral implantation resulted in a gain in quality of life of at least +0.04.

Chapter 8

Summary and General Discussion

This chapter summarises the findings of the studies reported in this thesis and discusses the implications of those findings. Ideas for further research are suggested.

8.1 Recap of research aims

The overall aim of the studies described in this thesis was to assess whether bilateral implantation for children is more effective than unilateral implantation in improving spatial listening skills and quality of life. The first study measured the relationship between spatial listening skills and age in normally-hearing children. The second study compared the spatial listening skills of unilaterally- and bilaterally-implanted children whilst attempting to minimise bias. The third study measured the spatial listening skills of normally-hearing adults when listening to simulations of unilateral or bilateral implants. The aim was to assess whether the differences in listening skill that had been observed between unilaterally- and bilaterally-implanted children would be replicated in a simulation study. The fourth and fifth studies obtained estimates of the quality of life of unilaterally- and bilaterally-implanted children from either parents or informants. The aim was to estimate the incremental gain in quality of life associated with bilateral implantation.

8.2 Summary of findings

8.2.1 Main findings of the study reported in Chapter 4

1. Normally-hearing children aged between 18 months and 7 years showed high levels of performance on tests of left-right discrimination, localisation, and movement tracking. By the age of 3 or 4 years, children's performance on these tests was at ceiling and similar to that of adults.

2. The ability of normally-hearing children to perceive speech in quiet and in noise

improved with age. On tests of speech perception in pink noise and in pulsatile noise, normally-hearing 7-year-olds (the oldest children in the study) did not perform as well as normally-hearing adults.

3. On average, normally-hearing children and adults showed SRM of 5 dB with noise on either side of the head. The amount of SRM did not differ significantly between the age groups.

8.2.2 Main findings of the study reported in Chapter 5

1. On average, bilaterally-implanted children performed better than unilaterally-implanted children on tests of left-right discrimination, localisation, movement tracking, and SRM with noise ipsilateral to the first implant. Significant differences between the groups were sustained following imputation of missing data and statistical control of confounds.

2. Bilaterally-implanted children showed significant SRM with noise on either side of the head, whereas unilaterally-implanted children showed significant SRM only when noise was contralateral to their implant.

3. Neither bilaterally- nor unilaterally-implanted children performed as well as normally-hearing children on tests of spatial listening.

8.2.3 Main findings of the study reported in Chapter 6

1. Normally-hearing adults performed better with simulated bilateral implants than with a simulated unilateral implant on tests of left-right discrimination, localisation, and SRM with noise ipsilateral to the first device. These results mirror the superior performance of bilaterally- compared to unilaterally-implanted children on similar tests (see Chapter 5). The concordance of the two studies provides further evidence that the differences in listening skill observed between groups of children were primarily caused by a difference in the number of implants the children used, rather than by confounds.

2. In simulation, bimodal devices resulted in better speech perception in steady-state noise than bilateral implants, but only when the former condition provided a greater degree of acoustic hearing than is likely to be observed in most cochlear-implant users.

3. On several of the outcome measures, the performance of adults listening to simulations of cochlear implants was similar to the performance of implanted children. This pattern of results suggests that the signal processing carried out by the implant system, or by the simulation of the implant system, limited the performance of both adults and children.

8.2.4 Main findings of the studies reported in Chapter 7

1. Parental estimates of health-related quality of life and general quality of life did not differ significantly between bilaterally- and unilaterally-implanted children. The mean increment in health-related quality of life associated with bilateral implantation was −0.01 (95% c.i. −0.11 to +0.09). The mean increment in general quality of life associated with bilateral implantation was +0.02 (95% c.i. −0.03 to +0.07). An increment of +0.04 (on a scale where perfect health takes the value one and dead takes the value zero) would be sufficient for bilateral implantation for children to be considered cost-effective in England and Wales (NICE, 2009).

2. Informants, who were not the parents of hearing impaired children, judged that bilateral compared to unilateral implantation resulted in an incremental gain of at least +0.05 (95% c.i. +0.04 to +0.06) in health-related quality of life and at least +0.06 (95% c.i. +0.05 to +0.07) in general quality of life.

8.3 General discussion

8.3.1 The effectiveness of bilateral cochlear implantation for children

The study reported in Chapter 5 demonstrated, more rigorously than previous studies, that bilaterally-implanted children display better spatial listening skills than unilaterally-implanted children. Similarly, normally-hearing adults showed better spatial listening skills with a simulation of bilateral implants than with a simulation of a unilateral implant (Chapter 6). Furthermore, the parents of bilaterally-implanted children rated their child's spatial listening skills more highly than did the parents of unilaterally-implanted children (Chapter 7). Collectively, these studies provide evidence that bilateral implantation is more effective than unilateral implantation in enabling spatial listening skills. These skills may help children to avoid hazards outdoors and to understand speech better in noisy environments at home and at school.

It is not clear whether the improvement in listening skill associated with bilateral implantation leads to an improvement in either health-related or general quality of life. The study of parents (Experiment 1 in Chapter 7) was underpowered to detect a small increment in quality of life associated with bilateral implantation. The study of informants (Experiment 2 in Chapter 7) relied on descriptions of a deaf child that were somewhat subjective. Consequently, although these studies indicate that bilateral compared to unilateral implantation may be effective in increasing the quality of life of deaf children, uncertainty remains regarding the exact extent of any increase.

8.3.1.1 Translating research into recommendations for clinical practice

Any research study leads to results that are equivocal, to a greater or lesser degree. The challenge facing researchers, and ultimately policy-makers, is to extrapolate from imperfect data in order to generate evidence-based recommendations for clinical practice. The main difficulty with the interpretation of the study of implanted children reported in Chapter 5 (and the study of the children's parents reported in Chapter 7) was that children were not randomly allocated to receive unilateral or bilateral implants. Consequently, the studies are at risk of selection bias. However, significant differences in listening skill between the bilateral and unilateral groups were sustained following statistical control over confounds.[1] Furthermore, the association between bilateral implantation and enhanced listening skill is supported by the simulation study (Chapter 6). Overall, the available evidence supports a policy of bilateral implantation for severely-profoundly deaf children, on the grounds that bilateral implantation is more effective than unilateral implantation in enabling spatial listening skills.

It is nonetheless possible that, for a subset of cochlear-implant candidates who have residual hearing, bimodal stimulation will result in better listening skills than bilateral implantation. A search of the literature did not reveal studies which tested that hypothesis (Chapter 3), nor was the study of implanted children (Chapter 5) designed to compare outcomes between bimodally-aided children with residual hearing and bilaterally-implanted children who had residual hearing prior to implantation. The study reported in Chapter 6 showed that a simulation of bilateral implants resulted in better spatial listening skills than a simulation of bimodal devices, when the latter condition provided a degree of acoustic hearing that is likely to be observed in most cochlear-implant users. However, different results may be obtained by a simulation study that employs different outcome measures (such as a test of speech perception with a competing talker). Further research is required to determine the best intervention for cochlear-implant candidates who have substantial residual hearing (see section 8.4.2).

Regarding quality of life, the studies reported in Chapter 7 indicate that bilateral implantation may be effective in improving the quality of life of deaf children. Previous studies of bilaterally-implanted children used either retrospective estimates of quality of life (Bichey & Miyamoto, 2008) or a questionnaire that does not yield a formal measure of health-related quality of life (Beijen et al., 2007). Thus, the available data do not exclude the possibility that bilateral implantation meets the criteria for cost-effectiveness in England and Wales, but nor do the data provide robust evidence

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[1] The analysis of parents' questionnaire responses (Experiment 1 in Chapter 7) did not exercise statistical control over confounds, for two reasons. First, the main outcome measures of quality of life yielded null results. Second, none of the outcome measures were distributed normally, so they would have to be transformed into categorical data and analysed using ordinal regression. Transformations of this type entail a loss of statistical power.

that bilateral implantation does meet those criteria.

8.3.2 The limitations of bilateral cochlear implantation for children

On average, bilaterally-implanted children showed poorer spatial listening skills than normally-hearing children with a similar average hearing age (Chapter 5). Thus, bilateral implantation had not restored normal listening skills in this sample of children. The performance of bilaterally-implanted children was similar to that of normally-hearing adults listening to a simulation of bilateral implants (Chapter 6), which suggests that the signal processing carried out by the implant system (or a simulation thereof) limited the performance of both children and adults. It is possible that future innovations in signal processing will lead to improvements in the listening skills of implanted patients. Considerable effort is being expended, by both manufacturers and academics, to improve the temporal and spectral resolution of cochlear implants (Rubinstein, 2004). Another line of enquiry concerns the development of a binaural cochlear-implant processor (Chambers, US Patent Application 20090030484, submitted January 29, 2009; Hartley and Faltys, US Patent 7292891, issued November 6, 2007). Such a processor could be a single unit that controls the electrode array in both ears, or two units that deliver coordinated signals. A binaural processor may deliver a more accurate representation of interaural differences in timing and level than the current processors which are independent at the two ears (see section 3.1.2.1 for a discussion of the limitations of current processors).

If improvements in cochlear-implant technology do lead to improvements in listening skill, then the incremental gain in quality of life associated with bilateral implantation may in time be greater than the gains measured with current implant systems (e.g. Experiment 1 in Chapter 7; Summerfield et al., 2006). As a result, bilateral implantation for both children and adults may be more likely to be viewed as cost-effective, but only if the increase in the cost of the implant system is proportionally smaller than the increase in the gain in quality-adjusted life years.

8.3.3 Why has the campaign for bilateral implantation for children gathered such momentum?

The review of the evidence presented in Chapter 3 revealed considerable uncertainty about the effectiveness of bilateral compared to unilateral implantation for children. The evidence mostly consisted of demonstrations of efficacy (meaning an intervention can provide benefit under optimal conditions) rather than demonstrations of effectiveness (meaning an intervention provides benefit in routine care). Demonstrations of efficacy are a crucial stage in the assessment of a healthcare intervention, but in isolation they do not typically warrant widespread adoption of that intervention

(Gartlehner et al., 2006). Against this background, and prior to the publication of the studies reported in this thesis, bilateral implantation for children has nonetheless become increasingly common in the UK and elsewhere (Kühn-Inacker et al., 2004; Papsin & Gordon, 2008; Peters et al., 2007; Van Deun et al., 2010).

The benefits of unilateral implantation are both proven and substantial, meaning that cochlear implants are a popular technology with clinicians, researchers, parents, and children. As a result, in several countries these groups campaigned for bilateral implantation for children, based on the available evidence and the intuitive assumption that stimulating both ears must be beneficial (Balkany et al., 2008; British Cochlear Implant Group, 2007; Broekhuizen & Byrne, 2009). Advocates also argued that society has a responsibility to do all it can to help deaf children, given the disadvantages that this group has faced both historically and in contemporary life (Broekhuizen & Byrne, 2009; Cochlear Implanted Children's Support Group, 2008).

It is difficult to know why the Appraisal Committee at NICE recommended bilateral implantation for severely-profoundly deaf children in England and Wales, given the uncertainty surrounding the cost-effectiveness of this intervention (Bond et al., 2007; NICE, 2009). Indeed, two commissioning groups in the National Health Service lodged an unsuccessful appeal against the final guidance, on the grounds that the available evidence did not show that bilateral implantation for children met the criteria for cost-effectiveness (Reference Note 1). Some light is cast on the decision-making process by the guidance document, which states that the decision to recommend bilateral implantation was influenced by the clinical experts who gave evidence to the committee (pp. 28–9, NICE, 2009). For the reasons outlined in the previous paragraph, these clinicians are likely to have been supportive of bilateral implantation. One can speculate that two additional factors played a role. First, severe to profound permanent childhood deafness has a low stable prevalence (see section 2.2.2). Therefore, the committee could be confident that the incremental cost of providing bilateral implantation for children would not rise substantially over time, provided that criteria of candidacy could be specified precisely and tightly controlled. Second, one would need a study of 500 children to detect the minimum gain in quality of life required for bilateral implantation to be considered cost-effective (see Chapter 7). Although such a study may be an efficient use of resources (and there are techniques to assess whether this is the case, Claxton & Sculpher, 2006), it would take several years and the committee may have decided it was preferable to make an immediate decision.

8.4 Future research

8.4.1 The criteria of candidacy for cochlear implantation

The studies reported in this thesis indicate that bilateral implantation for severely-profoundly deaf children is effective in enabling spatial listening skills. However, there is uncertainty about which groups of children should receive bilateral implants. As an extreme example, bilateral implantation would not be beneficial for normally-hearing children because the surgery damages the cochlea. There is a need for further research to define the point at which the advantages of bilateral implantation outweigh the disadvantages: in other words, to specify criteria of candidacy for bilateral implantation.

In adults, criteria of candidacy can be evaluated by measuring the listening skills of patients before and after implantation (Dowell, Hollow, & Winton, 2004). This approach cannot be used with congenitally-deaf children, who are assessed for implantation between the ages of 1 and 2 years. Furthermore, outcomes following implantation are variable, and outcomes for individual children cannot be predicted accurately prior to implantation (Geers et al., 2003). To address the twin challenges of the young age of implant candidates and variable outcomes, Boothroyd (1993) developed an actuarial approach to defining candidacy for unilateral implantation. The relationship between speech-perception performance and unaided HL was measured for a group of children with acoustic hearing aids, and summarised by a regression function. The speech-perception performance of a separate group of children with cochlear implants was measured. The distribution of both sets of scores allows one to calculate, for a young child with a known HL, the odds that the child would perform better with an implant than with acoustic hearing aids, on tests of speech perception administered later in life. Boothroyd proposed that an acceptable criterion would be the HL associated with odds of 4:1, meaning an implant would provide greater benefit than acoustic hearing aids for four out of five children with that HL. The UK Cochlear Implant Study Group (2004b) demonstrated that, when patients with odds of 4:1 or better were implanted, unilateral implantation in adults was cost-effective.

It has been difficult for policy-makers to determine criteria of candidacy for paediatric bilateral cochlear implantation based on the published literature (Bond et al., 2007). There are three main reasons for this difficulty. First, the available evidence pertains to unilateral, rather than bilateral, implantation. Second, the majority of recent studies identified the HL at which children were equally likely to succeed with hearing aids or with an implant (Eisenberg, Kirk, Martinez, Ying, & Miyamoto, 2004; Nakisa et al., 2001; Rotteveel, Snik, Vermeulen, Cremers, & Mylanus, 2008). Arguably, to justify implant surgery, the criterion should be set at a point where the odds of success are higher with implants than with hearing aids. Third, the published studies generally measured outcomes using a test of speech perception in quiet (Boothroyd, 1993; Eisenberg et al.; Nakisa et al.; Rotteveel et al.). Additional measures, such as tests of speech perception in noise and tests of sound-source localisation, would provide important information about the functioning of hearing-impaired children in everyday life. Measures of health-related quality of life would also allow the criterion to be defined as the HL above which it is acceptably cost-effective to provide cochlear implants rather than hearing aids.

To define criteria of candidacy, one would ideally conduct a study that compared outcomes between three groups: 1) children with bilateral acoustic hearing aids; 2) children with bimodal devices; 3) children with bilateral implants. The technique described by Boothroyd (1993) could be used to define two criteria: (i) the lowest HL at which children are likely to achieve better outcomes with bimodal devices than with acoustic hearing aids; and (ii) the lowest HL at which children are likely to achieve better outcomes with bilateral implants than with bimodal devices. Children with HLs greater than the first criterion would be eligible for unilateral implantation and the provision of a contralateral acoustic hearing aid, whilst children with HLs greater than the second criterion would be eligible for bilateral implantation. Unfortunately, it would be difficult to conduct such a study in England and Wales, because the current guidance only recommends bilateral implantation in a single surgical session (NICE, 2009). The guidance does not permit a newly-diagnosed child to be provided with a first implant and then, if the child gains insufficient benefit from a contralateral acoustic hearing aid, to be provided with a second implant at a later date. As a result, it seems likely that many parents will opt for immediate bilateral implantation, so it would be difficult to conduct a comparison of the three groups defined at the start of the paragraph. Instead, a study could compare outcomes between children with bilateral acoustic hearing aids and children with bilateral implants, in order to define criteria of candidacy for bilateral implantation.

8.4.2 Bimodal stimulation compared to bilateral implantation

Additional research is required to explore the potential advantages of bimodal stimulation over bilateral implantation, and vice-versa, for patients who have residual hearing. It would be interesting to replicate the simulation study reported in Chapter 6 using additional outcome measures, such as tests of speech perception in the presence of a competing talker and tests of music perception. These outcome measures may reveal advantages in pitch perception associated with simulated bimodal devices compared to simulated bilateral implants. The simulations of bimodal devices that were used in Chapter 6 simulated low-frequency residual hearing by low-pass filtering the signal to one ear. This type of simulation may not reflect the limited abilities of severely-profoundly deaf individuals in frequency selectivity and pitch perception. Future simulations of bimodal devices could incorporate a more sophisticated simulation of cochlear hearing loss. Andrew Faulkner proposed a method whereby signals are vocoded using a noise vocoder with two broadband channels centred on 250 and 500 Hz (personal communication, March 8, 2010). The vocoded signal is then modulated at the period of the voice F0. A simulation of bimodal devices could be created by presenting this low-frequency signal to one ear, and a six- or eight-channel vocoded signal to the other ear. Such processing would simulate the limited frequency resolution and pitch-perception abilities of severely-profoundly deaf individuals more accurately than low-pass filtering alone.

8.4.3 Short-electrode arrays

One advance in technology that has reached the stage of clinical trials is the cochlear implant with a short electrode array (Dorman et al., 2009; Turner, Reiss, & Gantz, 2008). Short electrode arrays are about half the length of standard electrode arrays. The short arrays were developed for patients who have good residual hearing at low frequencies (below about 500 Hz) and very little residual hearing at higher frequencies. The aim of the device is to use electrodes in the basal end of the cochlea to deliver a representation of mid- to high-frequency sounds, whilst preserving low-frequency acoustic hearing towards the apex of the cochlea. Potentially, the preserved low-frequency acoustic hearing could provide listeners with better frequency resolution than traditional cochlear implants, which may enhance the perception of speech in noise and the enjoyment of music (Turner et al., 2008). Moreover, preserving low-frequency acoustic hearing in both ears could enhance the ability to perceive ITDs, relative to standard bilateral cochlear implants, which may lead to an improved ability to localise sources of sound (Dunn, Perreau, Gantz, & Tyler, 2010). Children with short-electrode arrays were not included in the studies reported in this thesis, because this intervention has been provided to only a handful of children (Skarzynski & Lorens, 2010) and is not currently approved for use in England and Wales (NICE, 2009). If the clinical trials with adults prove successful, future work could assess whether there are groups of children who are likely to show better outcomes with either unilateral or bilateral short electrode arrays, rather than unilateral or bilateral standard electrode arrays.

8.4.4 The limitations of bilateral cochlear implants in everyday life

The study reported in Chapter 5 demonstrated that children with bilateral implants display better spatial listening skills than children with unilateral implants. However, bilaterally-implanted children did not localise sources of sound as accurately as normally-hearing children. This difference between bilaterally-implanted and normally-hearing children was observed in a sound-attenuated booth, which is quieter and less reverberant than a classroom or most homes. Future research could compare the localisation skills of normally-hearing and bilaterally-implanted children in noisy and/or reverberant environments that more closely represent the listening situations faced by children in everyday life.

When normally-hearing individuals attempt sound-source localisation tasks in a reverberant environment, their responses tend to be strongly influenced by the location of the source of the first sound that reaches the ears, rather than the source of later sounds (which are often reflections of the first sound). The dominance of the leading sound is known as the precedence effect (Litovsky, Colburn, Yost, & Guzman, 1999). When normally-hearing adults listen to a simulation of bilateral implants, their responses often indicate a single source of sound located inbetween the sources of the leading sound and the lagging sound (Seeber & Hafter, 2007). In other words, the precedence effect is reduced or absent. Two bilaterally-implanted adults did not show the precedence effect, despite showing good performance on tests of sound-source localisation in a sound-attenuating booth (Q. Summerfield & P. Kitterick, personal communication, March 8, 2010). The lack of a precedence effect with bilateral implants (or simulated bilateral implants) may occur because implants do not convey temporal fine structure: the coherent temporal fine structure of the leading sound and echoes of that sound may be one of the cues that enables normally-hearing listeners to identify a single source and show the precedence effect, rather than identifying two different sources.

Based on the data from adults, one would expect bilaterally-implanted children to perform proportionally more poorly than normally-hearing children on tests of sound-source localisation in reverberant environments compared to less reverberant environments. It is possible that parental ratings of children's listening skills would correlate more strongly with performance tests of the child's listening skills if the tests were conducted in a reverberant environment. The correlation between parental ratings of spatial listening skill and children's performance on the Left-Right Discrimination test was significant but weak (Kendall's τ = .32) in the study reported in Chapter 7.

8.5 Conclusion

Compared to unilateral implantation, bilateral implantation in severely-profoundly deaf children is associated with an enhanced ability to localise sources of sound and to perceive speech in noise. Bilateral implantation may also increase children's quality of life, but the extent of any increase remains uncertain.

Appendix A

Reducing the utility of monaural cues to source location

Sensitivity to interaural differences in timing and level (binaural cues) allows normally-hearing listeners to localise sources of sound on the horizontal plane (see section 2.4.1, Middlebrooks & Green, 1991). Monaural listeners are not able to use binaural cues, but they can potentially move their head and use the resulting changes in level and spectrum to localise sources of sound (Perrott et al., 1987). In a laboratory test, monaural listeners can also learn the level and spectral cues associated with a certain source location, if the same stimulus is presented repeatedly. This type of learning has been demonstrated both in unilaterally-implanted adults and in adults who are monaurally deaf but do not use an implant (Luntz et al., 2002; Van Wanrooij & Van Opstal, 2004). Learning the monaural cues generated by a particular stimulus will not help listeners to localise the unfamiliar or changeable sounds that occur in everyday life.

This appendix describes the development of the Toy Localisation test. The aim was to create a test of the ability to localise sounds on the basis of cues that are valid in everyday life, with minimal influence from cues that are valid only in laboratory tests. To reduce the repetition of the same stimulus, the test used speech stimuli that were recorded from five different talkers. These stimuli were processed in order to reduce the utility of monaural cues to localisation, whilst preserving binaural cues and monaural cues resulting from head turns.[1] Two sets of stimuli were created: one set resulted in a similar level and spectrum on arrival at the left ear, regardless of source location; the other set resulted in a similar level and spectrum at the right ear, regardless of source location. Each set contained one stimulus for each loudspeaker location. The subsequent sections describe the processing used to create the stimuli and present the results of two experiments that assessed the effect of the processing on the sound-source localisation skills of normally-hearing adults.

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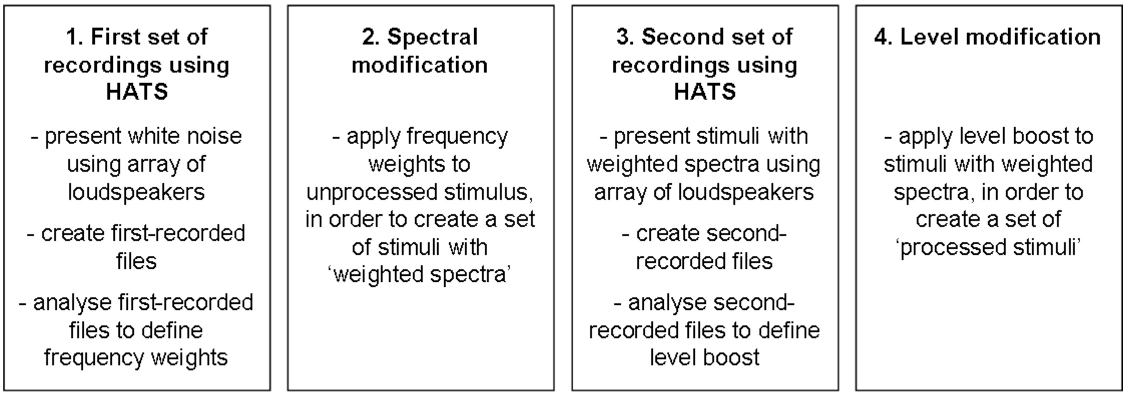
[1] In this appendix, 'utility' is used in its everyday meaning of usefulness, whereas in Chapter 7 'utility' is used as a technical term to denote preference.

A.1 Processing to reduce the utility of monaural cues

There were four principal stages of processing, as illustrated in Figure A.1.



1. First set of recordings using HATS

- present white noise using array of loudspeakers
- create first-recorded files
- analyse first-recorded files to define frequency weights

2. Spectral modification

- apply frequency weights to unprocessed stimulus, in order to create a set of stimuli with ‘weighted spectra’

3. Second set of recordings using HATS

- present stimuli with weighted spectra using array of loudspeakers
- create second-recorded files
- analyse second-recorded files to define level boost

4. Level modification

- apply level boost to stimuli with weighted spectra, in order to create a set of ‘processed stimuli’

Figure A.1. The four stages of processing that were applied to the stimuli. Further details of each stage are given in the text. HATS refers to a head and torso simulator.

A.1.1 Stage 1: First set of recordings using HATS

The aim of the first set of recordings was to measure the effect of source location on the spectrum of a sound on arrival at each ear. Recordings were made using a head and torso simulator (HATS) with integral microphones at the entry to each ear canal. The HATS (Brüel & Kjaer Type 4128C) was positioned in the centre of a ring of loudspeakers (see section 4.2.2), facing the same direction as participants during testing. The three conditions of the Toy Localisation test used loudspeakers situated at −60°, −30°, −15°, 0°, +15°, +30°, and +60° (see Figure 4.2). Each one of these loudspeakers in turn presented a 12-s sample of white noise at 60 dB(A) SPL. The signal from the microphones was digitised at 44.1 kHz with 16-bit amplitude quantization. A segment with a duration of 9 s was extracted from the middle of each recording using CoolEdit 2000 (Syntrillium Software Corporation, Phoenix, USA). For each loudspeaker and microphone, this segment will be referred to as the first-recorded file. There were 14 first-recorded files (7 loudspeakers x 2 microphones).

Subsequent stages of processing were performed in MATLAB (The MathWorks Inc., Natick, USA). Each first-recorded file was analysed using the fast fourier transform (FFT), a technique that calculates the amplitude and phase of *N* sine waves which, when summed together, best model the waveform. The results of the FFT were used to calculate the average power of the first-recorded file in 50 Hz-wide non-overlapping frequency bands up to 10 kHz. For each frequency band, the attenuation level (in decibels) was calculated as the average power in that frequency band minus the average power of the most intense frequency band for that first-recorded file. The absolute values of these attenuation levels defined the frequency weights for each first-recorded file.

A.1.2 Stage 2: Spectral modification

The aim of the spectral modification was to reduce monaural spectral cues to source location. The unprocessed stimulus was analysed using the FFT, and the results were used to calculate the average power of the unprocessed stimulus in 50 Hz-wide non-overlapping bands up to 10 kHz. The average power in each frequency band was then boosted by the amount specified in the frequency weights for the first-recorded file. This process was repeated for each first-recorded file, to yield 14 stimuli, each of which was specific for a loudspeaker-microphone combination. These stimuli will be referred to as stimuli with 'weighted spectra'. The total RMS power of each of the stimuli with weighted spectra was adjusted to match the total RMS power of the most intense stimulus with a weighted spectrum.

A.1.3 Stage 3: Second set of recordings

The aim of the second set of recordings was to measure the effect of source location on the level of a stimulus on arrival at each ear. The stimuli with weighted spectra were presented from the array of loudspeakers and the signals from the microphones in the HATS were digitised at 44.1 kHz with 16-bit amplitude quantization. These are known as the second-recorded files. The total RMS power of each second-recorded file was calculated. A boost factor for a loudspeaker-microphone combination was calculated as the maximum RMS power across all second-recorded files divided by the RMS power for the second-recorded file corresponding to that loudspeaker-microphone combination.

A.1.4 Stage 4: Level modification

The aim of the level modification was to reduce monaural level cues to source location. Each stimulus with a weighted spectrum was scaled by the boost factor for its loudspeaker-microphone combination. The stimuli were low-pass filtered using a finite impulse response filter with a cut-off at 10 kHz and 60 dB of attenuation in the stopband. Linear onset and offset ramps of 50-ms duration were applied. The resulting stimuli will be referred to as the processed stimuli. Each unprocessed stimulus generated 14 processed stimuli (7 loudspeakers x 2 microphones).

A.1.5 Processing of noise stimuli

A sample of white noise with a duration of 10 s was processed in order to illustrate the effect of the processing. The resulting 'processed noise stimuli' were presented via the ring of loudspeakers and recorded using the microphones in the HATS. Figure A.2 shows the spectra of some of the recordings, alongside recordings of the unprocessed noise stimulus. The processed noise stimuli shown in Figure A.2 had been processed to give a similar level and spectrum at the left ear. The left panel of Figure A.2 indicates that, for the unprocessed noise stimuli, the level and spectrum at the left microphone varied with source location. The centre panel of Figure A.2 indicates that, for the processed noise stimuli, the level and spectrum at the left microphone were similar regardless of source location. In other words, the processing reduced the monaural cues to source location conveyed by the stimuli on arrival at the left ear. The right panel of Figure A.2 indicates that, for the processed noise stimuli, the level and spectrum at the right microphone varied with source location, to a greater degree than for the unprocessed stimuli. In other words, the processing enhanced the monaural cues to source location conveyed by the stimuli on arrival at the right ear.

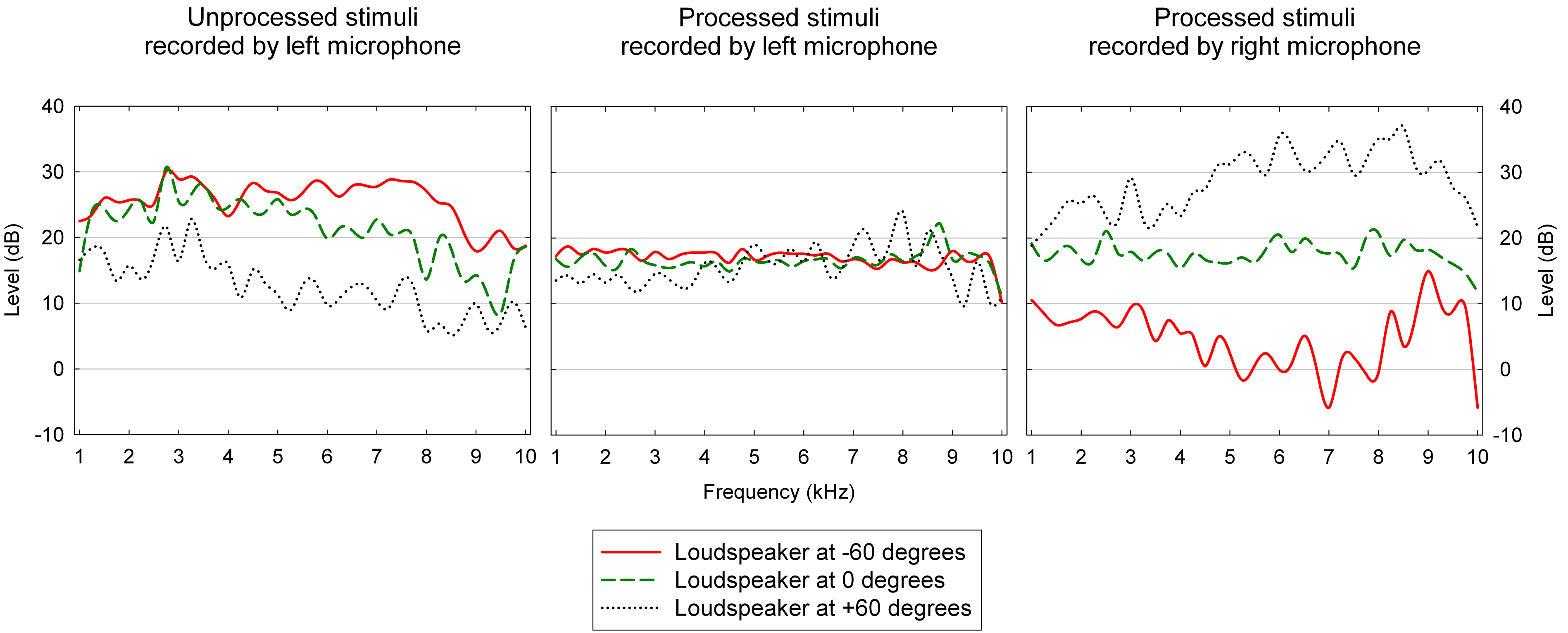


Figure A.2. The spectra of the unprocessed and processed noise stimuli, measured using the HATS. The processed stimuli shown in this figure are those that had been processed to give a similar level and spectrum at the left ear. Left panel: unprocessed noise stimuli measured using the left microphone. Centre panel: processed noise stimuli measured using the left microphone. Right panel: processed noise stimuli measured using the right microphone. The solid red line shows stimuli presented from a loudspeaker at −60° azimuth. The dashed green line shows stimuli presented from a loudspeaker at 0° azimuth. The dotted black line shows stimuli presented from a loudspeaker at +60° azimuth.

A.1.6 Processing of speech stimuli

The unprocessed stimuli for the Toy Localisation test consisted of recordings of five female talkers saying, “Hello, what’s this?”. Each recording was processed using the four stages described in Figure A.1.[2] The processed speech stimuli were highly intelligible to normally-hearing adults. The following sections describe two experiments that investigated the sound-source localisation skills of normally-hearing adults, using either unprocessed or processed speech stimuli.

A.2 Experiment A1: The effect of processing on the localisation skills of binaural or monaural listeners

A.2.1 Introduction

The first aim of this study was to assess whether participants could localise the source of the processed speech stimuli when binaural cues were available. The second aim was to compare monaural localisation performance using processed speech stimuli with monaural performance using unprocessed speech stimuli, in order to assess whether the processing had reduced the utility of monaural cues to source location.

Stimuli were presented by a ring of loudspeakers or by headphones. For the headphone conditions, the HATS was placed in the centre of the ring of loudspeakers and the participant listened to the output from the microphones in the ears of the HATS. This arrangement created an illusion of sound sources at different locations outside the head, whilst allowing for monaural presentation of the stimuli. The study used a repeated-measures design. Three conditions used the processed stimuli, which were presented: 1) by the ring of loudspeakers; 2) binaurally over headphones; or 3) monaurally over headphones. An additional condition used the unprocessed stimuli, which were presented monaurally over headphones.

A.2.2 Method

A.2.2.1 Participants

Eight adults aged between 19 and 37 years (mean age 22.8 years, standard deviation 6.0 years) were recruited via the University of York participant pool. Three of the participants were male. The participants had pure-tone thresholds equal to or better than 25 dB HL at octave frequencies between 0.25 and 8 kHz, inclusive, measured using the British Society of Audiology guidelines (1981). Approval was obtained from

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[2] The boost factors (see section A.1.3) for the speech stimuli with weighted spectra were the same as the boost factors for the noise stimuli with weighted spectra. In other words, measurements of the level of the noise stimuli were used to modify the level of the speech stimuli.

the Research Ethics Committee of the Department of Psychology of the University of York. Participants gave written informed consent and were paid for their time.

A.2.2.2 Outcome measure

Participants completed the 15° separation condition of the Toy Localisation test (see section 4.2.2.2). Briefly, a stimulus was presented from one of five possible source locations (between −30° and +30° in 15° intervals). The participant was asked to indicate the source location using a response screen that showed five boxes, arranged from left to right to reflect the arrangement of the loudspeakers. There were 120 trials in each condition. The root mean square (RMS) error was measured. No feedback was provided.

A.2.2.3 Procedure

For the condition which presented stimuli via loudspeakers, participants sat in the centre of the ring of loudspeakers and responded using a touchscreen monitor. For the conditions which presented stimuli via headphones (HP), participants sat in a quiet room and responded using a mouse and computer monitor. For the HP conditions, the HATS was placed in the centre of the ring of loudspeakers. The signals from the microphones in the ear canals were processed by a pre-amplifier (Brüel & Kjaer Type 2672) and then input to a Marantz solid-state recorder (Type PMD670). During testing, stimuli were presented by the loudspeakers and participants listened to the output from the solid-state recorder using Sennheiser HD580 headphones (Figure A.3).

The stimuli were presented either at a fixed level or a roved level. Four conditions were presented in an order counterbalanced across participants:

1. Processed stimuli with a roved level were presented by the ring of loudspeakers (‘Ring’).
2. Processed stimuli with a roved level were presented binaurally by headphones (‘HP binaural’).
3. Processed stimuli with a roved level were presented monaurally by headphones (‘HP monaural’).
4. Unprocessed stimuli with a fixed level were presented monaurally by headphones (‘HP monaural unprocessed’).

For the conditions with monaural presentation, half of the participants listened using the left ear and half used the right ear. Participants who listened monaurally with their left ear were presented with stimuli that had been processed to reduce monaural cues at the left ear, in all of the conditions with processed stimuli. Similarly, participants

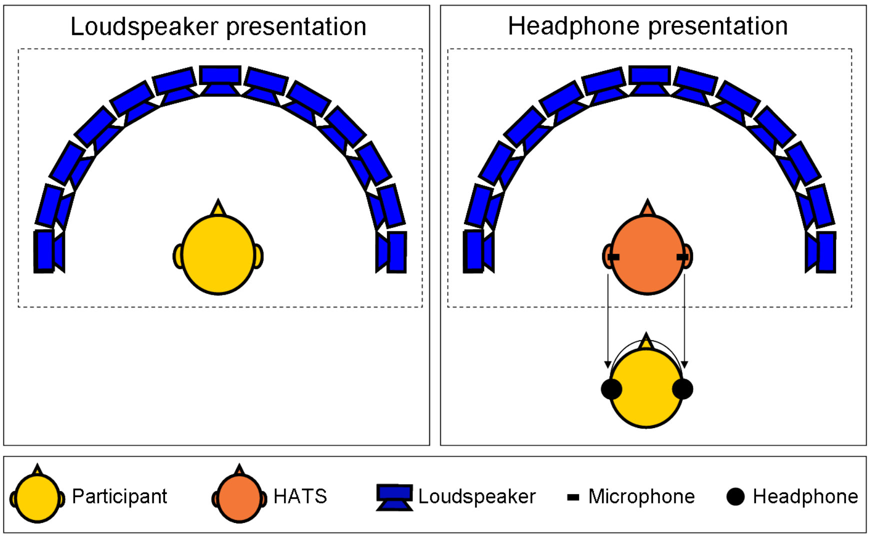


Figure A.3. The presentation of stimuli via loudspeakers (left panel) or headphones (right panel). Both panels show an array of loudspeakers within a sound-attenuating booth (indicated by the dashed line). Only the front 13 loudspeakers are shown. For the condition with loudspeaker presentation, the participant (shown in yellow) sat in the centre of the array of loudspeakers. For the conditions with presentation via headphones, a head and torso simulator (HATS, shown in orange) was placed in the centre of the array of loudspeakers. The participant sat outside the booth and listened to the signal from the microphones in the ears of the HATS.

who listened monaurally with their right ear were presented with stimuli that had been processed to reduce monaural cues at the right ear.

The loudspeakers presented the stimuli at an average level of 58 dB(A) SPL (measured using a free-field microphone in the centre of the ring—see section 4.2.2 for further details of how the levels were measured). For the conditions with a level rove, the level was randomly roved by ±5 dB in 1 dB steps. For the HP conditions, the gain on the solid-state recorder was set so that stimuli were delivered at a comfortable level.

A.2.2.4 Analyses

The data did not distribute normally, so the results are displayed using box plots overlaid with the scores of individual participants. To assess whether condition had an effect on performance, a Friedmans ANOVA was carried out followed by Wilcoxon signed-rank tests with a Bonferroni correction. Bonferroni-adjusted p values (p_{bf}) are reported (see section 4.2.5). Wilcoxon tests were used to make the following key comparisons: Ring compared to HP binaural, HP binaural compared to HP monaural, HP monaural compared to HP monaural unprocessed. Effect sizes for Wilcoxon comparisons were calculated using the formula $r = z/\sqrt{N}$ where z is the standardised test statistic and N is the number of observations in the analysis (see section 4.2.5.2 for a discussion of how to interpret effect sizes).

A.2.3 Results

The results are shown in Figure A.4. There was a significant effect of condition on performance [$\chi^2(3) = 20.7$, $p < .001$]. Error scores were lower in the Ring condition than the HP binaural condition [$z = -2.38$, $p_{bf} < .05$, $r = .60$]. Error scores were lower in the HP binaural condition than in the HP monaural condition [$z = -2.52$, $p_{bf} < .05$, $r = .63$]. Error scores in the HP monaural condition did not differ significantly from those in the HP monaural unprocessed condition [$z = -1.40$, $p_{bf} > .05$, $r = .35$].

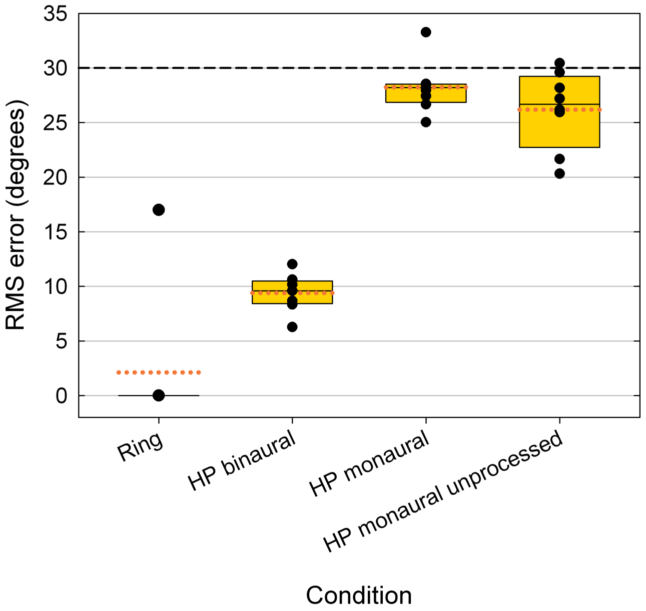


Figure A.4. Results of Experiment A1. The yellow boxes show the area between the 25th and 75th percentile scores. The solid black horizontal lines within the boxes show median scores; the dotted orange horizontal lines within the boxes show mean scores. Circles show individual scores. The dashed line indicates the level of performance one would expect by chance.

A.2.4 Discussion

Seven of the eight participants made no errors in sound-source localisation when processed stimuli were presented via the ring of loudspeakers. Thus, normally-hearing adults were able to localise the source of the processed stimuli when binaural cues and/or level and spectral cues resulting from head turns were available. It is not clear why one participant showed poorer performance than the other participants in the Ring condition; the same participant performed similarly to the other participants in the HP conditions.

Normally-hearing adults showed an impaired ability to localise sources of sound when stimuli were presented binaurally via headphones rather than via a ring of loudspeakers. This deficit may have arisen because the percept of spatial location was generated by the HATS rather than the listener's own pinna, head, and torso. Furthermore, with headphone presentation, listeners could not turn their head and use the resulting changes in level and spectrum to localise sources of sound.

Normally-hearing adults showed an impaired ability to localise sources of sound when stimuli were presented monaurally via headphones rather than binaurally via headphones. Under monaural conditions, there was no significant difference in performance between the processed and unprocessed stimuli, although some individuals did appear to make smaller errors in the latter condition. On the basis of these results, the processing to reduce the utility of monaural cues to source location appears to be unnecessary—monaural performance was equally poor with both processed and unprocessed stimuli. However, the adults in the present study did not have an opportunity to practise the localisation task using the unfamiliar monaural stimuli, whereas unilaterally-implanted children are experienced monaural listeners. Moreover, future studies were planned in which listeners would receive training on localisation tasks with monaural stimuli (see Chapter 6). Accordingly, Experiment A2 measured the ability of experienced monaural listeners to localise the source of processed and unprocessed stimuli.

A.3 Experiment A2: The effect of processing on the localisation skills of practised monaural listeners

The aim of this study was to assess the localisation skills of practised monaural listeners, using either processed or unprocessed speech stimuli. Throughout the study, stimuli were presented monaurally via headphones, using the arrangement described for Experiment A1 (see section A.2.2.3). The study used a within-subjects design. During practice trials, stimuli were unprocessed. During test trials, stimuli were either unprocessed or processed.

A.3.1 Method

A.3.1.1 Participants

Eight adults aged between aged 19 and 26 years (mean age mean 21.1 years, standard deviation 6.0 years) were recruited via the University of York Department of Psychology participant pool. Two of the participants were male. The participants had pure-tone thresholds equal to or better than 25 dB HL at octave frequencies between 0.25 and 8 kHz, inclusive, in the ear that they used for the experiment. That ear was chosen in a counterbalanced order. One participant took part in both experiments. Approval was obtained from the Research Ethics Committee of the Department of Psychology of the University of York. Participants gave written informed consent and were paid for their time.

A.3.1.2 Listening tasks

The training task was the same as the outcome measure for Experiment A1 (see section A.2.2.2), except that feedback was given after each trial by illuminating the correct response. Each participant completed 240 training trials at the beginning of the experiment. Following training, the test trials used the same task but no feedback was provided.

A.3.1.3 Procedure

The stimuli were delivered monaurally via headphones. Each participant used the same ear throughout the experiment: the left ear for half of the participants, the right ear for the other half. As for Experiment A1, in the conditions with processed stimuli, participants who listened with their left ear were presented with stimuli that had been processed to reduce monaural cues at the left ear. Similarly, in the conditions with processed stimuli, participants who listened with their right ear were presented with stimuli that had been processed to reduce monaural cues at the right ear. For the training task, the stimuli were unprocessed and were presented at a constant level. Following training, each participant completed 120 trials in each of three test conditions:

1. Unprocessed stimuli were presented at a constant level (‘unprocessed’).
2. Processed stimuli were presented at a fixed level (‘processed-fixed’).
3. Processed stimuli were presented with a level rove of ±5 dB, in 1 dB steps (‘processed-roved’).

Trials of each condition were presented in a random order.

A.3.1.4 Analyses

The data were analysed in the same way as for Experiment A1. Wilcoxon tests were used to make the following key comparisons: unprocessed compared to processed-fixed, processed-fixed compared to processed-roved.

A.3.2 Results

The results are shown in Figure A.5. There was a significant effect of condition on performance [$\chi^2(2) = 13.0$, $p < .001$]. Error scores were lower in the unprocessed condition than in the processed-fixed condition [z = -2.52, $p_{bf} < .01$, $r = .63$]. Error scores in the processed-fixed condition were not significantly different to those in the processed-roved condition [$z = -0.98$, $p_{bf} > .05$, $r = .25$].

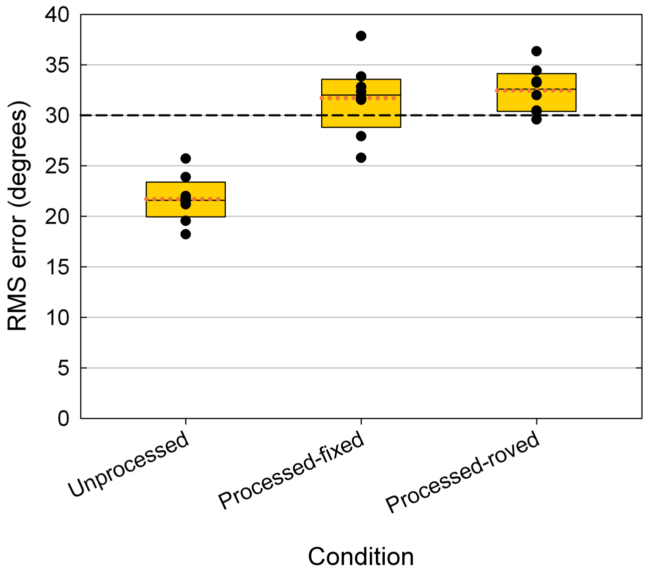


Figure A.5. Results of Experiment A2. The yellow boxes show the area between the 25th and 75th percentile scores. The solid black horizontal lines within the boxes show median scores; the dotted orange horizontal lines within the boxes show mean scores. Circles show individual scores. The dashed line indicates the level of performance one would expect by chance.

A.3.3 Discussion

After practising the task for approximately 30 minutes, normally-hearing adults were able to localise the unprocessed stimuli at a level better than would be expected by chance. Binaural cues and cues resulting from headturns were not available, so participants must have learnt the level or spectral cues that were associated with each source location. The majority of participants performed at a level close to chance with the processed stimuli. Thus, Experiment A2 demonstrated that the processing had the desired effect of reducing the utility of monaural cues to source location. Experiment A1 demonstrated that it was nonetheless possible to localise the processed stimuli on the basis of binaural cues, and/or cues resulting from headturns. Therefore, the processing described in this appendix reduces the utility of monaural cues to source location, without affecting the utility of binaural cues or cues resulting from headturns.

A.4 Stimuli used in the final version of the test

After these experiments were concluded, Advanced Bionics (a manufacturer of cochlear implants) loaned equipment to our laboratory which enabled the output from a cochlear-implant microphone to be recorded. The equipment is described in section 6.2.2.1. The recordings and processing described in section A.1.6 were repeated using a cochlear-implant microphone situated behind each ear of the HATS, rather than the integral microphones in the HATS. This arrangement meant that the processing reflected the cues to source location that are picked up by a cochlear-implant microphone. The implant microphone attenuated frequencies above 8 kHz, so the processed stimuli were low-pass filtered using a finite impulse response filter with a cut-off at 8 kHz and 60 dB of attenuation in the stopband. The resulting stimuli were used throughout the rest of this thesis.

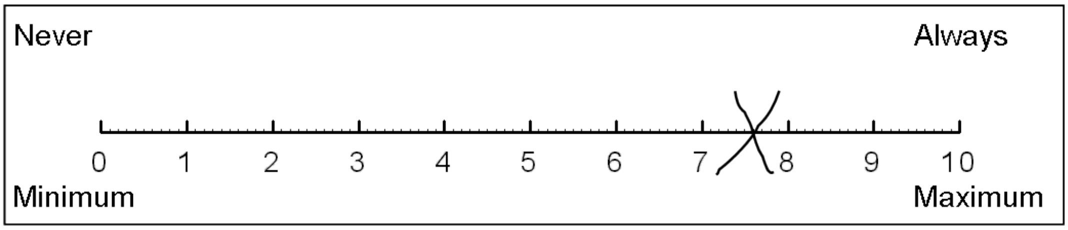
An analysis of the spectra of the processed stimuli (Figure A.2), and behavioural testing (Experiment A2), indicated that the processing reduced the monaural cues to source location at a nominated ear. However, Figure A.2 indicated that the processing amplified the monaural cues to source location at the non-nominated ear. When testing bilaterally-implanted or bimodally-aided children, this creates a dilemma: which ear should receive the reduced monaural cues? Furthermore, if bilaterally-implanted or bimodally-aided children were able to attend to the non-nominated ear, it may be possible to localise the stimuli on the basis of monaural cues at that ear. As a result, nominating one ear to receive reduced monaural cues could give an advantage to bilaterally-implanted and bimodally-aided children that would not be present in everyday life. Accordingly, during testing with all participants throughout the rest of this thesis, the nominated ear was selected at random from trial to trial. Consequently, the processed stimuli introduced variability into the level and spectrum on arrival at both ears.

Appendix B

The Speech, Spatial, and Qualities of Hearing Scale for Teachers of the Deaf

This questionnaire asks about your child's ability to hear and listen in everyday situations. You should answer each question by making a mark on a horizontal line. Here is an example question. The answer, marked by the cross on the line, shows that the child has cornflakes for breakfast on most days, but not everyday. If you do not know the answer to a question, please put a tick in the box labelled 'I do not know'. If the situation described in a question does not happen for your child, please put a tick in the box labelled 'This situation does not happen for my child'. The real questions start on the next page.

1. Does your child have cornflakes for breakfast?



☐ I do not know ☐ This situation does not happen for my child

Section A: Speech

1. You are talking with your child and there is a TV on in the same room. Without turning the TV down, can your child follow what you're saying?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

Minimum Maximum

☐ I do not know ☐ This situation does not happen for my child

2. You are talking with your child in a quiet, carpeted room. Can your child follow what you're saying?

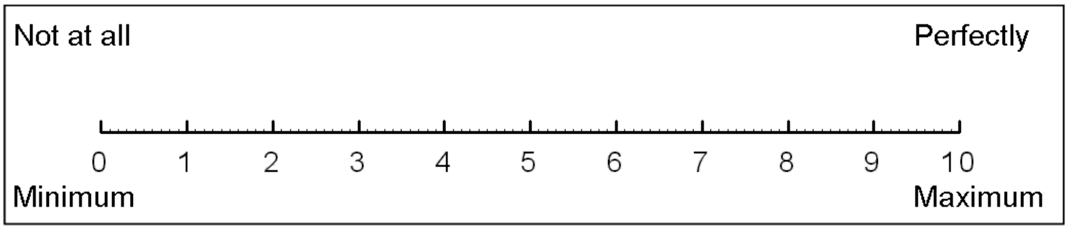
Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

Minimum Maximum

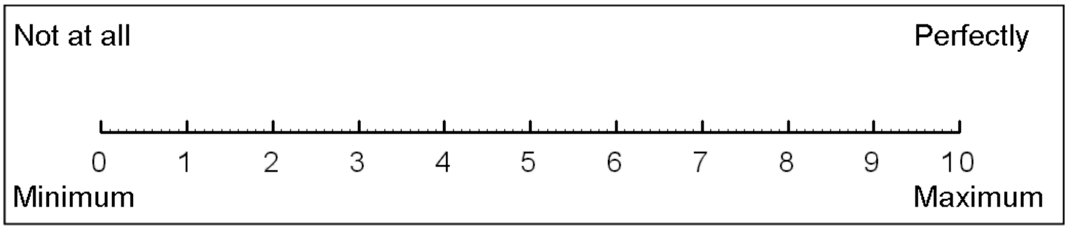
☐ I do not know ☐ This situation does not happen for my child

3. Your child is in a group of about five people, sitting around a table. It is an otherwise quiet place. Your child can see everyone else in the group. Can your child follow the conversation?



☐ I do not know ☐ This situation does not happen for my child

4. Your child is in a group of about five people, sitting around a table. It is a noisy room, such as a busy classroom. Your child can see everyone else in the group. Can your child follow the conversation?



☐ I do not know ☐ This situation does not happen for my child

5. You are talking with your child. There is a continuous background noise, such as a fan or running water. Can your child follow what you say?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

Minimum Maximum

☐ I do not know ☐ This situation does not happen for my child

6. Your child is in a group of about five people, sitting around a table. It is a noisy room, such as a busy classroom. Your child cannot see everyone else in the group. Can your child follow the conversation?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

Minimum Maximum

☐ I do not know ☐ This situation does not happen for my child

7. You are talking to your child in a place where there are a lot of echoes, such as a school assembly hall. Can your child follow what you say?

Not at all										Perfectly
0	1	2	3	4	5	6	7	8	9	10
Minimum										Maximum

☐ I do not know ☐ This situation does not happen for my child

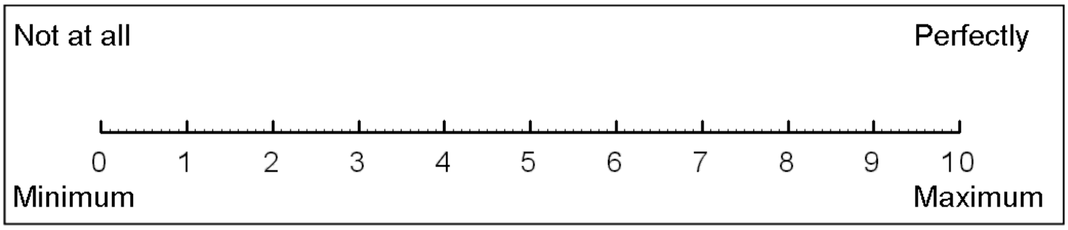
8. You are talking to your child in a room in which there are many other people talking. Can your child follow what you say?

Not at all										Perfectly
0	1	2	3	4	5	6	7	8	9	10
Minimum										Maximum

☐ I do not know ☐ This situation does not happen for my child

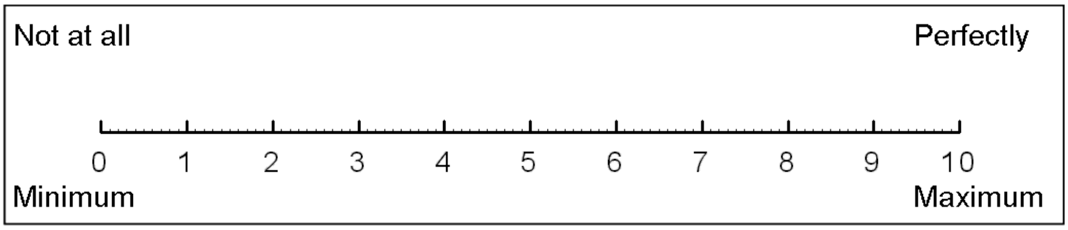
Section B: Spatial Hearing

1. Your child is outdoors in an unfamiliar place. A loud constant noise, such as from an aeroplane, can be heard. The source of the sound can't be seen. Can your child tell right away where the sound is coming from?



☐ I do not know ☐ This situation does not happen for my child

2. Your child is sitting around a table with several people. Your child cannot see everyone. Can your child tell where any person is as soon as they start speaking?



☐ I do not know ☐ This situation does not happen for my child

3. Your child is sitting in between two people. One person starts to speak. Can your child tell right away whether it is the person on their left or their right who is speaking, without having to look?

Not at all										Perfectly
0	1	2	3	4	5	6	7	8	9	10
Minimum										Maximum

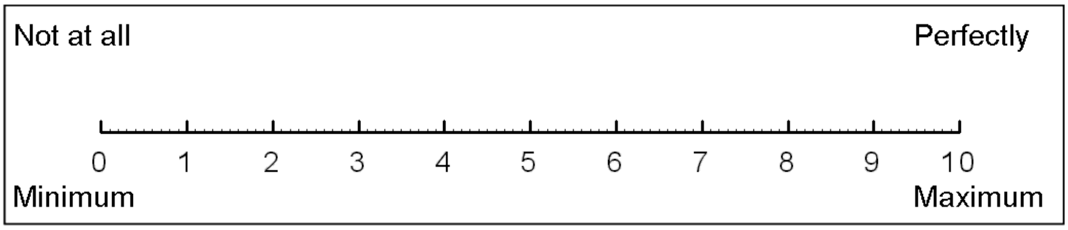
☐ I do not know ☐ This situation does not happen for my child

4. You and your child are outside. You call out their name. Can your child tell immediately where you are without having to look?

Not at all										Perfectly
0	1	2	3	4	5	6	7	8	9	10
Minimum										Maximum

☐ I do not know ☐ This situation does not happen for my child

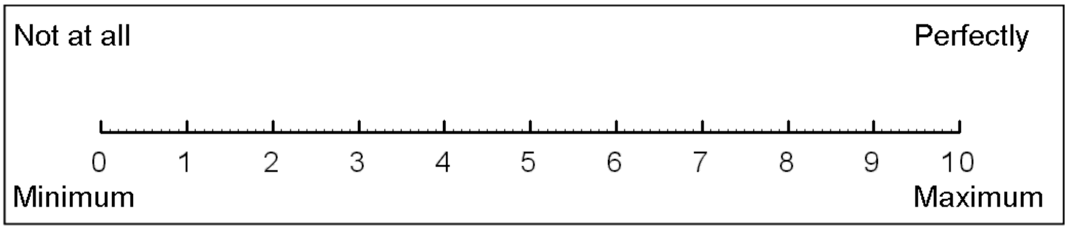
5. Your child is standing in a corridor. A noisy group of children is approaching. Can your child hear right away which direction they are coming from before seeing the children?



☐ I do not know ☐ This situation does not happen for my child

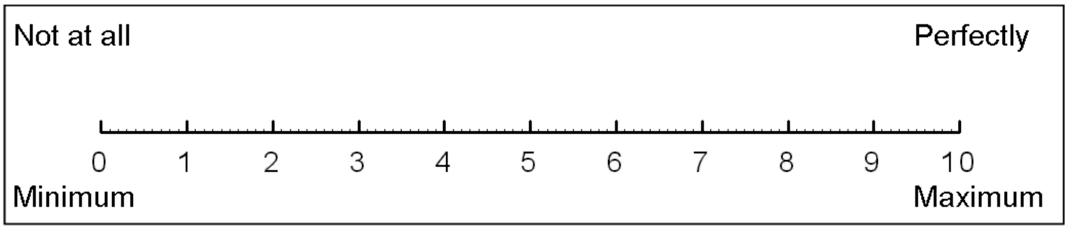
Section C: Qualities of Hearing

1. Think about when there are two noises at once, for example, music playing and the sound of knocking at the door. Is your child able to identify the two separate sounds?



☐ I do not know ☐ This situation does not happen for my child

2. You are in a room with your child and music is playing. Will your child be aware of your voice if you start speaking? Note that your child does not have to understand what you say.



☐ I do not know ☐ This situation does not happen for my child

3. Can your child recognise familiar people by the sound of each one's voice without seeing them?

Not at all Perfectly
0 1 2 3 4 5 6 7 8 9 10
Minimum Maximum

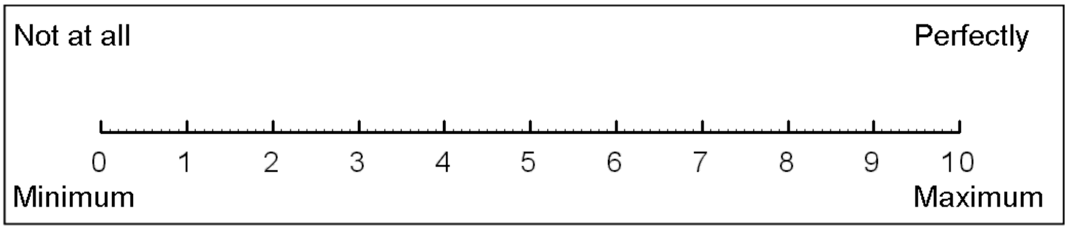
☐ I do not know ☐ This situation does not happen for my child

4. Can your child distinguish between pieces of music such as different nursery rhymes played on a cassette tape or CD? Note that producing relevant words or movements can indicate recognition.

Not at all Perfectly
0 1 2 3 4 5 6 7 8 9 10
Minimum Maximum

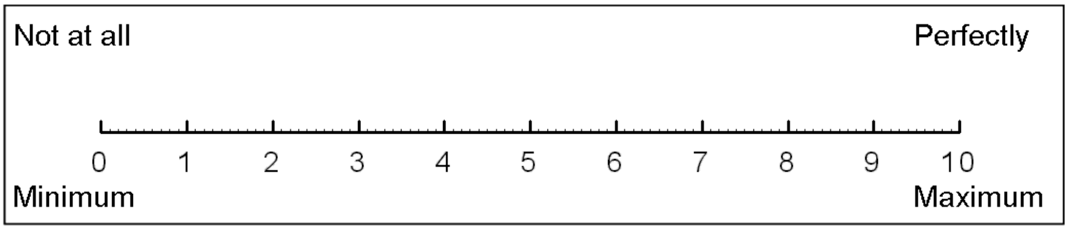
☐ I do not know ☐ This situation does not happen for my child

5. Can your child tell the difference between sounds that are somewhat similar, for example, a car versus a bus, OR a school bell versus knocking at the door?



☐ I do not know ☐ This situation does not happen for my child

6. Can your child easily judge another person’s mood from the sound of their voice?



☐ I do not know ☐ This situation does not happen for my child

7. Does your child have to put in a lot of effort to hear what is being said in conversation with others?

A lot of effort No effort

0 1 2 3 4 5 6 7 8 9 10

Minimum Maximum

☐ I do not know ☐ This situation does not happen for my child

8. Can your child easily ignore other sounds when trying to listen to something?

Not easily ignore Easily ignore

0 1 2 3 4 5 6 7 8 9 10

Minimum Maximum

☐ I do not know ☐ This situation does not happen for my child

Thank you for completing this questionnaire

Appendix C

The Health Utilities Index Mark 3

Instructions: This set of questions asks about your child's day-to-day health. You may feel that some of these questions do not apply to you, but it is important that we ask the same questions of everyone.

Please read each question and consider your answers carefully. For each question, please select one answer that best describes your child's usual level of ability or disability. Please indicate the selected answer by marking (X) the box beside the answer.

A few of the questions are similar to others; please excuse the apparent overlap, and answer each question independently. Thank you.

1. Which one of the following best describes your child's usual ability to see well enough to see pictures in a book?
   ☐ Able to see well enough without glasses or contact lenses
   ☐ Able to see well enough with glasses or contact lenses
   ☐ Unable to see well enough even with glasses or contact lenses
   ☐ Unable to see at all

2. Which one of the following best describes your child's usual ability to see well enough to recognize you across the room?
   ☐ Able to see well enough without glasses or contact lenses
   ☐ Able to see well enough with glasses or contact lenses
   ☐ Unable to see well enough even with glasses or contact lenses
   ☐ Unable to see at all

3. Which one of the following best describes your child's usual ability to hear what is said in a group conversation with at least three other people?
   ☐ Able to hear what is said without a hearing aid or cochlear implant
   ☐ Able to hear what is said with a hearing aid or cochlear implant
   ☐ Unable to hear what is said, even with a hearing aid or cochlear implant
   ☐ Unable to hear what is said, but don't wear a hearing aid or cochlear implant
   ☐ Unable to hear at all

4. Which one of the following best describes your child's usual ability to hear what is said in a conversation with one other person in a quiet room?
   ☐ Able to hear what is said without a hearing aid or cochlear implant
   ☐ Able to hear what is said with a hearing aid or cochlear implant
   ☐ Unable to hear what is said, even with a hearing aid or cochlear implant
   ☐ Unable to hear what is said, but don't wear a hearing aid or cochlear implant
   ☐ Unable to hear at all

5. Which one of the following best describes your child's usual ability to be understood when speaking the same language with strangers?
   ☐ Able to be understood completely
   ☐ Able to be understood partially
   ☐ Unable to be understood
   ☐ Unable to speak at all

6. Which one of the following best describes your child's usual ability to be understood when speaking with people who know him/her well?
   ☐ Able to be understood completely
   ☐ Able to be understood partially
   ☐ Unable to be understood
   ☐ Unable to speak at all

7. Which one of the following best describes how your child usually feels?
   ☐ Happy and interested in life
   ☐ Somewhat happy
   ☐ Somewhat unhappy
   ☐ Very unhappy
   ☐ So unhappy that life is not worthwhile

8. Which one of the following best describes your child's usual level of pain and discomfort?
   ☐ Free of pain and discomfort
   ☐ Mild to moderate pain that prevents no activities
   ☐ Moderate pain that prevents a few activities
   ☐ Moderate pain that prevents some activities
   ☐ Severe pain that prevents most activities

9. Which one of the following best describes your usual child's ability to get around?
   ☐ Able to walk, bend, lift, jump and run normally for age
   ☐ Walks, bends, lifts, jumps or runs with some limitations but does not require help
   ☐ Requires mechanical equipment (such as canes, crutches, braces or wheelchair) to walk or get around independently
   ☐ Requires the help of another person to walk or get around and requires mechanical equipment as well
   ☐ Unable to control or use arms and legs

10. Which one of the following best describes your child's usual ability to use his/her hands and fingers? Note: Special tools refer to hooks for buttoning clothes, gripping devices for opening jars or lifting small items, and other devices to compensate for limitations of hands or fingers
    ☐ Full use of two hands and ten fingers
    ☐ Limitations in the use of hands or fingers, but do not require special tools or help of another person
    ☐ Limitations in the use of hands or fingers, independent with the use of special tools (do not require the help of another person)
    ☐ Limitations in use of hands or fingers, require the help of another person for some tasks (not independent even with use of special tools)
    ☐ Limitations in use of hands of fingers, require the help of another person for most tasks (not independent even with use of special tools)
    ☐ Limitations in use of hands or fingers require the help of another person for all tasks (not independent even with use of special tools)

11. Which one of the following best describes your child's usual ability to remember things?
    ☐ Able to remember most things
    ☐ Somewhat forgetful
    ☐ Very forgetful
    ☐ Unable to remember anything at all

12. Which one of the following best describes your child's usual ability to think and solve day-to-day problems?

☐ Able to think clearly and solve day-to-day problems normally for age

☐ Have a little difficulty when trying to think and solve day-to-day problems

☐ Have some difficulty when trying to think and solve day-to-day problems

☐ Have great difficulty when trying to think and solve day-to-day problems

☐ Unable to think or solve day-to-day problems

13. Which one of the following best describes your child's usual ability to perform basic activities?

☐ Eat, bathe, dress and use the toilet normally for age

☐ Eat, bathe, dress and use the toilet independently with difficulty

☐ Requires mechanical equipment to ear, bathe, dress and use the toilet independently

☐ Requires the help of another person to eat, bathe, dress or use the toilet

14. Which one of the following best describes how your child usually feels?

☐ Generally happy and free from worry

☐ Occasionally fretful, angry, irritable, anxious or depressed

☐ Often fretful, angry, irritable, anxious or depressed

☐ Almost always fretful, angry, irritable, anxious or depressed

☐ Extremely fretful, angry, irritable, anxious or depressed, usually requiring hospitalization or psychiatric institutionary care

15. Which one of the following best describes your child's usual level of pain?

☐ Free of pain and discomfort

☐ Occasional pain; discomfort relieved by non-prescription drugs or self-control activity without disruption of normal activities

☐ Frequent pain; discomfort relieved by oral medicines with occasional disruption of normal activities

☐ Frequent pain, frequent disruption of normal activities; discomfort requires prescription narcotics for relief

☐ Severe pain; pain not relieved by drugs and constantly disrupts normal activities

Appendix D

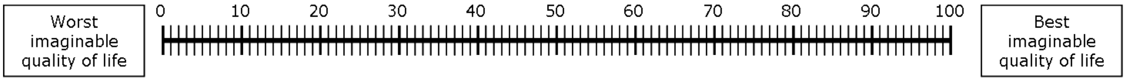
Visual-Analogue Scales for Parents

Part one: Visual-analogue scales for parents of unilaterally-implanted children

Question 1

To help people express their thoughts about their child's quality of life, we have drawn a scale. The best quality of life that you can imagine is marked 100, and the worst quality of life that you can imagine is marked 0. We would like you to use the scale to help us understand your thoughts on your child's quality of life.

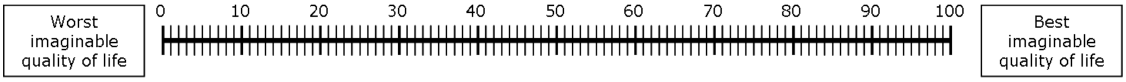
Please make a mark on the scale to show us how good or bad your child's quality of life is with his/her **cochlear implant**.



Question 2

Now we would like you to imagine how your child's quality of life would be if it had **not been possible** to get a cochlear implant for him/her.

Please make a mark on the scale to show us how good or bad your child's quality of life would be if he/she had **not received a cochlear implant**.

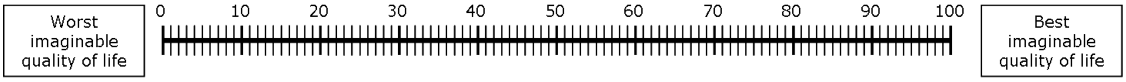


Part two: Visual-analogue scales for parents of bilaterally-implanted children

Question 1

To help people express their thoughts about their child's quality of life, we have drawn a scale. The best quality of life that you can imagine is marked 100, and the worst quality of life that you can imagine is marked 0. We would like you to use the scale to help us understand your thoughts on your child's quality of life.

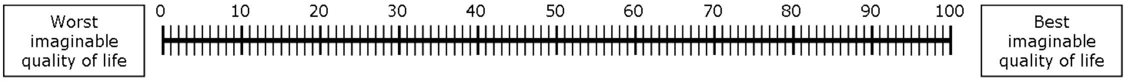
Please make a mark on the scale to show us how good or bad your child's quality of life is with his/her **two cochlear implants**.



Question 2

Now we would like you to imagine how your child's quality of life would be if it had **only been possible** to get **one** cochlear implant for him/her.

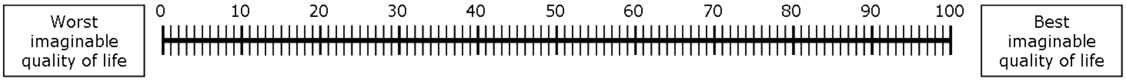
Please make a mark on the scale to show us how good or bad your child's quality of life would be if he/she had **only one cochlear implant.**



Question 3

Now we would like you to imagine how your child’s quality of life would be if it had **not been possible** to get **any** cochlear implants for him/her. Please make a mark on

the scale to show us how good or bad your child’s quality of life would be if he/she had **not received any cochlear implants**.



Appendix E

Questionnaire for Informants

Please could you give us the following information about yourself:
Your date of birth: . . . / . . . / . . . . . .

Your gender: Male / Female

Are you the parent or guardian of any children?
Yes / No
If you answered 'yes', please could you tell us their age/s and whether they have been diagnosed with any disability?
Age: Disability? . . . .
Age: Disability? . . . .
Age: Disability? . . . .
Age: Disability? . . . .

Do you have a family history of hearing loss or deafness?
Yes / No
If you answered 'yes', please could you give us brief details:

Have you worked with people who have hearing loss or deafness?

Yes / No
If you answered 'yes', please could you give us brief details:

Instructions

We would like you to imagine that you are 33 years old. You have a daughter who is profoundly deaf. You are in a stable relationship with your daughter's mother/father and you are financially secure.

We will now describe four scenarios that relate to your daughter's deafness. Each scenario is followed by two questions. Please start by reading all four of the scenarios. Then, read through each scenario again and answer the two questions that follow it. Please read the scenarios very carefully.

The questions ask about the quality of life of your imaginary daughter. There are no right or wrong answers. We are simply trying to find out how people relate a description of a child to the quality of life that they imagine the child might have.

Scenario No. 1

Your child was born deaf and does not have a cochlear implant or a hearing aid

Your child was born profoundly deaf and is now 6 years old. The cause of her deafness is not life-threatening, but there is no cure. She has so little hearing that hearing aids cannot help her. She will be unable to hear throughout her life. Physically, however, she is a completely healthy child.

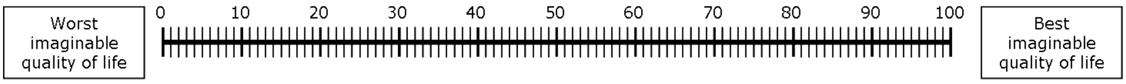
- Your daughter is unable to hear everyday sounds, such as music, voices, and traffic. She cannot hear the sound of her own voice.
- She can understand some of what you say by lipreading, but her main means of communication is Sign Language. You are taking courses in Sign Language in order to communicate with her.
- Your daughter attends a mainstream school, although she spends most of her time in a specialised class for children with impaired hearing, where she works with a small number of other children.
- Your child's ability to use spoken language is progressing at a slower rate than normal. She is finding it difficult to learn to read. You have been advised that she is likely to find reading and writing difficult in the future.
- Socially, she gets on well with other hearing impaired children. She finds it difficult to make friends with normally hearing children because of problems with communication.
- You worry about your daughter's safety when she is outdoors because she cannot hear warning signals. You feel that you cannot give her as much independence as you would like.
- Your child's deafness sometimes places a strain on your family life because of the level of assistance and attention which she requires.
- You have been advised that it is probable that your daughter will have restricted job opportunities when she is an adult because of difficulties in speaking on the telephone and in other situations that require spoken communication.

Questions about Scenario No. 1

Question 1

To help you express you thoughts about your imaginary child's quality of life, we have drawn a scale. The best quality of life that you can imagine is marked 100, and the worst quality of life that you can imagine is marked 0. We would like you to use the scale to help us understand your thoughts on your imaginary daughter's quality of life.

Please make a mark on the scale to show us how good or bad your daughter's quality of life is **with no cochlear implant and no hearing aid**. You may make the mark anywhere on the scale not just at the points marked by the numbers.



Question 2

Now we would like you to think about your daughter's quality of life in a different way.

Remember, you are 33 years old. Imagine you will live for 50 more years until you are 83 years old.

Now, imagine that you could give up some years of your own life in order for your child to have normal hearing. She would have normal hearing immediately and then for the rest of her life. Imagine that the years you give up would be taken off the end of your life. This question does not measure whether you are a good or bad parent — it is simply a method of obtaining your judgement about how challenging this scenario would be for your daughter.

Please write the number of years that you would give up in this box:

I would give up this number of years:

Scenario No. 2

Your child was born deaf and has a cochlear implant in one ear

Your child was born profoundly deaf and is now 6 years old. When she was 2 years old, she received a cochlear implant in one ear. (A cochlear implant is an electronic device which surgically implanted in the inner ear. It helps deaf people to hear by by-passing parts of the ear that are not working and stimulating the nerve of hearing directly with electrical signals.) The operation was a success. There were no complications.

- Your daughter can speak. Everyone can understand what she is saying without much effort.
- She can understand most of what is said to her, especially if she can see the talker's face and lips.
- She finds it difficult to understand speech when there is background noise, even at low levels where you have no difficulty.
- Your daughter's spoken language is developing at the normal rate, but she is a couple of years behind children with normal hearing.
- Your child attends a mainstream school where she is a member of a regular class of children. She receives about 6 hours of help each week during lessons from a learning support assistant. Even so, she is tired at the end of the school day because of the need to concentrate when she listens.
- Your daughter is starting to read and write. She is making progress but she is a bit behind many other members of her class.
- Most of the time, you and your child forget that she has a cochlear implant. However, you have to keep an eye on her if she stars to play rough games that could result in her receiving a blow on the side of her head where her implant is.
- You are not too concerned about your daughter's future in terms of academic achievement, employment, and independent living. You have been advised that it is likely that she will live a relatively normal life.
- You have to take a couple of days away from your usual activities each year for routine hospital appointments to have her implant checked.
- Occasionally, you have to take time away from your usual activities at short notice to attend unforeseen hospital appointments. For example, if your daughter bangs her head or feels sick or dizzy, you need to check with a doctor

to find out whether her cochlear implant has been damaged or is causing the symptoms.

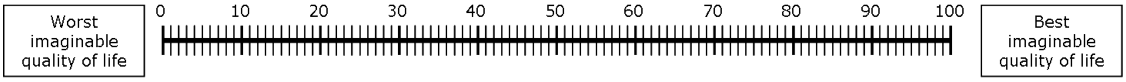
- Your child is unable to tell which direction sounds are coming from. Because of this, she doesn't always know where to look to see who is talking and you worry a little about her safety when she is outdoors.
- You are slightly concerned that the cochlear implant could fail and that another operation would be required to replace it. You have been advised that there is a small possibility that it might not be possible to put a new implant in the same ear. In which case, it would be necessary to implant the other ear. You have been advised that there is a very small possibility that it might not be possible to implant the other ear. If this happened, your daughter would be permanently deaf.

Questions about Scenario No. 2

Question 1

To help you express you thoughts about your imaginary child’s quality of life, we have drawn a scale. The best quality of life that you can imagine is marked 100, and the worst quality of life that you can imagine is marked 0. We would like you to use the scale to help us understand your thoughts on your imaginary daughter’s quality of life.

Please make a mark on the scale to show us how good or bad your daughter’s quality of life is **with a cochlear implant**. You may make the mark anywhere on the scale not just at the points marked by the numbers.



Question 2

Now we would like you to think about your daughter’s quality of life in a different way.

Remember, you are 33 years old. Imagine you will live for 50 more years until you are 83 years old.

Now, imagine that you could give up some years of your own life in order for your child to have normal hearing. She would have normal hearing immediately and then for the rest of her life. Imagine that the years you give up would be taken off the end of your life. This question does not measure whether you are a good or bad parent — it is simply a method of obtaining your judgement about how challenging this scenario would be for your daughter.

Please write the number of years that you would give up in this box:

I would give up this number of years:

Scenario No. 3

Your child was born deaf and has a cochlear implant in one ear and a hearing aid in the other ear

Your child was born profoundly deaf and is now 6 years old. When she was 2 years old, she received a cochlear implant in one ear. (A cochlear implant is an electronic device which is implanted surgically in the inner ear. It helps deaf people to hear by by-passing parts of the ear that are not working and stimulating the nerve of hearing directly with electrical signals.) The operation was a success. There were no complications. Your child also uses a hearing aid in her other ear. (A hearing aid is an acoustic device that amplifies sounds. It is fitted without an operation.) The hearing aid enables your child to hear some very low-frequency sounds.

Your daughter has many of the same advantages and disadvantages as were described in the previous scenario (Scenario No. 2) with some additional advantages, as follows:-

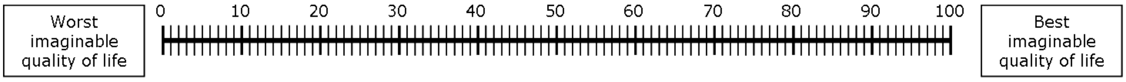
- She has grasped the concept of “where” sounds come from. She can tell whether a sound is coming from the left or right, though she finds it difficult to be more accurate than that.
- She can sometimes tell whether a motor vehicle is coming from her left or her right. Also, sometimes she knows where to look to see who is talking.
- As a result, you are a little less worried abut her safety when she is outdoors.

Questions about Scenario No. 3

Question 1

To help you express you thoughts about your imaginary child's quality of life, we have drawn a scale. The best quality of life that you can imagine is marked 100, and the worst quality of life that you can imagine is marked 0. We would like you to use the scale to help us understand your thoughts on your imaginary daughter's quality of life.

Please make a mark on the scale to show us how good or bad your daughter's quality of life is **with one cochlear implant and a hearing aid**. You may make the mark anywhere on the scale not just at the points marked by the numbers.



Question 2

Now we would like you to think about your daughter's quality of life in a different way.

Remember, you are 33 years old. Imagine you will live for 50 more years until you are 83 years old.

Now, imagine that you could give up some years of your own life in order for your child to have normal hearing. She would have normal hearing immediately and then for the rest of her life. Imagine that the years you give up would be taken off the end of your life. This question does not measure whether you are a good or bad parent — it is simply a method of obtaining your judgement about how challenging this scenario would be for your daughter.

Please write the number of years that you would give up in this box:

I would give up this number of years:

Scenario No. 4

Your child has two cochlear implants, one in each ear

Your child was born profoundly deaf and is now 6 years old. When she was 2 years old, she received two cochlear implants, one in each ear. (A cochlear implant is an electronic device which is implanted surgically in the inner ear. It helps deaf people to hear by bypassing parts of the ear that are not working and stimulating the nerve of hearing directly with electrical signals.) The operation was a success. There were no complications.

Your daughter has all of the abilities described in Scenario No. 2, with some additional advantages, as follows:-

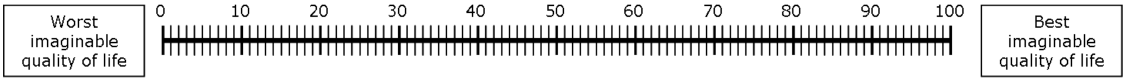
- She has grasped the idea of “where”’ sounds come from. She can tell whether sounds come from the left, straight ahead, or the right.
- She can hear speech better in noisy situations because she has the choice of which ear to listen with and can therefore attend with the ear closer to the talker.
- Your daughter can usually tell whether a motor vehicle is coming from her left or her right. As a result, you are less worried about her safety when she is outdoors.
- She can usually understand most of what is said to her, even when she cannot see the talker’s face. Also, she usually knows where to look to see who is talking.
- Your child attends a mainstream school and only rarely needs help from a learning support assistant.
- Overall, it is easier for her to listen. As a result, she is less tired at the end of the school day.
- You are not worried about one cochlear implant failing, because she has a backup in the other ear.
- You are less concerned about your daughter’s future in terms of academic achievement, employment, and independent living.

Questions about Scenario No. 4

Question 1

To help you express you thoughts about your imaginary child’s quality of life, we have drawn a scale. The best quality of life that you can imagine is marked 100, and the worst quality of life that you can imagine is marked 0. We would like you to use the scale to help us understand your thoughts on your imaginary daughter’s quality of life.

Please make a mark on the scale to show us how good or bad your daughter’s quality of life is **with two cochlear implants**. You may make the mark anywhere on the scale not just at the points marked by the numbers.



Question 2

Now we would like you to think about your daughter’s quality of life in a different way.

Remember, you are 33 years old. Imagine you will live for 50 more years until you are 83 years old.

Now, imagine that you could give up some years of your own life in order for your child to have normal hearing. She would have normal hearing immediately and then for the rest of her life. Imagine that the years you give up would be taken off the end of your life. This question does not measure whether you are a good or bad parent — it is simply a method of obtaining your judgement about how challenging this scenario would be for your daughter.

Please write the number of years that you would give up in this box:

I would give up this number of years:

Thank you for completing this questionnaire. Your answers will be stored securely and will be treated confidentially.

Glossary

*n*AFC	An *n*-alternative forced-choice task
AGC	Automatic gain control
ANOVA	Analysis of variance
BKB	Bamford-Kowal-Bench
c.i.	Confidence interval
CI-CI	Listening with bilateral cochlear implants
CI-HA	Listening with a unilateral cochlear implant and a contralateral acoustic hearing aid
CI-only	Listening with a unilateral cochlear implant only
CRISP	Children's Realistic Index of Speech Perception
F0	Fundamental frequency
FFT	Fast fourier transform
HL	Hearing level
HRTF	Head-related transfer function
HUI	Health Utilities Index Mark 3
ILD	Interaural level difference
ITD	Interaural time difference
JND	Just-noticeable difference
MAA	Minimum audible angle
NICE	National Institute for Health and Clinical Excellence
QALY	Quality-adjusted life year
RMS	Root mean square
SRM	Spatial release from masking
SRT	Speech-reception threshold
SSQ	Speech, Spatial and Qualities of Hearing Scale for Teachers of the Deaf
VAS	Visual-analogue scale

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