UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

INSTITUTE OF SOUND AND VIBRATION RESEARCH

Binaural hearing with a synchronised bilateral cochlear implant system in adult users

by

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ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT
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BINAURAL HEARING WITH A SYNCHRONISED BILATERAL COCHLEAR IMPLANT IN ADULT USERS

Noura Ibrahim Alothman

Most bilateral cochlear implant (CI) users have horizontal sound-source localisation and speech perception in noise that is better than that of unilateral CI users and worse than that of normal-hearing listeners. The discrepancy between bilateral CI users and normal-hearing people is thought to partly represent technical limitations in current CI signal processing, which hinders the use of interaural time and level differences. One such limitation is the independent and unsynchronised signal processing in the two CIs. The Digisonic® SP Binaural (DSPB) CI aims to improve binaural hearing by providing synchronised processing of the acoustical inputs, using a single speech processor and two microphones. Two further studies have been published since the commencement of this research project on the spatial hearing ability of DSPB users. Although both these studies concluded that both horizontal sound-source localisation and speech perception in noise can be accessible though the DSPB CIs, consistently with what is provided by conventional bilateral CIs, these studies have some limitations that may have influenced their conclusions. For example, the way the localisation data of their subjects were analysed does not help to determine whether DSPB CI subjects can localise sounds at better than expected from guessing and whether their localisation ability is based on interaural cues or monaural cues introduced by the head shadow. Spatial benefits for speech perception were also not fully reported by the previous studies. The aim of the studies reported in this thesis was to address the limitations of the previous studies and explore in more depth the spatial benefits of the DSPB CIs.

The spatial benefits experienced by eight DSPB CI subjects were assessed in horizontal sound-source localisation, speech perception in noise and self-reported measures. Their ability was also compared to eight unilateral CI subjects, who were chosen as likely to be representative of the better unilateral CI performers. Results showed that the majority of the postlingually deaf DSPB subjects could localise sounds at a better than chance range, defined by unbiased and biased guessing, which seems similar to previous results with conventional bilateral CI adults. Although the results for unilateral CI subjects indicate that monaural cues may provide some useful information for localisation, such cues were found to provide lower localisation accuracy than binaural cues provided by DSPB implants. Speech perception thresholds were also assessed with the speech and noise spatially co-located and separated. Results showed that, as with unilateral CI subjects, the DSPB subjects were not able to take advantage of separating speech from noise for speech perception. Results from the Speech, Spatial and Qualities of Hearing Scale indicated better self-reported spatial hearing ability for the DSPB than unilateral CIs groups, although it was not statistically significant. It is concluded that the DSPB CIs seem to provide advantages for horizontal localisation over unilateral CIs for the majority of postlingually deaf DSPB adults. There is, however, no evidence that the way the processing is synchronised in the DSPB CIs can offer any advantages over conventional bilateral CIs for localisation.

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Declaration of authorship

I, Noura Alothman, declare that the thesis entitled ''Binaural hearing with a synchronised bilateral cochlear implant system in adult users'' and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
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- Parts of this work have been published as:
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List of Abbreviations

A	Angle of separation
AC	Auditory cortex
ACE	Advanced Combination Encoder
AGC	Automatic gain control
AM	Amplitude modulated tone
AN	Auditory nerve
ANOVA	Analysis of variance
APHAB	Abbreviated Profile of Hearing Aid Benefit
AVCN	Anteroventral auditory nerve
ATT	Automated Toy Test
B	Bias
BBN	Broadband noise
BILD	Binaural intelligibility level difference
BKB	Bamford-Kowal-Bench
BMLD	Binaural masking level difference
BPF	bandpass filters
BTE	Behind-the-ear
$\bar{C}$	Constant error
CCTV	Closed-circuit television
CF	Characteristic frequency
CI	Cochlear implant
CIS	Continuous interleaved sampling
CN	Cochlear nucleus
$\bar{D}$ error	Overall root mean square error
dB	Decibel
dB (A)	A-weighted decibel

DCN	Dorsal cochlear nucleus
DNLL	Dorsal nucleus of the lateral lemniscus
DSPB	Digisonic® SP Binaural
$\bar{E}$	Signed constant error
EL	Electrode
GBI	Glasgow Benefit Inventory
HL	Hearing level
HPN	High-pass noise
HPN_burst	High-pass noise burst
HRTF	Head-related transfer function
IC	Inferior colliculus
ICC	Intra class correlation
ILD	Interaural level difference
IPD	Interaural phase difference
ITD	Interaural time difference
JND	just noticeable difference
K	Loudspeaker
KEMAR	Knowles Electronics Manikin for Acoustic Research
LPF	Low-pass filtering
LPN	Low-pass noise
LSO	Lateral superior olive
m	Metre
MPIS	Main Peak Interleaved Sampling
ms	Millisecond
MAA	Minimum audible angle
MAE	Mean absolute error
MGB	Medial geniculate body
MNTB	Medial nucleus of the trapezoid body

MSO	Medial superior olive
N	Noise
n	Number
N-Contra	Noise on the contralateral side of the listening ear
N-Ipsi	Noise on the ipsilateral side of the listening ear
PDT	Peak Derived Timing
pps	Pulses per second
r	Reponses
RMS	Root mean square
$\bar{s}$	Ransom error
SAM	Sinusoidal amplitude-modulated tones
SC	Superior colliculus
SD	Standard deviation
SNR	Signal to noise ratio
SOC	Superior olivary complex
SPEAK	Spectral peak
SPL	Sound pressure level
SRM	Spatial release from masking
SRT	Speech reception threshold
SSQ	Speech, Spatial and Qualities of Hearing scale
T	Trials
TDT	Telephone Triple Digits Test
TM	Tympanic membrane
VAS	Visual-analogue scale
VNLL	Ventral nucleus of the lateral lemniscus
W	Width
µs	Microseconds

Chapter 1: Introduction

1.1 Motivation for the research

Humans spend most of their daily listening time in an environment that contains multiple sound sources. One aspect that allows normal-hearing listeners to determine the location of sound sources and to distinguish target from competing sounds that are spatially separated is the combination of acoustic information received from the two ears (i.e. binaural hearing). Binaural hearing provides the most important cues in the form of differences in the arrival time of sounds at the two ears (interaural time differences; ITDs) and differences in the level of sounds at the two ears (interaural level differences; ILDs). Both ITDs and ILDs allow normal-hearing listeners to perform auditory tasks such as horizontal sound-source localisation (i.e. determining the locations of sound sources in the horizontal plane) and speech perception in noise (i.e. distinguishing between speech and competing noise). When listening with only one ear (i.e. monaural hearing), however, performing such tasks becomes difficult (Blauert, 1997; Hawley et al., 1999). Binaural hearing, therefore, provides the listener with advantages that are not possible with monaural hearing (Levitt and Voroba, 1980).

The role of binaural hearing in cochlear implant (CI) users has been a topic of considerable interest. CIs are successfully provided to adults and children who are severely-to-profoundly deaf in order to restore part of their hearing function. Although CI users generally acquire good speech perception in quiet situations, they still face difficulties in performing more challenging listening tasks, such as sound-source localisation and speech perception in noisy environments. These difficulties are thought to be partly related to the shortcomings in current CIs in mimicking all the capacities of the normal auditory system. When a single CI (i.e. a unilateral CI) is used, an additional limitation is introduced in the form of the inability to use the binaural cues that normal-hearing listeners use to localise sounds and to understand speech in noise. Therefore, there has been a growing interest in providing bilateral CIs (one in each ear) rather than just one.

Research with adults and children indicates better horizontal sound-source localisation and speech perception in noise with bilateral CIs; however, these benefits do appear to be somewhat limited (Van Deun et al., 2009; van Hoesel and Tyler, 2003). Most bilateral CI users have sound localisation and speech perception in noise that is better than unilateral CI users and worse than normal-hearing listeners (Grantham et al., 2007; Loizou et al. 2009; Verschuur et al., 2005). The discrepancy between bilateral CI users and normal-hearing listeners derives partly from technical limitations in the current CI signal processing that hinder the use of binaural cues. One such limitation is the independent operation of both speech processors. Having two independent and unsynchronised speech processors might introduce differences in processing between the two sides, which could distort binaural cues. For example, when compression that is routinely used in CIs operates independently at the two ears, the gain provided at each ear can differ, with less gain provided at the ear with greater level and more gain at the ear with lower level. The independent operation of compression between the two ears may, therefore, limit the accuracy with which ILDs are presented.

A synchronised bilateral CI system called Digisonic® SP Binaural (DSPB) was recently introduced with the aim of improving binaural cues, and thus hearing, through synchronised processing of the acoustical inputs using a single speech processor and two microphones linked via a connection cable. In such a system, the speech processor receives signals from both microphones and then processes them simultaneously but independently in two signal processing lines. Information from the right microphone is then sent to the right electrode array and the information from the left microphone is sent to the left electrode array. The synchronised CI system uses a sequential stimulation between the two electrode arrays, such that stimulation is performed from electrode EL of the ipsilateral electrode array to electrode EL+1 of the contralateral electrode array. The stimulation is timed synchronously at a fixed time of about 15 microseconds (μs).

Given that the sounds are still processed independently between the two ears, it is unlikely that this system would provide benefits for bilateral CI users above those of the conventional bilateral CIs where two independent processors are used. The compressions in the two signal processing lines of the DSPB implants, for example, will be processed independently, similarly to the case with the conventional bilateral CIs, and thus the limited ILD accuracy experienced with two independent CI processors is more likely to be experienced with the DSPB implants. With regard to ITDs, there is also unlikely to be benefit with the new system over the conventional CIs. The random envelope ITD experienced with two independent processors is replaced with a fixed ITD, and most importantly, the fine structure ITD is also not encoded by this system. Although one might expect that synchronising the processing between two ears may improve sensitivity to ITDs in the envelope, this may not be the case, given that it has been shown that the bilateral CI users already assign little weight to envelope ITDs. Previous studies have demonstrated that bilateral CI users, including those who showed close to normal envelope ITD thresholds, weighted envelope ITDs low, and relied on ILDs for spatial hearing (Grantham et al., 2007; Seeber and Fastl, 2008).

Prior to starting this project, to this researcher’s knowledge, no study on binaural benefits with this kind of cochlear implant has been conducted. However, two studies have been published over the time span of this research project (Bonnard et al., 2013; Verhaert et al., 2012). Both studies reported that adults with synchronised bilateral CIs performed similarly to users of conventional bilateral CIs on sound-source localisation and speech perception in noise. Verhaert et al. (2012) also reported a significantly better performance for the synchronised bilateral CI subjects when listening with both implants than when one implant was deactivated, which led the authors to suggest that the DSPB implant subjects can take advantage of binaural cues that are not available when either implant is deactivated.

Although such results agree with what has been theoretically anticipated from the way the processing is synchronised, these two studies have some limitations that may have influenced their conclusions. For example, the way the localisation data of their subjects were analysed does not help to determine whether the subjects can localise sounds at better than expected from guessing. Although studies by Bonnard et al. (2013) and Verhaert et al. (2012) reported the overall localisation error scores of their subjects, neither study took into account the chance performance when reporting localisation ability. It is therefore difficult to determine whether the DSPB implant subjects can localise sounds at better than chance. Most localisation studies compared overall localisation error to the value expected from unbiased guessing (i.e. chance level). However, such a method of analysis may also lead to an inappropriate conclusion for two reasons. The first reason is that the overall localisation error is often compared to a single value which represents chance level. Comparing the observed localisation ability to a single value might, however, lead to an inappropriate conclusion. Statisticians usually use a range (i.e. credible interval) in order to differentiate correct scores from chance, and thus a probable range of errors occurring by guessing, rather than just a single value, should be calculated. The second reason is that chance level is usually estimated assuming unbiased guessing. Such an assumption, however, may lead to an inappropriate conclusion when a different guessing behaviour actually occurs. For example, the responses of a person who is responding consistently towards a particular loudspeaker regardless of the sources (i.e. biased guessing) might be erroneously treated as localisation ability rather than the biased guessing. It is therefore necessary to take into consideration the appropriate guessing behaviour of a listener when calculating chance range. Another limitation with the previous studies is that it is not clear what cues the synchronised bilateral CI subjects were using to localise sounds. Given that some unilateral CI users were reported to be able to localise at better than chance performance (Grantham et al., 2008; Nava et al., 2009), it is not clear whether the localisation ability of DSPB implant subjects reported in the two previous studies is based on binaural cues (ITDs and/or ILDs) or monaural cues introduced by head shadow. With regard to speech perception in noise, neither of the above two studies reported whether the subjects can obtain binaural benefit from spatially separated target speech from competing sounds (i.e. spatial release from masking).

This research project was motivated by the possibility of providing more insights into spatial hearing with the synchronised bilateral CI system and the potential benefits for clinical practice. If the synchronised processing of the acoustical inputs that is implemented in the DSPB implants can support or limit binaural hearing ability, this may have implications for spatial hearing research as well as for clinical populations. While binaural cues are thought to be distorted partly by the independent processing of conventional bilateral CIs, further research is needed to determine if and how synchronised stimulation with the DSPB implant can lead to improved spatial hearing ability. Based on the limitations in the literature summarised above, the broad aims of the experimental part of the study were determined as follows:

- Design a suitable methodology for investigating spatial hearing abilities of hearing-impaired listeners, particularly CI users.
- Explore the spatial hearing benefits in users with the DSPB CIs, and if present, evaluate the relative contribution of binaural cues (ITDs and ILDs) in these spatial hearing benefits.
- Determine whether the spatial benefits associated with the synchronised bilateral CIs are based on binaural cues rather than monaural cues: in other words, whether the DSPB implants provide any advantages over unilateral CIs.
- Compare spatial benefits with the synchronised bilateral CIs to those reported previously from conventional bilateral CIs, where two independent processors are used. Given that the sounds are still processed independently between the two ears, it is unlikely that this system would provide benefits for bilateral CI users above those of the conventional bilateral CIs.

1.2 Overview of the following chapters

Chapter 2 (Background): this chapter gives a general introduction and review of background information on spatial hearing in both those with normal hearing and with cochlear implants. Sections on the acoustic, psychoacoustic and neurophysiological aspects of spatial hearing are first presented. An overview of spatial hearing benefits of normal-hearing adults is also given. The rest of the chapter reviews the emerging evidence regarding the possibilities and limitations of bilateral implantation. At the end of the chapter, the possible benefits of synchronised processing in CI stimulation are discussed.

Chapter 3 (General methods)**:** this chapter presents the general methodology for investigations of spatial hearing ability in this research through three measures: horizontal sound-source localisation, speech perception in noise, and self-assessed questionnaire. Horizontal sound-source localisation ability was assessed using different types of stimuli with different combinations of binaural cues (i.e. speech, broadband noise, low-pass noise, high-pass noise and high-pass noise burst). Each stimulus was presented randomly from one of 11 loudspeakers extending from -90° to +90° azimuth, repeated six times. Spatial speech perception benefits were determined using an adaptive procedure for estimating unilateral and bilateral thresholds for different spatial configurations of speech and noise. The Telephone Triple Digits Test (TDT) was used to measure spatial speech perception benefits in this project. The subjective experience of everyday listening was also explored through the Speech, Spatial and Qualities of Hearing scale (SSQ).

Chapter 4 (Reference data on sound-source localisation): this chapter reports an experiment that measured localisation performance of 20 normal-hearing adults with the aim of ensuring that the localisation set-up and stimuli used in this project produced similar results to what was anticipated from previous localisation studies. This chapter also presents a computer simulation that was mainly performed to deal with the uncertainties in the current interpretation of localisation data mentioned in the previous section. The simulation was performed in MATLAB (The Mathworks Inc.) to clarify the significance of chance range of the appropriate guessing behaviour and the impact of this on the conclusions drawn in the existing literature. Results from the simulation are intended to help to interpret localisation results in this project in more effective way.

Chapter 5 (Reference data on speech perception in noise): this chapter reports an experiment that measured spatial benefits for speech perception using the TDT of 30 normal-hearing adults. Given that the spatial benefits have not been determined previously with the TDT, it was necessary to obtain normative values for these benefits of the TDT. The results were intended to help in interpreting the results of the CI users in this project. The results also helped to ensure the speech perception thresholds obtained from the TDT were similar to what was anticipated from previous studies and that the method did not need any further refinements.

Chapter 6 (Sound-source localisation by adults fitted with a single cochlear implant): this chapter reports an experiment that measured localisation performance of eight unilateral CI users who had been implanted on only one side and who had become acclimatised to listening with one implant in everyday life. The main aim was to establish the “better” localisation performance that would be expected from adults with unilateral CIs. This would help to draw a solid conclusion on whether the synchronised bilateral CIs can actually provide any advantage for localisation over signal CIs. The second aim was to determine whether the monaural cues are sufficient to localise sounds at better than chance range. Unilateral CI subjects who performed better than chance range were tested in a follow-up experiment with different ranges of level roving, with the aim to determine whether the better than chance ability could be maintained with larger level roving and whether this means they could actually localise.

Chapter 7 (Sound-source localisation by adults fitted with synchronised bilateral cochlear implants): this chapter reports an experiment that measured localisation performance of eight subjects implanted with the synchronised bilateral CIs (i.e. DSPB CIs). The main aim was to determine whether the synchronised bilateral CI users can localise different types of stimuli at better than chance range, and whether stimulus type has an effect on their localisation performance. The second aim was to compare their performance to that of unilateral CI users reported in Chapter 6 and of normal-hearing adults reported in Chapter 4. This would help to determine whether the synchronised bilateral CI users can take advantage of binaural cues for localisation. The third aim was to compare their performance to that of subjects with conventional bilateral CIs reported previously in our laboratory using a similar set-up (Verschuur et al., 2005). Since Verschuur et al. (2005) only reported overall localisation error scores averaged across all their subjects, a re-analysis of their data was performed taking into consideration the simulation results presented in Chapter 4. Comparing the localisation performance of users of synchronised and conventional bilateral CIs would help to determine whether the synchronised processing offers any advantages over conventional bilateral CIs which are independent between ears.

Chapter 8 (Speech perception in noise with synchronised bilateral and unilateral cochlear implants): this chapter presents two experiments that measured spatial benefits for speech perception in noise. The spatial benefits for speech perception were measured for the eight unilateral CI subjects in the first experiment and for the eight synchronised bilateral CI subjects in the second experiment. All the subjects who participated in the localisation experiments also participated in speech perception experiments. The main aim is to determine whether the synchronised bilateral CI users can experience spatial benefits for speech perception, including spatial release from masking, binaural squelch, head shadow and summation effects. The second aim was to compare these benefits to those provided by the unilateral CI users to determine whether the synchronised bilateral CIs offer any advantage over the unilateral CIs for speech perception in noise. The spatial benefits provided by the synchronised bilateral CIs were also compared to those experienced by normal-hearing listeners, as reported in Chapter 5.

Chapter 9 (Self-reported assessment with synchronised bilateral and unilateral cochlear implants): this chapter presents the subjective outcomes measured by the SSQ for the synchronised bilateral CI users, unilateral CI users and normal-hearing adults. All subjects who participated in this study also participated for psychoacoustic measures (i.e. localisation and speech perception). The main aim was to determine how the synchronised bilateral CI subjects were coping in everyday life, and how these abilities experienced in everyday life related to their performance on psychoacoustic measures. The second aim was to compare the self-assessed abilities of the synchronised bilateral CI users to those of unilateral CI users and normal-hearing adults.

Chapter 10 (Summary, conclusions and future research): this chapter summarises the results of the studies reported in this thesis and discusses the implications of these results. It also presents the main conclusions of this research project. Areas for possible further research are also suggested.

1.3 Original contribution to knowledge

The primary contribution to knowledge made by this thesis is a clearer understanding of spatial hearing abilities with synchronised bilateral CIs. As mentioned in Section 1.1, two studies have been published since the commencement of this research on the spatial hearing ability of DSPB users. Although both these studies concluded that both horizontal sound-source localisation and speech perception in noise can be accessible though the DSPB CIs, these studies have some limitations that may have influenced their conclusions. The studies reported in this thesis aimed to address the limitations of the previous studies and explore in more depth the spatial benefits of the DSPB CIs.

The studies reported in this thesis show that spatial hearing benefits are apparent with the DSPB implants for sound-source localisation, though not for speech perception in noise. Localisation results show that the majority of the postlingually deaf DSPB CI subjects could localise sounds in the horizontal plane at a better than chance range expected from guessing, defined by unbiased and biased guessing. There is, however, no clear evidence that they were able to take advantage of separating target speech from interfering noise for speech perception. With regard to subjective outcomes, the self-ratings of the synchronised bilateral CI users were generally in the mid-range on the SSQ scoring scale (0-10), suggesting that they can show some ability in everyday hearing functions with respects to speech, spatial and qualities, yet they were still not able to do them well.

The current research project also contributes to knowledge in showing that the synchronised bilateral CI users seem to be able to take advantage of binaural cues that are not available for unilateral CI users. The present project shows that synchronised bilateral CIs can offer advantages over unilateral CIs in sound-source localisation for the majority of the postlingually deaf DSPB CI adults. There is, however, no evidence that the synchronised bilateral CI system can offer more spatial benefits for speech perception in noise than unilateral CIs. Although it was not statistically significant, the synchronised bilateral CI users were found to rate their spatial ability at an almost three-point level higher (i.e. better) than that the self-rating of unilateral CI subjects.

Despite the lower performance shown by the unilateral CI subjects compared with the synchronised bilateral CI users, the study on localisation performance of unilateral CI users indicates that four out of the eight unilateral CI subjects can show overall localisation error scores on a simple sound-source identification task at better than expected from guessing (unbiased and biased guessing). It was also found that the better than chance performance is still achievable with stimulus presentation level roves of ±4 dB and ±8 dB and no spectral-shape roving. These findings contribute to knowledge in that they indicate that the level rove used in this project as well as in previous studies investigating localisation performance of CI users may not be sufficiently large to lead CI users using monaural cues into chance performance.

The spatial benefits experienced by the synchronised bilateral CI users seem broadly consistent with what is reported in the existing literature on conventional bilateral CIs. Specifically, localisation results indicated a similar localisation performance of the synchronised bilateral CI subjects to that reported by a previous study conducted in our laboratory with conventional CI subjects, using similar stimuli and set-up (Verschuur et al., 2005). These findings may potentially have important implications for clinical populations. For example, the present study raises the possibility that the DSPB implant might be considered as an alternative option for deaf adults who are only eligible, under the healthcare policy used in the UK, for a single CI. Furthermore, the finding that DSPB implants do not offer any practical advantage over conventional bilateral CIs may indicate that the way the stimulation is synchronised with the DSPB implant is not enough to offer any better spatial ability than two separate CIs. Such a finding may have implications for the design of further speech processors.

The present research project also highlights some common issues associated with the interpretation of localisation data. For example, the modelling of different guessing behaviour described in the present study shows how to distinguish observed localisation ability from guessing in a more effective way. Results indicate that an individual's overall localisation error score can appear to be better than the conventional statistical account of guessing behaviour, which assumes unbiased guessing, through biased guessing. The present project raises the possibility that localisation studies that do not provide a detailed description of localisation performance may lead to unreliable conclusions. A comprehensive system of localisation measurement analyses was implemented in MATLAB, with the aim of providing an accurate interpretation of localisation data. The development of the MATLAB code was motivated by the possibility of encouraging the researchers in our laboratory to report the full system of measurements when analysing localisation data. It was envisaged that this would lead to more robust data interpretation in future studies of localisation in our research group.

Parts of the studies of the current research project have been reported at a number of international auditory research meetings, which were listed previously in the Declaration of Authorship form (page xiii).

Chapter 2: Background

2.1 Introduction

With the aim to provide a context for the remainder of the thesis, the chapter begins with a review of spatial hearing with regard to acoustics (Section 2.2), psychoacoustics (Section 2.3) and neurophysics (Section 2.4). An overview of how a cochlear implant works and the benefits of unilateral implantation for adult users is provided in Section 2.5. At the end of the chapter, the emerging evidence regarding the possibilities and limitations of bilateral implantation is reviewed in Section 2.6. Before doing so, terminology related to binaural hearing is defined and explained to begin with.

2.1.1. Terminology

Spatial hearing refers to the ability of the auditory system to analyse the acoustic cues reaching the two ears. Hearing with two ears refers to binaural hearing, whereas hearing with just one ear is known as monaural hearing. These two terms are used to describe the manner in which the stimulus is processed in the auditory system. With regard to describing how the auditory system is stimulated, the term "bilateral stimulation" is used when stimulation is of both ears simultaneously, whereas stimulation of one ear only is referred to as "unilateral stimulation". For example, provision of a cochlear implant (CI) in one ear only is referred to as a unilateral CI, whereas provision of two CIs (one in each ear) is termed bilateral CIs.

Since bilateral stimulation utilises both ears, a distinction should be made between the terms "diotic" and "dichotic". In "diotic" stimulation, identical stimulation is applied to both ears, whereas in "dichotic" stimulation, different stimuli (either temporally or spectrally) are applied to each ear. Diotic stimulation, for instance, employs bilateral CIs with only one microphone and one amplifier. Having two completely independent CIs (with two microphones and two amplifiers) in each ear is an example of dichotic stimulation. Diotic and dichotic stimulations can be created by means of presenting either identical or different stimuli though a set of headphones respectively. The perception of dichotic stimuli, typically over headphones, is referred to as binaural sensitivity. Interestingly, the perception received from headphone listening differs from the perception received from loudspeaker listening.

When diotic signals are presented to both ears, a single and fused sound image is perceived via a process known as binaural fusion. There are generally two ways to present signals to the ears: either by loudspeakers or headphones. When signals are presented via a loudspeaker, the fused image is typically located outside of the head (i.e. "externalised"), and therefore, the term "localisation" is generally used with experiments using loudspeakers. In contrast, when the signals are presented to the two ears individually via headphones the fused image is typically located inside the head between the two ears (i.e. "internalised"). Therefore, the term "lateralisation" is usually used with experiments using headphones. The concept of lateralisation is essentially the same concept as that underlying the Weber test with a tuning fork (Hafter and Trahiotis, 1997). The Weber test is used to help determine whether a unilateral hearing loss is sensorineural or conductive by placing the tuning fork on the forehead (commonly in the midline) and then asking the listener to determine where the tone is heard. Hearing the tone in the better ear suggests a sensorineural hearing loss in the opposite ear. Hearing the tone in the poor ear indicates a conductive hearing loss in that ear. Nevertheless, there are some circumstances in which the signal presented via headphones can be perceived externally, rather than being perceived internally through virtual auditory space (also known as virtual acoustics). In virtual auditory space, a headphone-presented signal containing free-field cues can be produced by recording the head-related transfer function (HRTF) for both ears (Macpherson and Middlebrooks, 2002).

The auditory space is described relative to the angles around the head. A head-centred coordinate system is commonly used to specify the position of the sound source relative to the centre of the head (Figure 2.1). By assuming a source which lies on a surface at the head level, the imaginary line through the two ears is called the interaural axis. In such a system, the horizontal plane which passes through the interaural axis divides three-dimensional auditory space into upper and lower halves. The median plane, on the other hand, passes vertically through the centre of the head from front to back, dividing auditory space into right and left halves. The angles between a sound source and the median and horizontal planes are referred to as azimuth and elevation, respectively. Sounds coming from straight ahead and directly behind have azimuths of 0° and 180°, respectively. Azimuths of +90° and -90° indicate that the sounds come directly from the right (+) and the left (-) of the head's centre, whereas an elevation of 90° means directly above the head.

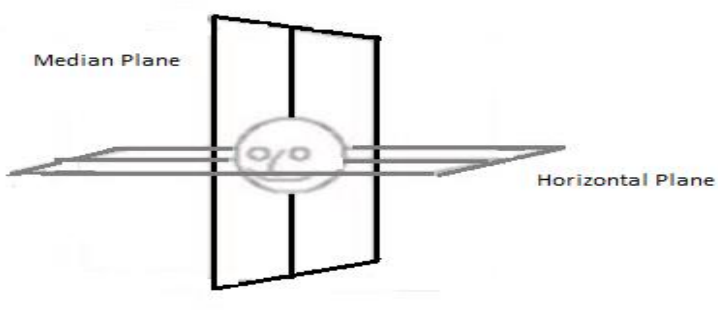

Figure 2.1: The head-centred coordinate system for spatial hearing.

2.2 Acoustics of spatial hearing

When a sound source is on the horizontal plane, the sound arrives at one ear momentarily with a higher sound level than the other ear. The differences between sounds at the two ears that arise from the separation of the ears by the head are called ‘binaural cues’: these are described in section 2.2.1. Other cues, which are based on the spectral characteristics of the signal resulting from direction-dependent filtering by the pinnae, are introduced in Section 2.2.2. These so-called ‘spectral cues’ can help to some extent to localise sounds in the horizontal plane, although they are less robust than binaural cues (Duda, 1997).

2.2.1 Interaural differences in timing and level

Consider a sound source placed somewhere to one side of a listener (for example, at -90° azimuth, as shown in Figure 2.2): the sound arrives at the near ear before the far ear. The difference in the time of arrival of a sound at the two ears is termed the interaural time difference (ITD). The sound pressure level (SPL) may also be higher at the near ear than the far ear. The difference in level of sound at the two ears is referred to as the interaural level difference (ILD). Figure 2.2 illustrates the ITD and ILD cues for a sound source at -90°, which can only be determined through binaural hearing.

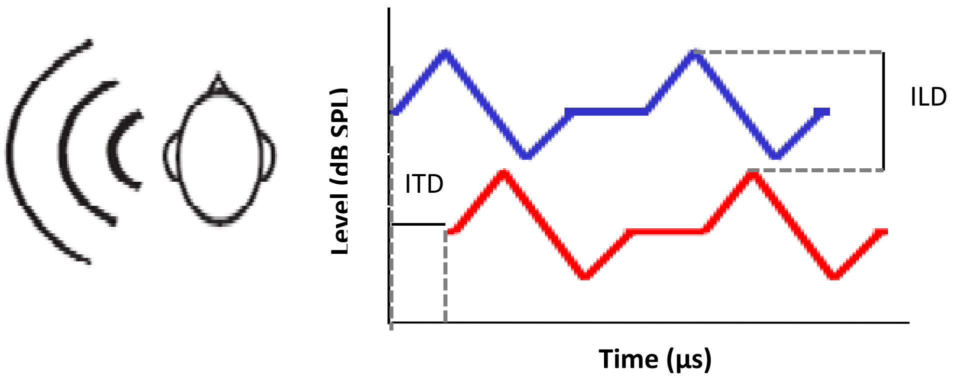

Figure 2.2: The binaural cues for a sound source at -90°. The sound reaches the left ear (blue line) earlier and with higher level than the right ear (red line), forming differences in arrival time (ITD) and in level (ILD) between the two ears.

ITD only exists when the distance between the sound source and one ear is shorter than between the source and the other ear. Measurements using microphones placed in the ear canals of normal-hearing listeners show that ITD of zero microseconds (µs) is obtained for a sound source placed straight ahead (at 0° azimuth) or behind (at 180° azimuth), since there is a no difference in distance between the source of sound and two ears (Feddersen et al., 1957). The ITD becomes progressively larger as the sound source is moved towards one ear, reaching the maximum value of about 660 µs for human adults at an azimuth of +/-90° (Blauert, 1997; Kuhn, 1977). The rate of ITD change with increasing azimuth slows at around +/-100°, meaning that a small change in the location of a sound source results in a larger ITD when the change in location is at the front of listener rather than at the side. Sensitivity to ITD can be explained through the increase in the rate of the firing of the spiral ganglion cells in each auditory nerve, which reflects the arrival of the signal at that ear.

In addition to the difference in time of arrival at the ears, such as sound onsets and offsets, ITDs can also be extracted from the ongoing portion of a stimulus. When the signal is periodic, such as pure tone or amplitude modulated tone (AM), ITD in the ongoing signal corresponds to interaural phase difference (IPD). Sensitivity to IPD is related to the phase locking of the auditory nerve. Given that the auditory nerve is only able to phase lock to frequencies below about 1500 Hz, ITD cues can only be useful at lower frequencies (Moore, 1997). IPDs can be an ambiguous cue to sound location for stimuli above 770 Hz, because the phase ambiguity occurs when half the period of a tone is equal to or greater than the maximum ITD afforded by the head.

Nevertheless, this is not to say that humans are not sensitive to ITDs at high frequency sounds. In fact, humans are able to make use of ITDs of certain high frequency sounds such as sinusoidal amplitude-modulated tones (SAM), high-pass filtered clicks and noise. An example of a SAM tone is provided in Figure 2.3. Here, the amplitude of a high frequency (fine structure) tone is modulated at a low frequency (envelope). This envelope is prepared in a manner which allows the SAM tones to produce a similar pattern of neural firing as at a frequency below 1500 Hz. The ongoing ITD is apparent in both the fine structure of the waveform and the envelope, and can be manipulated independently over headphones. Henning (1974) designed a lateralisation experiment where a 4 kHz tone was modulated at 300 Hz. Henning (1974) found that lateralisation performance for the modulated signal was similar to that of a 300 Hz tone, suggesting that lateralisation based on ITD is possible from the envelope, even though the fine structure of the modulated signal contains only high frequencies. Thus, the ongoing ITDs in the fine structure and in the envelope of the waveform provide cues for the low and high frequencies, respectively.

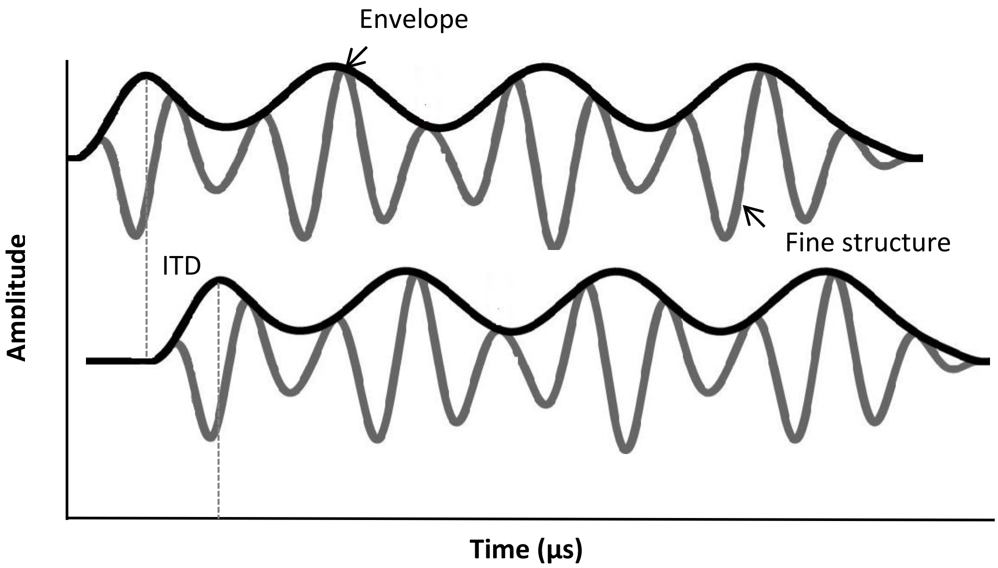

Figure 2.3: The interaural time difference (ITD) obtained from the envelope of an amplitude-modulated (AM) tone.

ILDs, on the other hand, are produced due to the head shadow effect. As shown in Figure 2.2, the right ear is shadowed by the head, so it receives less SPL than the left ear, creating an ILD. ILDs are also strongly dependent on frequency; the ILD is larger with higher frequency. The amount of head shadow is determined by the wavelength of the sound as compared to the size of the head. If the wavelength is large, such as at low frequencies, the shadowing is minimal, since the signal is able to diffract around head, neck and torso. Conversely, if the wavelength is small (for example at high frequencies) the shadowing is deeper, since the signal is effectively blocked by the head. Therefore, the ILD is strongly dependent on frequency and it ranges from about 5 dB (for frequencies lower than 500 Hz) to 35 dB (at 10 kHz frequency) for sound presented from a source at +/-90° (Feddersen et al., 1957). Complexities at high frequencies can, however, lead to exceptions. As an example of this, Hafter and Trahiotis (1997) found that at the azimuth region from 130° and 180°, the ILD is greater for 1000 Hz than for 5000 Hz. They suggest that this is caused by the complex interference patterns of the head and pinna, and from the reflections from the torso at high frequencies. The rate of change in ILD with increasing azimuth slows more between 60° to 110° than at locations directly in front of or behind the listener. Sensitivity to ILD can be explained by the increase of the rate of firing of the spiral ganglion cells in the auditory nerve with amplitude.

The fact that that both the ITD and ILD cues are systematically related to azimuth indicates that they are only useful in localising sounds in the horizontal plane, but not in the median plane. Normal-hearing listeners can detect an ITD as small as 10 µs for a 1 kHz pure tone or repeated clicks. Listeners cannot detect ITDs of tones above 1.5 kHz (Klumpp and Eady, 1956). However, listeners can detect ILDs as small as 0.5 to 2 dB, for tones between 0.2 and 10 kHz (Mills, 1958). The smallest ITD or ILD which listeners can discriminate from an ITD or ILD of zero is referred to as the just noticeable difference (JND), measured through headphones (i.e. lateralisation).

2.2.2 Spectral cues

The torso, head and pinnae provide a frequency and direction dependent filter of sound. These so-called spectral cues depend on how the sound coming from different directions in space are spectrally shaped as a function of the shape of the head and pinnae (Hofman and Van Opstal, 2003). Although the spectral cues created by the torso and head play a role in spatial hearing, those created by the pinnae were found to play an essential role in sound location, and most of these cues come from the unique shape of the concha (Lopez-Poveda and Meddis, 1996). The effect of the pinna becomes significant at high frequencies, since the size of the pinna is much smaller compared to the head (Searle et al., 1976). At higher frequencies, a complicated pattern of peaks and notches can be obtained, which varies with sound source direction (Figure 2.4), providing spectral cues for spatial hearing.

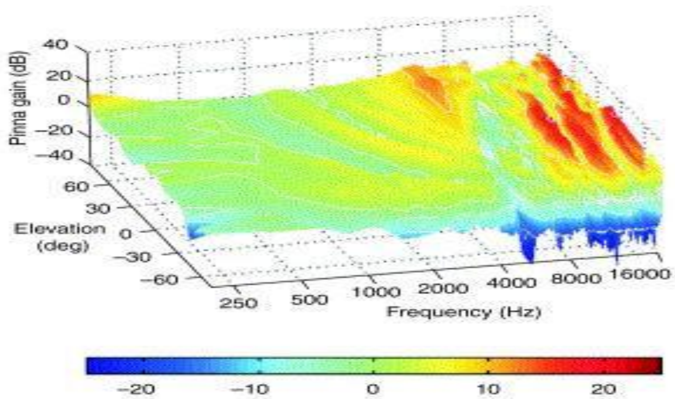

Figure 2.4: Spectral cues for sound location, where broadened sounds were presented in front of the listeners at different elevations. Changes in amplitude (gains) are shows as a function of frequency and elevation. The figure is reprinted with permission from King et al. (2001).

Spectral cues are largely responsible for localising sounds in the median plane, especially sounds at frequencies between 6 to 12 kHz that correspond to large peaks and notches measured in the HRTF (Langendijk and Bronkhorst, 2002). Spectral cues also help to resolve horizontal source locations within the ‘‘cone of confusion’’ where interaural differences remain constant (Langendijk and Bronkhorst, 2002). Sounds presenting from different locations where the distance which the sound has to travel to reach the far ear is kept constant will, assuming the two ears are symmetrical, have similar ITDs and ILDs, but will differ in their spectral content. Therefore, spectral cues can help to resolve front-back confusions. Given that the spectral cues require analysis of the amplitude spectrum of the sound, they can only be extracted from broadband sounds (Butler, 1986).

Spectral cues are known as monaural cues because they can potentially provide information on sound location to a listener with monaural hearing. Previous studies on adults with single-sided deafness showed a good localisation performance in some of their subjects, perhaps due to their ability to make use of spectral cues to their functioning ears (Shub et al., 2008; Van Wanrooij and Van Opstal, 2004). However, Wightman and Kistler (1997) showed that normal-hearing listeners were generally unable to localise sounds when listening monaurally. Such a finding may suggest that spectral cues are poorly utilised in binaural listeners under monaural hearing conditions and that longer experience with monaural hearing might be required to make use of spectral cues.

2.2.3 Dynamic cues

In addition to the above stationary cues for spatial hearing, dynamic cues from head movement and visual cues may also play an important role in spatial hearing. Previous studies by Perrett and Noble (1997) and Wallach (1940) indicated that listeners could derive information on sound source location through head movement during stimulus presentation. Although such dynamic cues lead to small but significant improvements in sound location in the median plane, a larger improvement was found for sound location in the horizontal plane when head movement was allowed (Thurlow and Runge, 1967). Head movement helps to significantly reduce the rate of front-back errors (Perrett and Noble, 1997). With regard to visual cues, It was found that visual information improved localisation performance for different head postures (Lackner, 1974).

2.3 Psychoacoustics of spatial hearing

As shown in the previous section, the binaural cues, including ITD and ILD, can only be determined through binaural hearing. In this section, two important auditory mechanisms involving the processing of ITD and ILD, namely sound-source localisation and speech perception in noise, are discussed. It is well known that binaural cues allow normal-hearing listeners to determine the locations of sound sources in the horizontal plane and to distinguish speech and competing noise that are spatially separated. The perceptual tasks in which sound localisation and speech perception in noise can be measured are also presented. It should be noted that tasks that are only applied in this research project are included[1].

2.3.1 Sound-source localisation

The role of binaural cues (ITD and ILD) in sound-source localisation in the horizontal plane has been highlighted by the Duplex theory, using pure tone stimuli (Rayleigh, 1907). This theory proposes that fine structure ITDs are used to localise low frequency sounds and ILDs are used to localise high frequency sounds. As noted earlier, in Section 2.2.1, fine structure ITD-based localisation is predicted to be difficult above 770 Hz, and ILD-based localisation is predicted to be difficult below 500 Hz. This theory seems, however, insufficient to describe the roles of ITDs and ILDs in more complex situations. For example, high frequency sounds can be localised on the basis of ITD if the envelope of the signal has amplitude modulation of low frequency. Studies using contradictory ITDs and ILDs indicate that ITDs dominate localisation of low frequency stimuli, and ILDs dominate localisation of high frequency stimuli (Wightman and Kistler, 1992). However, listeners can use either cue in more challenging listening situations (Akeroyd, 2006).

Additionally, the role of spectral cues is not explicit in the Duplex theory. Although ITDs and ILDs generally dominate localisation in the horizontal plane (Macpherson and Middlebrooks, 2002), some information on the location of a sound source can also be provided by spectral cues (Shub et al., 2008). It should be noted that spectral cues are also available to monaural listeners. It has been suggested that the monaural spectral peaks and notches provide some information for monaural listeners (Fuzessery, 1996). Monaural listeners can use spectral and level cues to localise sound in the frontal horizontal plane. Monaural level cues depend on how sounds coming from different locations in the frontal horizontal plane are attenuated as a function of head shadow (Van Wanrooij and Van Opstal, 2004). It was found that monaural spectral cues can be more easily learned for familiar sounds, such as speech, than for unfamiliar sounds, whereas level cues can be easily learned and applied to a variety of sounds (Van Wanrooij and Van Opstal, 2004). In addition, monaural listeners can also move their heads to make use of the resulting spectral and level changes to localise sounds of long duration (Perrett and Noble, 1997).

The ability to localise sources of sound can be assessed using a left-right discrimination task and gradually decreasing the angular separation between two loudspeakers on the horizontal plane (Figure 2.5). The smallest angular separation for which listeners can reliably discriminate between left and right locations on the horizontal plane is called the minimum audible angle (MAA). Using pure tone stimuli, the MAA can be as

[1] More detailed reviews of the psychoacoustic aspects can be found in the literature, such as Akeroyd (2006), Blauert (1997), Culling and Akeroyd (2010), Grantham (1995), and Hafter and Trahiotis (1997).

small as 1° for normal-hearing adults discriminating between sounds around midline at 0° azimuth (Mills, 1958). Such findings agreed with the previously mentioned studies of ITD sensitivity measured over headphones (Section 2.2.1), given that the change in ITD resulting from a 1° change in sound location at 0° azimuth is equivalent to 10 μs.

Another way of measuring the ability to localise sounds is to assess listeners' accuracy in identifying the location of a source when they are presented with a certain number of loudspeakers around the listener, who is then required to indicate the perceived location of the sound sources (Figure 2.5). Such a task is referred to as sound-source localisation/identification. Localisation performance is typically calculated with respect to the deviation between the actual location and the listener's response, and is often expressed in degrees as a root mean square (RMS) error or mean absolute error (MAE). When using MAE, all errors are weighted equally, and thus it is thought to be of greater use with children because short instances of lack of attention that are actually not attributable to localisation ability could lead to larger errors. RMS error, on the other hand, is more sensitive for larger errors and is greater than or equal to the MAE. The RMS better reflects the underlying causes that limit localisation ability of a listener (Hartmann et al., 1998). Normal-hearing adults are generally able to localise sounds with a localisation error of 6° to 10°, although the actual localisation error depends on different characteristics of the testing environment, set-up and stimuli used.

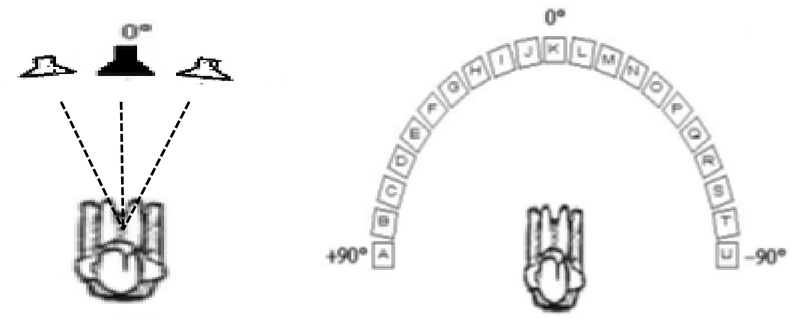

Figure 2.5: The standard tasks for measuring sound-source localisation ability using left-right discrimination task (left panel) and sound- source localisation task (right panel).

2.3.1.1 Localisation and environmental conditions

Localisation accuracy of a listener can be affected by the room acoustics, such as whether the environment is anechoic or reverberant. Giguère and Abel (1993) examined the ability of normal-hearing adults to localise broadband noise in both anechoic and reverberant conditions, and they found that localisation performance degraded more in reverberant rooms than in anechoic rooms. Reflected energy causes fluctuations in the short-term values of binaural cues from moment to moment, hence reducing localisation accuracy (Giguère and Abel, 1993; Hartmann, 1983). The fluctuations in ITD cues caused by reverberation increase ITD variability and so the interaural coherence is reduced (Rakerd and Hartmann, 2010). Reverberation also decreases ILDs, which depends on the listener's location in the room. For a long source distance, reverberant energy increases the energy in the ear far from the sound source, thus decreasing ILDs (Shinn-Cunningham et al., 2005).

This is not to say, however, that localising sounds in reverberant environments is impossible. Hartmann (1983) showed that normal-hearing adults can still manage to accurately localise sounds in reverberant environments, due to the precedence effect. When localisation ability of normal-hearing listeners was assessed in a reverberant environment, their responses tended to be strongly influenced by the location of the source of the first sound that reached the ears (i.e. leading sound), rather than the sources of the later sounds, which are the reflections of the first sound (i.e. lagging sound). The dominance of the leading sound is known as the precedence effect (Litovsky, 1997; Litovsky et al., 1999). When the normal-hearing listeners receive the same signal from different locations, their responses often indicate the location of leading sounds, but not those in between the sources of leading and lagging sounds (Litovsky et al., 1999).

Although reverberation can distort binaural cues for localisation, it does, however, provide a cue for perceiving the distance from a sound source. In a reverberant environment, the listener receives the direct sound followed by the reverberant sound. The proportion of direct sound compared to the proportion of reverberant sound can be an indicator of distance from the source, in that the energy of the direct sound decreases with distance from the source (inverse square law), whereas the energy of reverberation is roughly independent of the location. When the listener receives more direct sound than reverberant sound, it means that sound source is comparatively near. For a more distant source, the listener receives more reverberant sound than direct sound. Thus, it is necessary to have information about the room in order to make an effective judgment about distance (Shinn-Cunningham, 2000).

2.3.1.2 Localisation and testing set-up

Localisation accuracy can also be affected by the number of loudspeakers and the angular separation between them. It has been suggested that increasing the number of loudspeakers may decrease localisation accuracy (Giguère and Abel, 1993). This can be explained, as increasing the number of loudspeakers may increase the probability that a listener will make a mistake, although the penalty for the incorrect response would be greater if there were fewer loudspeakers. A detailed study by Hartmann et al. (1998) found that overall localisation error defined by the RMS error reached a plateau when there are at least six loudspeakers and the angular separation is greater than 5% of the span. When the angular separation between loudspeakers is greater than 20% of the span, the RMS error is extremely insensitive to the number of loudspeakers. With 13 loudspeakers separated by 15°, for example, the average RMS error is 6.4° for broadband noise (Bogaert et al., 2006). Grantham et al. (2007) reported similar RMS error of 6.8° for broadband noise with 9 loudspeakers separated by 20°. Given the theroretical advantage of an RMS error that is insensitive to the number of loudspeakers, it may indicate that the RMS can be used to compare across different localisation set-ups, as long there are at least six loudspeakers with angular separation of greater than 5% of the span.

2.3.1.3 Localisation and characteristics of stimuli

Localisation accuracy of a listener is strongly affected by the characteristics of the stimuli used. Bogaert et al. (2006) found an improvement in localisation performance when using broadband signals, with a mean value of 6.8° and 3.2° for RMS and MAE respectively, compared to that with narrowband signals. With narrowband stimuli, high frequencies were harder to localise, with mean RMS and MAE of 21.3° and 14.3° than low frequencies, with mean RMS and MAE of 13.5° and 8.7°. This can be explained by the limited availability of ITDs and ILDs and spectral cues in the narrowband signal compared to the broadband signal. As the bandwidth of a signal deceases, the opportunity to compare information across frequency bands becomes limited and thus the quantity of available localisation cues decreases. The periodic nature of the pure tones makes phase leads and lags indistinguishable, leading to ambiguity in the IPDs, particularly for high frequencies (Wightman and Kistler, 1993).

The intensity of a stimulus may also affect localisation performance. Localisation performance has been found to deteriorate at stimulus levels close to thresholds and improves with increasing levels (Vliegen and Van Opstal, 2004). This deterioration in localisation performance is most likely due to inaudibility of cues (Macpherson and Middlebrooks, 2000). As the signal level increases, the audible portion of the signal's spectrum increases. For normal-hearing listeners, all localisation cues that are distributed throughout the spectrum of the signal become audible, and hence available for them, meaning localisation performance is at its best for normal-hearing listeners.

2.3.2 Speech perception in noise

Spatial hearing not only helps to determine the direction of a sound source, but also helps to understand one voice in the presence of several competing voices (i.e. the ‘‘cocktail-party problem’’). Binaural cues allow listeners to segregate sounds that are spatially separated to better detect the target sound.

The detection of target sound in the presence of background noise has been found to improve when there is an interaural difference, such as lack of correlation of noise (Langford and Jeffress, 1964). Noise which is described as interaurally correlated is identical at both ears and appears as one percept, lateralised to the centre, whereas uncorrelated noise is generated independently for each ear and appears as two separate precepts, lateralised towards the left and right ears. The detection threshold of the signal in diotic condition (signal and noise are same to both ears) was found to be higher (i.e. worse) than in a dichotic condition where uncorrelated noise was applied (the signal was diotic at the two ears whereas the noise was phase shifted at one ear as opposed to the other) (Langford and Jeffress, 1964). Binaural hearing was found to provide advantages over monaural hearing for dichotic, but not necessarily for diotic conditions (Langhans and Kohlrausch, 1992). The dichotic advantage was also observed when speech and noise were presented from spatially different locations. Previous studies suggest that speech perception in noise improves when the speech is located spatially far from the noise location (Bronkhorst, 2000; Bronkhorst and Plomp, 1988; Hawley et al., 1999).

The capacity of a listener to understand speech in the presence of background noise is often measured by the speech reception threshold (SRT), which is defined as the lowest signal to noise ratio (SNR) at which the listener could correctly report a certain proportion of the target speech, such as 50% or 71%. Lower SRTs reflect an ability to tolerate more noise (i.e. more benefit). The benefit of spatial hearing for speech perception in noise can be demonstrated using four effects that are described in the remainder of this section. Several measures are used to quantify these effects by comparing SRTs for different listening conditions and different spatial configurations of speech and noise. Figure 2.6 displays the test configurations that are compared to measure each of the four effects.

2.3.2.1 Binaural effect: spatial release from masking

Spatial release from masking (SRM) is the improvement in speech perception obtained as a result of spatial separation of target sound (i.e. speech) from masker sounds such as noise. SRM is assessed by comparing binaural listening when speech and noise are presented from the front versus when speech is presented from the front and noise is presented from 90° to one ear (either +/-90º). SRM is then calculated by subtracting the SRT measured with noise from the front from the SRT with noise from the side (Figure 2.6, A). SRT is typically lower when noise occurs from the side than from the front. The SRM arises because separating the speech and the noise produces different ITDs, and thus the listener can potentially suppress some of the noise (see Section 2.3.2.2). Separating the speech and the noise also provides an acoustical advantage caused by the head shadow effect, through increasing the SNR at one of the two ears (see Section 2.3.2.3).

A wide range of SRM values are reported for normal-hearing adults, and are typically between 2 to 12 dB, depending on the methodology design of the studies (Drullman and Bronkhorst, 2000; Hawley et al., 1999; Marrone et al., 2008). The size of SRM is complicated by number of factors, such as number of maskers (Hawley et al., 2004; Peissig and Kollmeier, 1997), their characteristics (Brungart et al., 2001) and their spatial configuration (Culling et al., 2012; Peissig and Kollmeier, 1997). It has been found that SRM is larger when the masker is speech rather than noise (Hawley et al., 2004; Noble and Perrett, 2002) and when multiple maskers are used instead of just one (Hawley et al., 2004). The amount of SRM is not only determined by the energetic masking (i.e. overlap in the energies of the speech and masker), but also by the informational masking, which reflects the other characteristics of the masker, such as when the masker has different frequency channel or is presented to a different ear (Brungart et al., 2001; Freyman et al., 2007). A greater SRM can be achieved when the masker is placed at +/-60°, rather than the commonly used configuration where the masker is presented +/-90° (Culling et al., 2012). An even greater SRM can be achieved when the target and masker are presented as bilaterally symmetrical at 60°, such as target at +60° and masker at -60° (Culling et al., 2012).

2.3.2.2 Binaural effect: binaural squelch

Binaural squelch is the improvement in SRT as a result of the addition of an ear with a poorer SNR. It can be measured by comparing the SRTs between monaural listening with noise at the side of the non-listening ear and binaural listening (Figure 2.6, B). This benefit arises from the suppression of a masking noise as a result of different ITDs or ILDs between signal and noise. Durlach (1963) proposed an Equalization-Cancellation model to explain how the auditory system uses a difference between the ITD of a tone presented in a noise to improve the perception of the tone. Durlach (1963) suggested that the auditory system can cancel much of the noise if there is an ITD between the tone and the noise (see Section 2.4.3 for more details).

Normal-hearing adults typically show between 0.5 to 5 dB of binaural squelch (Bronkhorst and Plomp, 1988). Given that the Equalization-Cancellation model of binaural hearing depends upon the coherence of the masker, one might expect that, with multiple maskers with different ITDs, the mode is only able to cancel one of them. However, it has been found that the binaural squelch was robust when multiple maskers were spatially distributed on the left and right (Culling et al., 2004; Hawley et al., 2004). Such findings indicate that the robustness of the Equalization-Cancellation model to reduced coherence is higher than one might expect (Culling et al., 2004).

2.3.2.3 Monaural effect: head shadow

The head shadow effect can be measured by comparing monaural SRT with both speech and noise presented from the front versus when the speech is presented from the front and noise is presented at the non-listening ear (Figure 2.6, C). A benefit arises because separating the speech and the noise provides an acoustical advantage through increasing the SNR at the listening ear. The head shadow effect is a physical phenomenon and is considered as a monaural effect. The use of two ears allows focusing on the ear with the better SNR.

In normal-hearing adults, the head shadow effect is typically between 3 to 13 dB (Bronkhorst and Plomp, 1988). Unlike binaural squelch, the head shadow effect was only found to be robust when maskers were located on the side of the non-listening ear (Hawley et al., 2004). It disappeared once multiple maskers were spatially distributed on the right and left, since there is no more favourable SNR at one ear than the other. This finding implies that head shadow plays only a minor role in common listening situations, when maskers are distributed on both sides. Head shadow can also be disadvantageous for a person with unilateral hearing who happens to have the noise on the side of their listening ears (Dillon, 2001).

2.3.2.4 Binaural effect: binaural summation

Binaural summation refers to the advantage from listening with two ears, even when identical combinations of speech and noise are presented to each ear. As shown in Figure 2.6, the summation effect can be measured by comparing SRTs with speech and noise presented from the front when listening monaurally (i.e. monotic condition) and binaurally (diotic condition). This effect probably arises because the internal noise introduced by the auditory system itself can be minimised when listening binaurally by comparing the two received versions of the signal, leading to a better representation of the signal.

When the identical versions of a signal were presented to both ears of normal-hearing listeners in the presence of interaurally correlated noise (diotic condition), little advantage for binaural hearing over monaural hearing was found with regard to speech perception (Bronkhorst and Plomp, 1988; Cox et al., 1981) and signal detection (Durlach, 1972; Langhans and Kohlrausch, 1992). A summation effect of about 0.5 to 2 dB was reported for speech perception (Bronkhorst and Plomp, 1988). Such a finding can be predicted, given that the cues available in the monotic condition are the same as in the diotic condition. The similarity between monotic and diotic thresholds in interaurally correlated noise can be obtained as long as the masker level does not approach hearing thresholds (Colburn and Durlach, 1978). When the masker level approaches quiet, internal noise, which is highly unlikely to be interaurally correlated, begins to provide a certain level of dichotic perception, for which there is a definite binaural advantage.

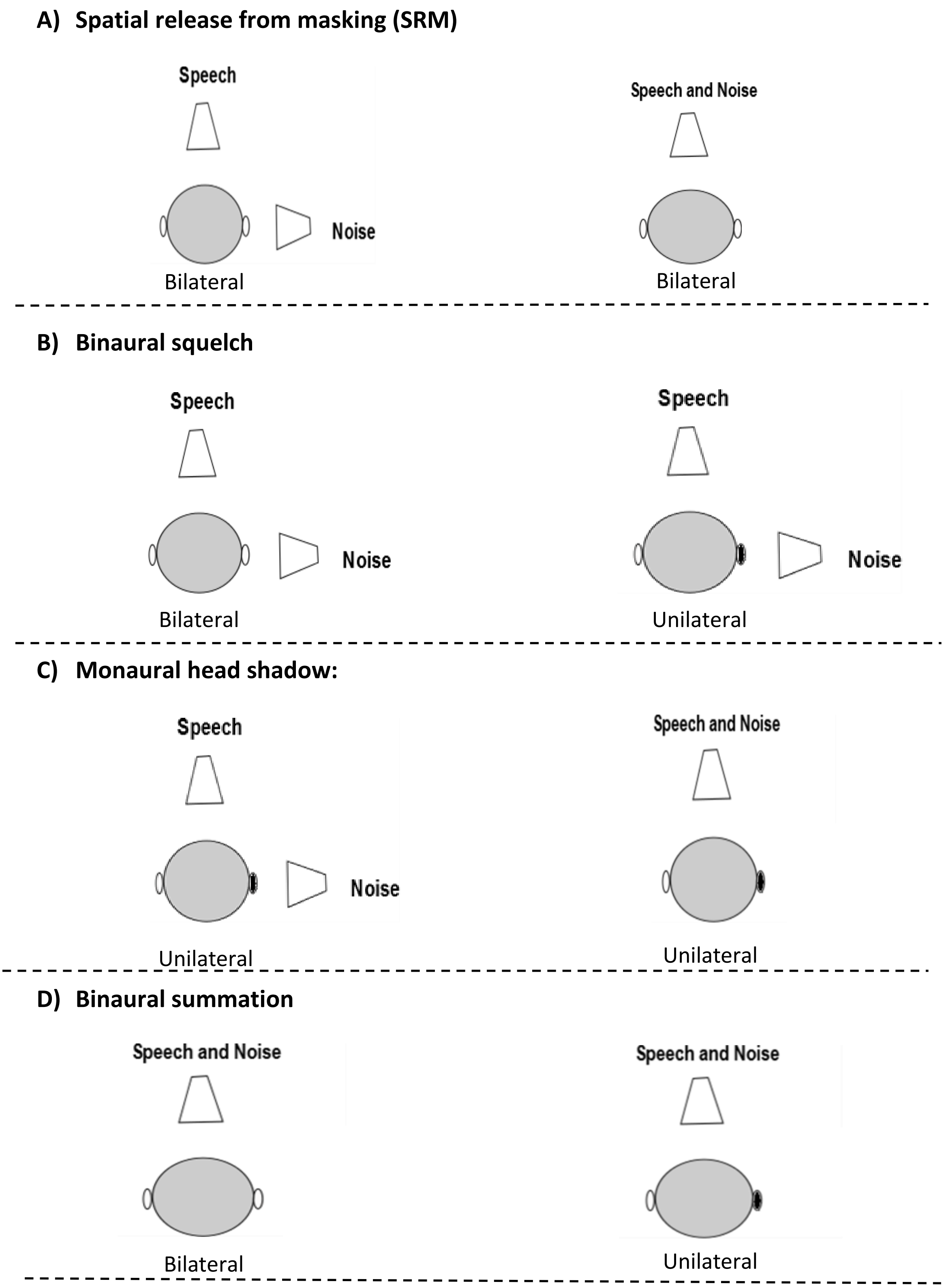

Figure 2.6: Measures of spatial benefits for speech perception in noise. Each panel shows the conditions that can be compared to calculate the binaural benefit: A) spatial release from masking (SRM), B) binaural squelch, C) head shadow effect and D) binaural summation. Shaded ear indicates non-listening ear.

2.3.2.5 Models of SRM

As noted previously in Section 2.3.2.1, the improvement in SRTs when speech and noise were spatially separated (i.e. SRM) is considered to result from binaural squelch and head shadow effects (Bronkhorst and Plomp, 1988; 1992). SRM is often represented as a sum of these two effects. One well-known approach divides SRM into monaural head shadow effect and binaural squelch effect. This approach has been applied successfully in the computational algorithm by Beutelmann et al. (2010) and in the predicted model by Lavandier and Culling (2010). Although some studies found that the combined effect of head shadow and binaural squelch (i.e. SRM) was smaller than the sum of the two isolated effects (Bronkhorst and Plomp, 1988; Culling et al. 2004), the ''additive'' approach was shown to work well in the studies by Hawley et al. (2004) and Zurek (1993). In these two studies the contribution of the head shadow to SRM was measured directly and binaural squelch was then calculated indirectly by subtracting (in dBs) the head shadow benefit from SRM.

Given that the suitability of the above approach has only been demonstrated when one masker is present, another approach was proposed by Bronkhorst (2000) that can account for any configurations of noise makers in the horizontal plane. In Bronkhorst's (2000) model, SRM is divided into two additive components: 1) the angular separation of maskers from the target (''separation'') and 2) the asymmetry of the masker array (''asymmetry''). This approach was proved to work well with the measured SRM in the presence of one or more noise maskers (Bronkhorst and Plomp, 1992; Peissig and Kollmeier, 1997). Considering the individual components, the predicted SRM for bilaterally symmetric two-masker configurations was found to be less sensitive to changes in angular separation near the front (i.e. target location) than near the left and right ears. Bronkhorst's model suggests that the predicted SRM is almost the same for angular separation of 0° to 45° and it increases as the angular separation approaches 90°.

Such predictions were, however, inconsistent with later studies by Culling et al. (2012) and Jones and Litovsky (2008). Culling et al. (2012) proposed a model predicting the SRM as a function of the azimuth of the noise masker. For speech presented in front, Culling et al. (2012) found that the predicted SRM reached the maximum for noise at 60°, and it was reduced by almost half when the noise moved to 90°. For speech and noise presented at equal and opposite azimuths, the predicted SRM was greater and reached the maximum for speech and noise at 60°. With more than one masker, Jones and Litovsky (2008) tested SRM for bilaterally symmetrical speech maskers, and found that the SRM for angular separation of 45° largely accounted for the maximum SRM measured in the frontal hemifield. With the aim of improving characterisation of the contribution of the angular separation component to SRM and to extend Bronkhorst's model to include speech maskers, a revised model was proposed by Jones and Litovsky (2011). In reverse to the approach used by Hawley et al. (2004) and Zurek (1993), the contribution of angular separation to SRM was first determined for bilaterally symmetric maskers, in which there is no better ear. The contribution of the asymmetry of the masker array was then calculated by taking the difference between SRM and separation component. It was found that the predicted SRM and the contribution of the angular separation to SRM were both greater for speech maskers than noise maskers, possibly due to the informational masking (Jones and Litovsky, 2011). The greater SRM with speech maskers is consistent with previous studies by Hawley et al. (2004) and Perrett and Noble (1997). Across masker types, the predicted SRM from Jones and Litovsky's model was found to be greatest in the frontal hemifield, which was inconsistent with the predictions of Bronkhorst's model noted above.

Although an accurate SRM for different numbers and types of maskers can be predicted with the model proposed by Jones and Litovsky (2011), it may not always necessarily be preferable to the approach used by Beutelmann et al. (2010) and Lavandier and Culling (2010). Table 2.1 summarises some of the strengths and limitations of these models. It seems that each model may be preferred in some cases rather than the others. The model of Jones and Litovsky, for example, might be preferable when modelling SRM for mutli-speech maskers.

Table 2. 1: Strengths and limitations of the models for predicting SRM.

Model	Strength	Limitations
Beutelmann et al. (2010)	• Can be used in normal-hearing and hearing-impaired listeners.	• Has been only used with the target presented from front of a listener. • Has been used for only one masker configuration. • Does not account for informational masking (speech maskers are replaced with noise prior to calculating the output of the model).
Lavandier and Culling (2010)	• Can be used in normal-hearing and hearing-impaired listeners. • Has been used for different target azimuths. • Has been used for multiple noise maskers.	• Limited to use with noise maskers.
Jones and Litovsky (2011)	• Has been used for multi-maskers. • Does account for informational masking.	• Currently restricted to normal-hearing listeners. • Has been used with the target presented from front of a listener.

2.4 Neurophysiology of spatial hearing

In the previous section, it has been shown that binaural cues allow normal-hearing listeners to localise sounds in the horizontal plane and to understand speech in the presence of noise. This section presents how these binaural cues processed in the mammalian brain (Section 2.4.2), and the models that have been developed to explain binaural interaction (Section 2.4.3). Evidence of the plasticity of binaural cue processing is also provided in Section 2.4.4[2].

2.4.1 Overview

Incoming sound at the eardrum is transmitted into the overall window, which is a membrane-covered opening in the outer wall of the fluid-filled cochlea, via three small bones in the middle ear known as ossicles. In the cochlea, sound sets up a travelling wave moving apically along the basilar membrane, in which the frequency that causes the peak of the travelling wave is known as the characteristic frequency (CF). The CF becomes progressively higher towards the base of the cochlea (i.e. cochleotopicity). The cochlea, therefore, act as a Fourier transform by breaking down sound into its component frequencies. The inner hair cells monitor vibration along the basilar membrane, converting the movement into neural impulses through changing the action potentials in their cell membrane. These action potentials are closely related to one phase of waveform (i.e. phase locked) for tones below 1500 Hz and to an envelope of high-frequency AM stimuli (Joris et al., 2004). The rate of action potentials may increase as the stimulus level increases. The change in potential causes the release of neurotransmitters into the synapse, leading to activation of the auditory nerve fibres, in which each is sensitive to a CF. All these fibres leave the cochlea and terminate on neurons in the homolateral cochlear nucleus (CN) in the brainstem.

Binaural cues are neurally processed in largely separate pathways in the brainstem (Figure 2.7). The binaural pathway arises from neurons in the anteroventral CN and sends information to neurons in the superior olivary complex (SOC) on either side of the brainstem. The SOC is involved in the extraction of ITD and ILD. Neurons in the SOC largely project to the inferior colliculus (IC), via the lateral lemniscus. The monaural pathway bypasses the SOC and projects predominately to the contralateral IC, via the lateral lemniscus. Spectral cues are thought to be processed in the dorsal cochlear nucleus (DCN) of the monaural pathway. Both binaural and monaural pathways converge in the IC. Binaural information from the IC is sent to the superior colliculus (SC), which receives multi–sensory input and interacts with the motor system, and to the auditory cortex (AC) via the medial geniculate body.

[2] More detailed reviews of the neurophysical aspects can be found in the literature, such as Grothe et al. (2010), Tollin (2003), Yin, (2002), and Yin and Chan (1990).

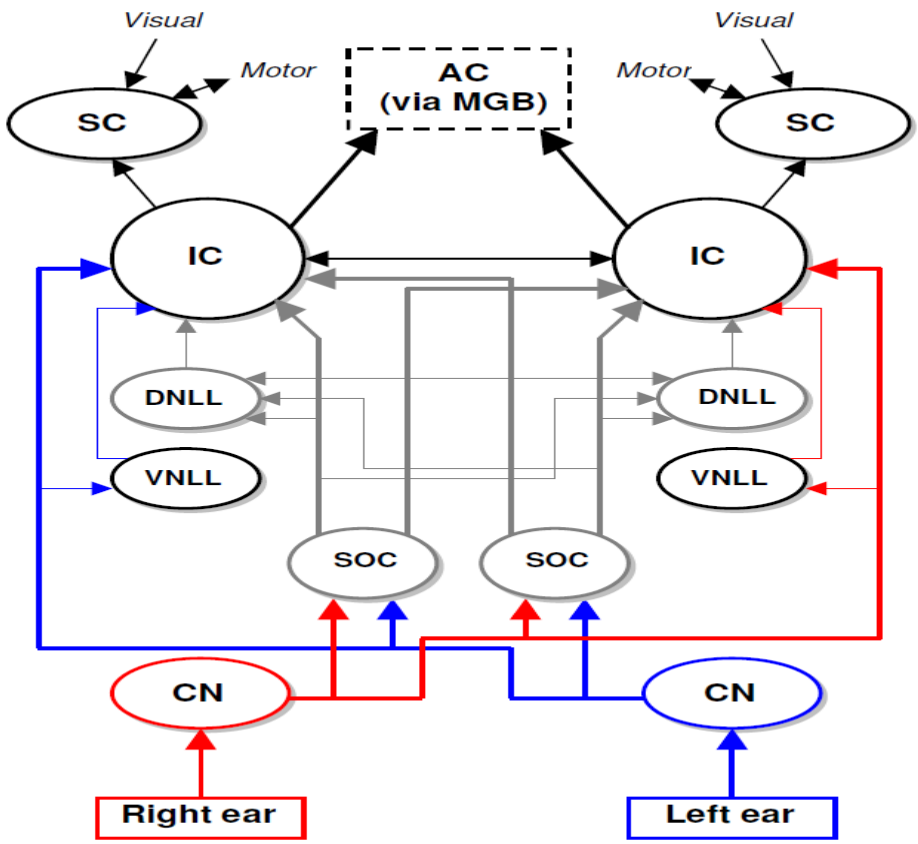

Figure 2.7: Schematic illustration of the brainstem pathways involved in binaural hearing in the mammalian brain. Cochlear nucleus (CN); superior olivary complex (SOC); ventral nucleus of the lateral lemniscus (VNLL); dorsal nucleus of the lateral lemniscus (DNLL); inferior colliculus (IC); superior colliculus (SC); medial geniculate body (MGB); auditory cortex (AC). The figure is reprinted with permission from Rowan (2005).

2.4.2 ITD and ILD extraction

Figure 2.8 shows the traditional scheme for the processing of interaural cues of tones in the mammalian brainstem. Two binaural pathways begin in the level of the CN, which are the medial superior olive (MSO) and the lateral superior olive (LSO). The neurons in the MSO and LSO are generally considered to extract ITD and ILD cues respectively (Tollin, 2003; Yin, 2002).

Neurons in the MSO receive bilateral inputs from both the ipsilateral and contralateral CN. Most of the neurons in the MSO receive excitatory inputs from the CN on both sides, and are referred to as ‘‘EE-type’’ neurons (Figure 2.8). Although the MSO is cochleotopically organised, the majority of the MSO receives predominately low frequency information, and it is generally considered to extract ITDs (Yin, 2002). The firing rate of EE-type MSO neurons to a CF tone is usually modulated by ITD. Neurons in the MSO fire maximally in response to a particular, characteristic ITD, referred to as ‘‘peak-type’’ response. Neurons in the MSO appear to be arranged according to their characteristic ITDs along the anteroposterior axis of the nucleus. These neurons act as coincidence detectors and only respond when bilateral action potentials arrive simultaneously. Neurons in the LSO, on the other hand, receive excitatory inputs from the ipsilateral CN and inhibitory inputs from the medial nucleus of the trapezoid body (MNTB), which receives excitatory inputs from the contralateral CN, and are referred to as ‘‘EI-type’’ neurons. Although the LSO is cochleotopically organised, it is predominately receptive to high-frequency information and is generally considered to extract ILDs (Tollin, 2003). Neurons in the LSO fire maximally in response to sounds from the ipsilateral side. The firing rate is greatest when the tone is presented to the ipsilateral ear, as shown in Figure 2.8.

The fact that the MSO is principally receptive to low frequency information and the LSO to higher frequency information may indicate that the ITD and ILD cues are processed in two parallel pathways. Given that neurons in the LSO may also display sensitivity to ITDs in the envelopes of high frequency sounds, this may suggest that ITD and ILD are not processed completely in parallel. One might imagine that the high-CF LSO neurons would not respond to ITD, given that most of the neurons are EI-type. However, Joris et al. (2004), suggest that high-CF neurons throughout the brainstem do phase-lock to the envelope of AM stimuli. Previous studies on mammals have identified neurons in the LSO that are sensitive to ITD in the envelopes of high frequency sounds, although they fire maximally in response to the troughs at the characteristic ITD (i.e. ‘‘trough-type’’ response), rather than ‘‘peak-type’’ response (Batra et al., 1997; Fitzpatrick et al., 2002). The mammalian MSO also contains some high-CF neurons that are sensitive to envelope ITD, showing ‘‘peak-type’’ responses (Batra et al., 1997; Yin and Chan, 1990). It appears, therefore, that processing of envelope ITD may be less divided between the MSO and ISO than processing of ITD and ILD with tones. Moreover, the outputs from the MSO and LSO project to IC, in which its high-CF neurons were found to be sensitive to envelope ITDs (Batra et al., 1997; Fitzpatrick et al., 2002).

Binaural information in the IC projects to the SC in the midbrain, which also receives multi-sensory inputs activated by visual, auditory and tactile stimuli and interacts with the motor system. Neurons in the SC are known to be highly plastic (Moore and King, 2004). The SC is of interest in spatial hearing, as it seems the only region of the mammalian brain that contains a topographic map of auditory space (King et al., 2001; Middlebrooks, 1988).The topographic map of auditory space has not been identified in the IC or AC (Grothe et al., 2010; Yin, 2002) since both are cochleotopically organised, so they are highly frequency-tuned. Perceiving spatial location, however, presumably requires substantial convergence across frequency. Although the possible additional contributions that the AC might make for spatial hearing is still not clear, its essential role for sound localisation has been demonstrated in different ways. In humans, temporal lobe damage that includes the auditory cortex often impairs localisation performance (Clarke et al., 2002). Unilateral lesions of the AC in cats (Jenkins and Marsterton, 1982) and ferrets (Kavanagh and Kelly, 1987) produce localisation deficits in the contralateral hemifield. In these species, bilateral lesions cause a deficit in localisation performance in both hemifields (Jenkins and Marsterton, 1982; Kavanagh and Kelly, 1987).

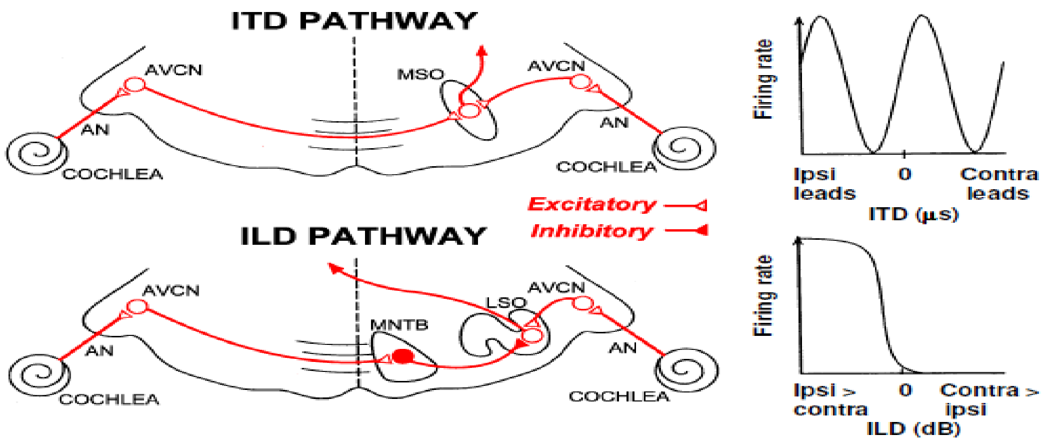

Figure 2.8: Illustration of the traditional scheme for processing ITD (upper panel) and ILD (lower panel) in the brainstem. Auditory nerve (AN); anteroventral auditory nerve (AVCN); medial superior olive (MSO); lateral superior olive (LSO); medial nucleus of the trapezoid body (MNTB). The figure is reprinted with permission from Rowan (2005).

2.4.3 Models of binaural interaction

Several models have been proposed to explain binaural interactions. An overview of these is given by Colburn and Durlach (1978) and Stern and Trahiotis (1995). Most models are essentially based on the neural coincidence mechanism suggested by Jeffress (1948) to detect ITD, in which the neurons in the MSO are thought to act as coincidence detectors, responding only when bilateral action potentials arrive simultaneously. The stimulus waveform to each ear is filtered by two sets of auditory nerve fibres that span a range of CFs. Pairs of auditory nerve fibres with the same CF from each ear provide input to an array of ‘‘delay lines’’ and coincidence detectors. The auditory nerve fibres fire when the neural inputs from the two sides coincide. Each coincidence detector responds maximally to a single ITD. Figure 2.9 illustrates the Jeffress coincidence detection of ITD processing, where the longer axons from an ear compensate for the earlier arrival of sound at this ear. For example, sound that arrives at the right ear first will fire a specific coincidence detector (red detector in the figure). If the sound has no ITD for sound located at the midline, the detector on the equal-length delay line (green detector on the figure) will fire.

Depending on the way the output of the coincidence detectors is represented, two basic types of binaural interactions on the neural level have been proposed. First, the Cross-Correlation-based model, in which the output of the coincidence detectors is represented as interaural cross-correlation function (Hafter and Carrier, 1970; Jeffress, 1948). These functions are time-averaged to determine the sound-source location. Second, the Equalisation-Cancellation model, in which the signals received in both ears are first equalised in timing and level of the signal across the two ears and then the signal at one ear subtracted from the signal at the other ear (Durlach, 1963). The amount of internal decorrelation of the signals within the frame of the Equalisation-Cancellation model may also serve a cue to detect signals (Gabriel and Colburn, 1981; Goupell and Hartmann, 2007).

Although both models of interaural interaction are based on Jeffress's scheme, researchers such as McAlpine and Grothe (2003) started to doubt the adequacy of applying such a scheme to mammals in general, given that that the mechanism of ITD in mammals is different from that seen in birds. Jeffress's scheme has been shown to exist in the nucleus luminaries of the owl (Carr and Konishi, 1988) and chicken (Hyson, 2005). Studies of the guinea pig and Mongolian gerbil suggest that the characteristic ITD is generally outside the physiological range created by the separation of the ears (Brand et al., 2002). Further, the ITD sensitivity appears to depend upon the inhibitory input in the MSO, and so there is only limited evidence for delay lines. Brand et al. (2002) and Harper and McAlpine (2004) suggest that the ITD coding can be explained under a single network where the rate of activity across the two sides of the brain is compared.

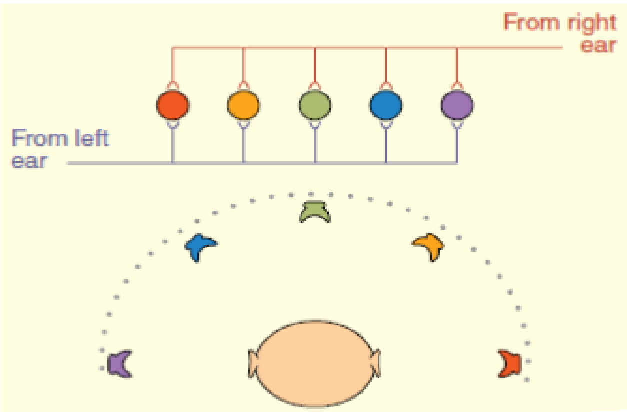

Figure 2.9: Schematic illustration of Jeffress coincidence detection of ITD processing. The figure is reprinted with permission from Campbell and King (2004).

2.4.4 Plasticity of the binaural system

The anatomical development of the auditory system reveals that binaural cues change during development. The adult auditory system may, therefore, able to adapt to altered binaural cues (i.e. plasticity), for example to those induced by unilateral ear listening. However, the capacity for adaptation seen in the adult auditory system is limited compared to that seen during development. King and Moore (1991) suggest that the immature auditory system has a greater capacity for changes than the mature system. This does not necessarily mean that the link between the development of auditory areas and auditory activity disappears after this critical period; however, it does become progressively weaker with age. This is evidence that the longer the duration of auditory deprivation, the longer it takes to learn to use binaural cues (Ito et al., 1993; Pelizzone et al., 1991). Evidence from electrophysiological recordings of neural responses to speech reveals that a waveform known as P1 is assumed to be caused by activity in the auditory regions of the thalamus and auditory cortex. The latency of P1 decreases with age, in normal-hearing children (Gilley et al., 2005).

In addition to age, it is assumed that binaural processing continues to develop with experience (Litovsky, 1997; Moore, 1997). Studies on animals have revealed that auditory experience plays an essential role in the full maturation of auditory pathways (Trune, 1982). It has been suggested that a loss of binaural experience, such as in the case of unilateral hearing loss, could arrest the development of binaural processing (Moore, 1997). Long-term experience with listening bilaterally could improve sensitivity to binaural cues, particularly in young children, whose brains are highly plastic (Tyler et al., 2003). Several studies have examined the influence of experience on binaural cues in adults in order to assess the capacity of the auditory system to change in response to altered inputs (i.e. perceptual learning). Florentine (1976), for example, altered ILD, induced by unilateral ear plugging, and found experience with the plug over weeks generally resulted in location being perceived to the centre, rather than perceived away from the plugged ear. In another study, Javer and Schwarz (1995) altered the ITD cue by fitting listeners with bilateral devices which produced a fixed interaural delay of 171 to 684 µs. They found that the spatial location is perceived towards one ear immediately after introducing the delay; however, the subjects' performance improved after many days of experience with the devices. Studies by Rowan (2006) and Wright and Fitzgerald (2001) showed that sensitivity to the ITD and ILDs also depends on experience. In these studies, listeners were trained to discriminate ITD and ILD cues presented over headphones in order to allow each cue to be varied independently. They concluded that learning with binaural cues may potentially related to auditory plasticity for ITD (Rowan, 2006) and ILD (Rowan, 2006; Wright and Fitzgerald, 2001).

2.4.5 Summary

The above sections have demonstrated that the normal auditory system is sensitive to differences in level and timing of sounds at the two ears. Such differences allow normal-hearing listeners to determine the location of sounds in the horizontal plane and to understand speech in the presence of background noise. When listening binaurally, normal-hearing adults can localise sounds in the horizontal plane with an overall localisation error of 6° to 10°. Binaural hearing also leads to various advantages for speech perception in noise, including SRM, binaural squelch, summation and head shadow effects.

The ability to localise sounds and understand speech in noise is, however, likely to be affected by hearing impairment, due to the reduced sensitivity as a result of the etiology of the hearing loss (Noble et al., 1994). It has been suggested that the use of electronic prostheses, such as cochlear implants, could restore some of the binaural hearing ability. By December 2012, approximately 324,200 individuals with severe-to-profound hearing loss were using a cochlear implant worldwide (National Institute on Deafness and Other Communication Disorders, 2015). A detailed overview of spatial hearing with cochlear implants is provided in the following sections.

2.5 Cochlear Implants

This section provides an overview of how a cochlear implant works and the benefits of unilateral implantation (a single cochlear implant in one ear) for adult users. The emerging evidence regarding the possibilities and limitations of bilateral implantation (two cochlear implants, one in each ear) is reviewed in Section 2.6. A detailed overview of the studies on spatial hearing with bilateral implantation is provided in terms of sound localisation (Section 2.6.1), speech perception in noise (Section 2.6.2) and a self-reported measure (Section 2.6.3). Factors limiting binaural hearing with bilateral cochlear implantations are discussed in Section 2.6.4. At the end of the chapter, there is an overview of the evidence regarding whether the synchronised processing between the two implants could enhance binaural hearing ability for cochlear implant adult users.

2.5.1 Overview

A cochlear implant (CI) is an electronic device that is implanted into the inner ear of individuals who have severe-to-profound hearing loss, typically caused by loss of or damage to the hair cells in the cochlea (Wilson, 2004). It works by electrically stimulating the spiral ganglion cells. A CI consists of a speech processor, a head-piece transmitter, an implanted receiver-stimulator and an electrode array placed in the scala tympani in the cochlea (Figure 2.10). The speech processor, which is worn above the ear, similarly to a behind-the-ear hearing aid, picks up sounds through its microphone and then processes and converts them to digital signals. Next, these sound signals are sent across the skin to the implanted receiver-stimulator, using a radio frequency transmitter which is placed externally on the head, just behind the ear. The implanted receiver-stimulator converts the signals into electrical pulses and sends them to a group of electrodes within the cochlea, stimulating the auditory nerve, which will then send the signals to the brain, where they are interpreted. A current CI usually contains 12 to 22 electrodes, depending on the manufacturer, with a ground electrode placed outside the cochlea.

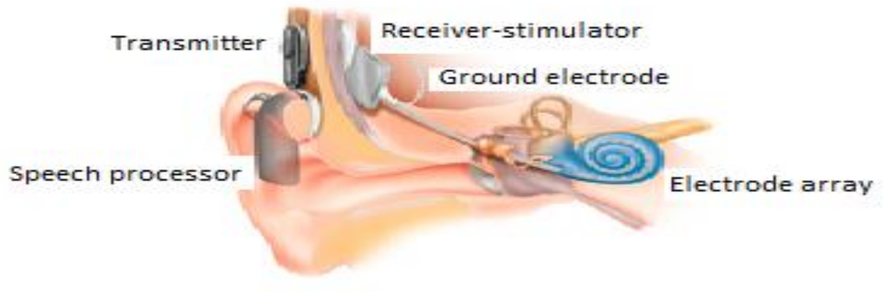

Figure 2.10: A schematic diagram of a cochlear implant. The figure is reprinted with permission from Cochlear™ Ltd.

Although the speech processing strategy in clinical CI processors varies between CI systems, many share a similar processing procedure, as shown in Figure 2.11. The incoming signal is first passed through an optional automatic gain control (AGC) and a pre-emphasis filter, which attenuates the frequency component below 1.2 kHz at 6 dB/octave. The output is then filtered into many frequency bands (i.e. channels), via the Fast Fourier transform or a bank of bandpass filters, and the envelopes are extracted from each band. The envelope output is then compressed in order to ensure that the output fits into the electrical dynamic range of the CI user, and finally the compressed envelope signal is used to modulate a train of electrical pulses. This means that the amplitude of the pulses corresponds to the amplitude envelope of that channel. A train of electrical pulses are then directed to electrodes which are designed to stimulate the auditory nerve in a limited region in the cochlea, so that different pitches can be perceived (Wilson, 2004). Current implants have usually between 12 and 22 electrodes, depending on the manufacturer. Signals delivered to electrodes near the base of the cochlea are derived from high frequency band-pass filters, whereas signals delivered to electrodes near the apex are derived from low frequency band-pass filters. Although the frequency-to-place mapping of the auditory system is approximated by the CI, it is still limited by the anatomical positioning of the electrodes, in which they are typically not inserted all the way to the apex (Skinner et al., 2002).

The most widely used speech processing strategies implemented in CIs are continuous interleaved sampling (CIS), Advanced Combination Encoder (ACE), *n*-of-*m* and spectral peak (SPEAK), depending on how the electrodes should be activated. The key feature of the CIS strategy (the one shown in Figure 2.11) is that all channels are stimulated and interleaved in time. In the ACE, *n*-of-*m* and SPEAK strategies, on the other hand, only the filters with the largest amplitude are stimulated. The incoming signal is filtered into 20 filters with the centre frequency ranging from 250 Hz to 10 kHz. Only the filters with the largest amplitude for stimulation, *n,* are selected. Pulses are then delivered to a subset of the corresponding *n* electrodes out of the *m* electrodes. The main differences between SPEAK and the other two strategies (ACE and *n*-of-*m*) is that the *n* in SPEAK may vary from one stimulus to the other, depending on the spectral details of the stimulus. Additionally, *n* in the SPEAK are stimulated at a higher rate.

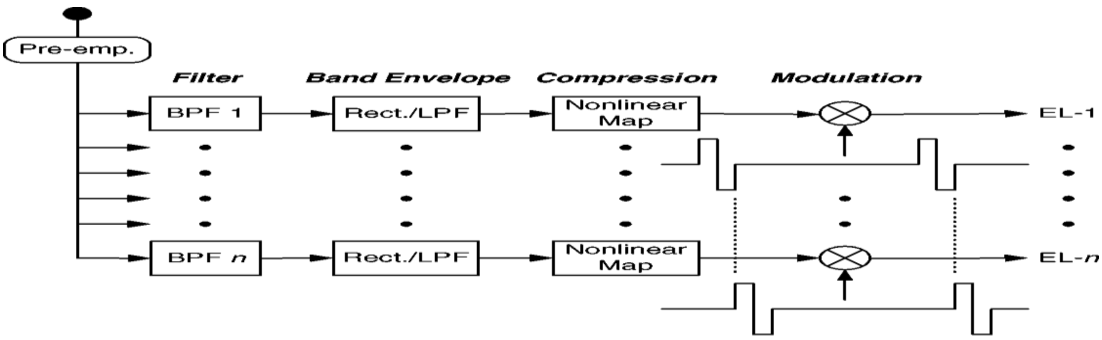

Figure 2.11: Block diagram for typical continuous interleaved sampling (CIS) speech processing strategy for a cochlear implant with *n* electrodes. The input from the microphone is pre-emphasised (Pre-emp.) to boost frequencies above 1.2 kHz and then processed by *n* of the bandpass filters (BPF). The amplitude envelope is extracted using half-wave rectification (Rect.) and low-pass filtering (LPF) and then compressed and used to modulate a pulse train. The pulse trains in different frequency bands are interleaved so that the electrodes (EL) are not stimulated simultaneously. The figure is reprinted from Wilson et al. (1991) with permission from the Nature Publishing Group.

2.5.2 Performance with CIs

There are about 13,000 implant users in the UK, where 650 adults are implanted each year (British Cochlear Implant Group, 2015). Cochlear implantation in severely-to-profoundly deaf adults is generally associated with improved speech perception ability and higher health-related quality of life (Rauschecker and Shannon, 2002; UK Cochlear Implant Study Group, 2004). The outcome of cochlear implantation varies widely across CI users, and it generally depends on multiple factors such as age at implantation, age at onset of deafness, duration of deafness and CI experience, and cognitive skills. Better speech perception following implantation is typically associated with a younger age at implantation, shorter duration of deafness, a later onset of deafness and a longer time since implantation (O'Donoghue et al., 2000; Stacey et al., 2006). The average CI adult is able to understand more than 50% of the words in sentences presented in quiet, compared to less than 20% prior to implantation (UK Cochlear Implant Study Group, 2004).

The best performance of a CI user, however, does not achieve that of normal-hearing listeners. In addition, most CI users experience major difficulties in more challenging listening tasks such as sound-source localisation and speech perception in noise. Such difficulties are expected to arise for two reasons. Firstly, cochlear implantation does not fully restore normal hearing, and so their hearing sensitivity is still reduced due to pathology in the auditory system. For example, degeneration of nerve fibres limits the activated spectral regions. Secondly, there are some limitations in the current CI system to perfectly mimic normal hearing. Spectral resolution in the CI is reduced by the position of the microphones and the limited number of channels. The microphone of a CI is placed above the ear, which may minimise the capture of spectral cues. Spectral resolution in the CI is also disrupted by the spread of current across a wide range of channels (i.e. channel interaction). Coding of temporal information in the electrical signals is limited to the envelope of the sounds. In addition, the pulse rate is constant across time and channels.

The fact that most CI users are implanted in only one ear is also considered an important factor that limits performance in CI users. As noted in Section 2.2.1, the binaural cues that are known to underlie humans' ability to localise sounds in the horizontal plane and to understand speech in noise can only be determined through binaural hearing. Thus, bilateral implantation may give users the potential to take advantage of binaural hearing, and thus could improve the ability of CI users to localise sources of sounds and avoid hazards and to perceive speech in noise. There is, indeed, growing interest in providing bilateral cochlear implantation: as of December 2008, bilateral CI users represented 5% of the total estimated CI users worldwide (Peters, et al., 2010).

2.6 Spatial hearing with bilateral CIs

As mentioned in section 2.2.1, ITD is present both in the fine structure of sounds up to 770 Hz and the envelope of high frequency sounds, whereas ILD is larger at higher frequency sounds. One might expect that ITDs measured at the microphone of the CI speech processor should be similar to those measured at the eardrum of normal-hearing listeners. However, given that the current speech processing strategies use a fixed pulse rate, the fine structure of a stimulus is not conveyed to the CI users (van Hoesel et al., 2008). Moreover, users of bilateral CIs are often fitted with two independent speech processors, meaning that the timing at which pulses are generated is independent at the two ears. Given that the commonly used pulse rate in the speech processor is 1000 Hz, the difference between right and left stimulation could be between 0 to 1/pulse rate, meaning that the ITDs varied from 0 up to 1 millisecond (ms). Such variability is outside the naturally occurring range for humans (660 µs). Additionally, the lack of the natural time that it takes for waves to physically travel along the basilar membrane can possibly lead to imprecise ITDs. In the CI system, a delay of about 10 to 20 ms is produced to process CI stimulation. However, since this delay is fixed, CI users may possibly be able to adapt to such differences.

More positively, all speech processing strategies do represent ITD in the amplitude envelope. However, the sensitivity of bilateral CI users to envelope ITDs varies considerably and is rather unreliable, because the processors have independent sampling clocks (van Hoesel, 2004). While some bilateral CI users showed high sensitivity to envelope ITDs of about 25 µs, close to thresholds seen in a normal-hearing listener (Lawson et al., 2001), others showed ITD sensitivity of about 290 µs (van Hoesel and Tyler, 2003) or 389 µs (Laback et al., 2004). Grantham et al. (2008) reported that, out of 11 bilateral CI users, only five adults could detect ITDs smaller than 1000 µs, with the best having ITD of about 400 µs, and that their ITD sensitivity is likely limited to sound onsets.

With regard to ILD cues, bilateral CIs seem to provide a relatively accurate ILD cue which is within normal limits, for some bilateral CI users (van Hoesel, 2004). Some bilateral CIs are indeed sensitive to ILDs as small as 1-2 dB (Grantham et al., 2008). However, ILDs in bilateral CIs are limited by the fact that processors are not synchronised between the ears. The independent processing of both speech processors involves possible asymmetric activation of non-linear processing, such as through AGCs and compression settings, which adversely affects ILDs (van Hoesel et al., 2002). If the signal at one ear, for example, is above the AGC activation threshold and the signal at the other ear is below the AGC activation threshold, the ILD could be reduced. Grantham et al. (2008) reported that the sensitivity of bilaterally implanted adults to ILDs was reduced when the AGC circuit was active (mean ILD threshold= 3.8 dB) compared to when the AGC circuit was switched off (mean ILD threshold =1.9 dB). Although the differences in microphone characteristics and loudness mapping methods in the two ears for bilateral CI users could also affect accuracy of ILD representation, long-term experience with bilateral implants may accommodate for such effects, as has been demonstrated for normal-hearing listeners (Bauer et al., 1966). A strong dominance of ILDs in spatial hearing ability in bilateral CI users has been reported (Grantham et al., 2008; Seeber and Fastl, 2008; van Hoesel et al., 2008). Given that the ITD cues vary considerably and unreliably, it seems that the higher sensitivity for ILDs is more likely to provide a reliable and consistent binaural cue for bilateral CI users.

The following sections review evidence regarding spatial hearing ability with bilateral CI adults in terms of sound-source localisation (Section 2.6.2), speech perception in noise (Section 2.6.3) and self-reported measures (Section 2.6.3).

2.6.1 Sound-source localisation with bilateral CIs

The ability of bilateral CI users to identify the location of sound source has mostly been studied using sound source localisation/identification tasks in which the bilateral CI user is required to identify which loudspeaker the sound comes from[3]. Table 2.2 summarises localisation outcomes from some bilateral CI studies, showing overall localisation errors calculated over the entire loudspeaker array. All studies but one compared overall localisation errors when using both implants (i.e. bilateral CI use) to when only one implant was activated (i.e. unilateral CI use). All studies reported RMS error rather than MAE, except for Verschuur et al.'s study. Given that the RMS error is often more preferable to use for adults (Section 2.2.1), localisation data of Verschuur et al. (2005) has been re-analysed to represent RMS error. Although the calculated RMS errors were greater than the MAEs reported by Verschuur et al. (2005), both errors follow similar trends. Also shown is the 'chance' level reported by each study, which was calculated assuming unbiased guessing by a subject responding randomly, irrespective of the actual sound sources.

The results show significant improvement in localisation performance when using two implants compared with only one. Unilateral performance is often near chance levels, although a few subjects in some studies show good localisation performance, even when stimulus levels are roved. However, localisation errors when using both implants are significantly better than chance level and are typically much smaller than with one ear alone. The smallest RMS error when using both ears was found to be about 10° for a study that used a relatively small loudspeaker span of about 100° (van Hoesel and Tyler, 2003). The increase in localisation error with span can be explained by the ILD cues (van Hoesel et al., 2008). For a small span, the ILD cue is relatively unambiguous across the entire array. As the span increases beyond about 100°, the ILDs do not increase further, and thus the ambiguity increases with increasing azimuth (Seeber and Fastl, 2008). Much larger localisation errors were also obtained for a span of a 360° circle, mainly due to the large number of front and back confusions (Laszig et al., 2004).

The evidence from several studies suggests that localisation performance of bilaterally implanted users is mediated largely by ILD cues, with little or no contribution from ITD

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[3] The term ''localisation'' is used in this research project as well as much of the CI literature to describe the ability to identify the location of a sound source. However, this term seems inaccurate to describe the ability to identify the locations without considering the actual perceived locations.

cues (Grantham et al., 2007; Seeber and Fastl, 2008; van Hoesel, 2004; Verschuur et al., 2005). Results from studies that investigated the contribution of binaural cues to localisation with bilateral CI users consistently showed that bilateral CI users predominantly relied on ILD for localising all types of sounds and that the envelope ITD cues are ineffective for sound containing ILD cues. Although ILDs are smaller at lower frequencies, they can still provide some information for localisation, particularly for the frontal hemifield. Seeber and Fastl (2008) measured ILDs from HRTFs at the input of a CI speech processor and reported ILD of about 5 dB for low frequency channels at ±30° azimuths around the midline. In support of the dominance of ILD, it has been found that bilateral CI users tend to compress sounds coming from the sides more towards the centre (Schleich et al., 2004; Seeber and Fastl, 2008; van Hoesel and Tyler, 2003). This might contribute to the effects of the AGC and compression settings in the CI processor, which could severely reduce ILDs. Given that the AGC and compression settings do not severely affect envelope ITD, the observation of the increase in localisation error scores for the lateral side loudspeakers may support the dominance of ILD in sound localisation of bilateral CI users. Envelope ITD was found to contribute to localisation only when ILDs are unavailable or ambiguous, although its contribution is still far below that of ILDs (Grantham et al., 2007; Seeber and Fastl, 2008; van Hoesel, 2004).

Results of the studies listed in Table 2.2 also show that bilateral CI users are likely to be able to process binaural cues quite well after about three months of bilateral experience. Grantham et al. (2007) also reported localisation performance of some of their bilateral CI users 10 months after their original testing and found no significant change in localisation performance between about 4-6 to 12-16 months after receiving bilateral CIs. This may indicate that localisation performance has reached its asymptote by 4-6 months for most bilateral CI users. Two of their 12 subjects, however, showed significant improvement in localisation performance over a 5- to 15-month period. Such results suggest that a few bilateral CI users might need more time with bilateral listening than the average CI user to develop localisation abilities. Litovsky et al. (2009) showed that, after three months experience with bilateral listening, the majority of bilateral CI users demonstrated greater improvement in performance for left-right discrimination analysis, when using two implants compared with only one, than they achieved for a within hemifield analysis. From this, Litovsky et al. (2009) suggest that spatial hearing might emerge in a two-step process, beginning with simple left-right discrimination and converging on fine-grained localisation that may develop with prolonged bilateral CI use. However, the RMS error reported by Litovsky et al. (2009) is comparable to that reported by other studies which involved bilateral CI users with longer experience with bilateral listening (Grantham et al., 2007; Verschuur et al., 2005).

Table 2.2: Details of studies comparing the localisation performance of bilateral CI adults when listening with both implants (bilateral condition) and with one implant only (unilateral condition). Mean RMS (root mean square) error and chance levels are given. The chance level reported by each study assumed unbiased guessing.

Study	**No. of subjects (mean age)**	**Bilateral experience**	**Set-up**	**Results**
van Hoesel and Tyler (2003)	*n*=5 (58.8 years)	At least 12 months	Set-up: 8 loudspeakers between +/-54° at 15.5° intervals. Stimuli: pink noise roved at level (±4 dB).	• Bilateral =10° • Unilateral =40° • Chance level=50°
Verschuur et al. (2005)	*n*=20 (58.9 years)	At least 9 months	Setup: 11 loudspeakers between +/-90° at 18° intervals. Stimuli: speech, pink noise, tone at 1 kHz and transient. Each was roved at Level (±5 dB).	• Bilateral: speech=31.6°, noise=36.1°, tone=38.3° and transient=35.0° • Unilateral=79.9° (only reported across all stimuli) • Chance level= 65°
Grantham et al., (2007)	*n*=22 (47.6 years)	At least 4 months	Set-up:9 loudspeakers between +/-90° at 20° intervals. Stimuli: speech and pink noise. Each was roved at Level (±5 dB).	• Bilateral: speech=29.1° and noise=30.8° • Unilateral: speech=69.4° and noise=75.8° • Chance level= 71.7°, with 95% confidence interval of 2.9°.
Neuman et al. (2007)	*n*=8 (51.6 years)	At least 5.6 months	Set-up: 9 loudspeakers between +/-90° at 22.5° intervals. Stimuli: speech and pink noise. Each was roved at Level (±3 dB).	• Bilateral: speech=30.4° and noise=32.1° • Unilateral: speech=52.3° and noise=56.8° • Chance level =80°

Litovsky et al. (2009)	*n*=17 (52.7 years)	At least 3 months	Set-up: 8 loudspeakers between +/-70° at 20° intervals. Stimuli: pink noise Each was roved at Level (±6 dB).	• Bilateral: 28.4° • Unilateral=58.5° • Chance level =60°
Dorman et al. (2014)	*n*=16 (53.8 years)	At least 5 months	Set-up: 13 loudspeakers between +/-90° at 15° intervals. Stimuli: pink noise, high-pass and low-pass noises Each was roved at Level (±2 dB).	• Bilateral: noise=20.4° , high-pass noise=19.6° and low-pass noise=43.3° • Chance level=73.5°

Although it is clear that bilateral CI users are better at localising using both implants rather than one, their localisation performance varies across users and is not readily predicted from factors such as age at implantation, duration of deafness or hearing experience. Given that the bilateral CI users in the studies listed in Table 2.2 were all postlingually deaf, it might be possible that the clear benefits of using both implants are entirely dependent on having had access to bilateral auditory stimulation early in life. The finding that bilateral CI children implanted in the second ear at a relatively late age had poor localisation performance (Litovsky et al., 2004) may support the role of early exposure to sound in both ears. In support of this, Nopp et al. (2004) reported that two bilateral CI adults who were bilaterally deafened early childhood did not show bilateral benefits from bilateral implantation. Asp et al. (2011), however, investigated the localisation ability of 60 bilateral CI children and found that the largest predictor of localisation ability of bilateral CI children was the duration of their bilateral CI listening experience. Taken together, it seems that the age at onset of deafness and amount of bilateral experience are factors among many others that need to be taken into consideration when considering outcomes of CI users.

While the above studies show clear benefits of using both implants, there are a number of uncertainties with their interpretation regarding localisation ability of bilateral CI users. Firstly, most studies often compared overall localisation error to a single value that represents chance level. Comparing the observed localisation ability to a single value might, however, lead to an inappropriate conclusion. Statisticians usually use a range (i.e. confidence interval) in order to differentiate correct scores from chance. To be more certain that chance is not the basis of observed localisation ability, for a given level of confidence, a probable range of errors occurring by guessing should therefore be calculated. The overall localisation error of an individual needs to be below the chance range in order to be more confident that this error did not reflect guessing. To the best of this researcher's knowledge, only the studies by Grantham et al. (2007; 2008) have considered the issue of chance range. In their studies, RMS error scores were compared to 95% confidence range of unbiased guessing.

The second issue when reporting localisation ability is that chance performance is often calculated, explicitly or implicitly, assuming unbiased guessing (i.e. random guessing). Such an assumption, however, may lead to an inappropriate conclusion when a different guessing behaviour actually occurs. Without considering the appropriate guessing behaviour, the responses of a person who is biased in guessing might, for example, be erroneously treated as actual localisation ability rather than the outcome of guessing behaviour. van Hoesel and Tyler (2003), for example, showed an RMS of 20° for one of their bilateral CI users while listening with one implant, and that result was postulated to be due to the use of monaural spectral and/or level cues. More examination of the pattern of responses given by that subject, however, indicated that the small RMS by that subject reflects a consistent bias towards the frontal loudspeakers. It is, therefore, necessary to take into consideration the appropriate guessing behaviour of a listener when calculating chance range. Alternatively, a whole system of localisation measures, including bias (constant error) and variability in response (random error), should be reported. Values of constant and random errors are intended to help in estimating whether the overall error (RMS) shown by a listener reflects actual ability or just a different pattern of guessing. Although the studies by Grantham et al. (2007; 2008) reported such a system of measures, they did not rule out the possibility of biased guessing with their subjects. Given that the application of the above two mentioned issues when analysing localisation ability has been largely ignored, a simulation was performed in MATLAB (The Mathworks Inc.) to clarify the significance of these issues and their impact on the conclusions drawn in the existing literature and is presented in Chapter 4.

Further uncertainly is associated with the design of the studies in Table 2.2, in which localisation ability of bilateral CI users with both implants was compared to unilateral listening with one implant only. Such studies are at risk of bias caused by the unfamiliarity of bilateral CI users with listening unilaterally with one implant. It is possible that the higher overall localisation error of bilateral CI users listening unilaterally was attributable to the fact that they were not accustomed to listening in everyday life with a single implant, and thus the actual improvement is probably somewhat underestimated. A fairer assessment would be, therefore, to compare localisation performance of bilateral CI users to another group of unilateral CI users who had been implanted on only one side and who had become acclimatised to listening with one implant in everyday life.

A search in the literature reveals three studies that assessed localisation abilities of CI users who are implanted with single CIs (Table 2.3). Although Buhagiar et al. (2004) concluded that unilateral CI users have poor localisation abilities, the other two studies show that some of the unilateral CI users could localise at better than chance. Grantham et al. (2008) compared localisation abilities of their unilateral CI users to those of bilateral CI users who were tested in their previous study (Grantham et al., 2007), and found that localisation abilities of ''good'' unilateral CI users were still significantly poorer than those reported for bilateral CI users. This finding is of great interest for at least two reasons. Firstly, it suggests that monaural spectral and/or level cues may be sufficient to allow unilateral CI users to localise sounds in the horizontal plane, although they are less robust than the effect provided by binaural cues. Secondly, it indicates that a better than chance range does not necessarily mean an ability to use binaural cues.

Table 2.3: List of localisation studies on unilateral CI adults.

Study	Subjects	Set-up	Results
Buhagiar et al. (2004)	*n*=18, all postlingually deaf. Mean age= 52.2 years; mean CI experience =4.9 years	Set-up: 11 loudspeakers between +/-90° at 18° intervals. Stimuli: speech, pink noise, tone at 1 kHz and transient. Each was roved at level (±5 dB) and frequency content.	*''localisation performance was found to be close to chance for all stimuli''*
Grantham et al. (2008)	*n*= 6, all postlingually deaf. Mean age= 54.2 years; mean CI experience = 2.4 years	Set-up: 9 loudspeakers between +/-90° at 20° intervals. Stimuli: speech and pink noise. Each was roved at level (±5 dB).	*''Some unilaterally implanted subjects can localise sounds at a better than chance level''*
Nava et al. (2009)	*n*= 14, 10 prelingually deaf and 4 postlingually deaf. Mean age=33 years; mean CI experience= 5 years	Set-up: 8 loudspeakers at +/-30°, +/-60°, +/-120° and +/-150°. Stimuli: noise burst was roved at level (±3 dB).	*''some prelingually deafened adults implanted with a single CI can learn to localise sound at a better than chance level…postlingually deafened adults who have experienced auditory cues earlier in life can reach a more accurate performance than prelingual CI recipients''*

2.6.2 Speech perception in noise with bilateral CIs

Bilateral cochlear implantation can also yield benefits over unilateral implantation for speech perception in noise. Bilateral implantation primarily leads to greater ability to understand speech in noise when the sound sources are spatially separated than co-located (i.e. SRM). A secondary benefit is an improvement in both detection and identification of speech in noise when the two sound sources are co-located so that identical acoustic input reaches the two implants (i.e. a summation effect).

Table 2.4 summarises some of the studies that have previously examined spatial benefits with bilateral CI adults for speech perception in the presence of a single noise masker. All these studies presented sentences in noise, except for Ramsden et al. (2005) who used words. The noise maker was speech-shaped noise with the same spectral pattern as the long-term average spectrum of sentences for all studies, except in the studies of Litovsky et al. (2006) and Ramsden et al. (2005) who used multi-talker babble noise. A few studies used fixed SNR and reported their results as percentage correct, while the majority reported SRTs and used adaptive SNR, except for Litovsky et al. (2006) who used variable SNRs beginning at 21 to zero dB SNR with 3 dB steps. With the exception of two studies, all of these studies used the same spatial configurations for spatially separated conditions, in which the speech was presented at 0° azimuth and the noise was located at 90° either to the left or the right of the listener. In the studies of Laske et al. (2009) and Laszig et al. (2004), however, speech and noise were presented on opposite sides of the head at 45°. In the co-located condition, all these studies used the same spatial configurations, in which speech and noise were presented from the front of the listener at 0° azimuth.

When speech and noise were spatially separated, SRM of about 3 to 4.5 dB was reported for bilateral CI adults. Consistently with these results, an SRM of about 3.6 dB was predicted by a model developed by Culling et al. (2012) for noise at 90°. A greater SRM of 5.9 dB was predicted when the noise was placed at 60° (Culling et al. 2012). Inconsistently with these findings, Loizou et al. (2009) reported SRM for noise at 60° and 90° and reported no significant effect of noise location on SRM for bilateral CI users. Bilateral CI users also showed similar SRM for both noise and speech maskers (Loizou et al., 2009). This suggests that bilateral CI users are not able to use informational masking, which was found to enhance SRM for speech maskers in normal-hearing listeners (Hawley et al., 2004; Loizou et al., 2009).

Although the above SRM was measured or predicted for a listener facing the speech source, a greater SRM could, however, obtained when the listener happens to face somewhere between the speech and noise sources. Culling et al. (2012) reported an increase in SRM up to 9 dB if the listener oriented their head by 30°, so that SNR at the better ear was optimised. For speech and noise at equal and opposite azimuths, the SRM would also be maximised. As shown in Table 2.4, the head shadow effect was almost twice as large when the speech and noise are presented on opposite sides of the head at ±45° (Laske et al., 2009; Laszig et al., 2004) compared to speech at 0° and noise at 90°. It is worth remembering that the SRM measure combines monaural head shadow and binaural squelch effects where monaural effects relate to the change in SNR at each ear due to the head shadow, whereas squelch effect relates to the comparison of the waveform shapes at the two ears (Hirsh, 1948).

Results from the studies in Table 2.4 show that the largest contribution to SRM is that from the monaural head shadow effect. Bilateral CI users show considerable head shadow effect of 3.8 to 6.8 dB for noise at 90°, up to 12 dB for speech and noise at equal and opposite azimuth of 45°. Although unilateral implantation can also provide head shadow effect, it is only true for noise placed at the side of their unimplanted ears. Head shadow, however, can be disadvantageous for a unilateral CI user who happens to have the noise on their implanted side (i.e. negative SRM). Bilateral CI users, on the other hand, showed very small binaural squelch of about 0.9 to 2 dB, which is marginally or non-significant. The role of binaural squelch in bilateral CIs is expected to be minimal, mainly because the current CI processors do not preserve ITDs. Bronkhorst and Plomp (1988) suggest that binaural squelch with broadband noise is largely attributable to good ITD sensitivity, particularly at low frequencies. Only the study by Litovsky et al. (2009) reported a statistically significant binaural squelch effect of 2 dB for bilateral CI users. That benefit however, may be attributable to high variation between CI users. A close inspection of their data shows that the overall binaural squelch can be attributed to a few CI subjects who show a large squelch effect, with some of the subjects also showing negative squelch effect (worse performance with bilateral listening).

For co-located speech and noise conditions in which both speech and noise are presented at 0° azimuth, the benefit of listening with both implants (diotic condition) rather than with only one (monotic condition) is about 1-2 dB (i.e. the summation effect). Given that the cues available in the monotic condition are the same as in the diotic condition, the possible explanation for the summation effect in bilateral CI users is that complementary information about the stimulus can be obtained from both implants, through the asymmetrical electrode insertions or nerve survival. Previous studies have showed that hearing-impaired listeners had better SRTs when speech and noise are co-located in front of the listener and presented diotically than monotically (Wilson et al., 1985), but this was not the case for normal-hearing listeners. Normal-hearing listeners showed similar thresholds for monotic and diotic presentations (Hawley et al., 2004; Lavandier and Culling, 2010). Although the summation effect can also contribute to SRM, it seems unlikely to play much role when speech and noise are not co-located. When the speech and noise are spatially separated, the SNR at one ear will always be worse than the other ear, and so it will not be able to compensate for information received from the other ear.

Although performance of bilateral CI users, both under unilateral and bilateral listening conditions, generally improves with listening experience (Litovsky et al., 2006), changes in the above spatial effects remain unclear. The size of the head shadow effect in bilateral CI adults was found to approach that found in bilateral CI children only when the children were implanted at early age. A similar head shadow effect was reported between ears for bilateral CI children who were implanted early with small or absent delay between implantations. In contrast, children who were implanted late in the first ear and experienced large delays between implantations demonstrated considerably poorer performance, particularly for the second-implanted ear. Such findings point to the role of bilateral experience as a predictor for speech perception in noise ability in bilateral CI users.

Table 2.4: Details of studies investigating spatial benefits for speech perception in noise in bilateral CI adults including spatial release from masking (SRM), head shadow, squelch and summation effects.

		SRM	**Head shadow**	**Squelch**	**Summation**
% Correct	Müller et al. (2002)	Not given	31%	10.7%	Not given
	Ramsden et al. (2005)	40%	44%	10%	12.6%
	Buss et al. (2008)	Not given	38%	10.6%	5.7%
dB	van Hoesel and Tyler (2003)	4.5 dB	4.7 dB	2.0 dB	1.2 dB
	Laszig et al. (2004)*	Not given	10 dB	1.0 dB	2.5 dB
	Schleich et al. (2004)	3.0 dB	6.8 dB	0.9 dB	2.1 dB
	Litovsky et al. (2006)	Not given	5.6 dB	2.0 dB	1.2 dB
	Laske et al. (2009)*	Not given	12 dB	0.1 dB	1.75 dB
	Loizou et al. (2009)	4.0 dB	3.8 dB	Not given	Not given

*speech and noise were presented at opposite side at ±45°

2.6.3 Subjective outcomes with bilateral CIs

Subjective self-rating questionnaires have demonstrated benefits for bilateral CIs, particularly in relation to spatial hearing. Several studies have used the Speech, Spatial and Qualities of Hearing scale (SSQ) to assess spatial benefits for bilateral CI adults (Laske et al., 2009; Noble et al., 2008; Summerfield et al., 2006) and children (van Deun et al., 2010). All studies showed higher scores for bilateral CI users than unilateral CI users for all subscales, including speech, spatial and qualities of hearing. The higher score by bilateral CI users above that of unilateral CI users for spatial hearing was found to be marginal (Laske et al., 2009), or significant (Noble et al., 2008; Summerfield et al., 2006; van Deun et al., 2010). The correlation of their scores with measured localisation is, however, modest (Noble et al., 2008; Van Deun et al. 2010). Such findings are not surprising, given that the SSQ covers a wider range of functions, whereas the behavioural tests only provide a limited sample of ability.

2.6.4 Limitations of bilateral CIs

Although bilateral CI users using both implants have demonstrated improved sound localisation and speech perception in noise ability, they still do not perform as well as normal-hearing listeners. Factors limiting spatial hearing abilities in bilateral CI users fall generally into three main categories: 1) the degeneration in the auditory system due to lack of stimulation, 2) the mismatching of place of stimulation between the two ears and 3) the restricted availability of binaural cues by the current speech processors.

Limitations due to pathology in the auditory system are likely arise from degeneration in both peripheral and central auditory systems, due to lack of stimulation (Shepherd and McCreery, 2006). A prolonged period of auditory deprivation can lead to peripheral degeneration in both size and function of spiral ganglion cells (Leake et al., 1999). Given that the auditory cortex is assumed to become mature by 11 to 12 years of age (Moore, 2002), early profound deafness during this period of development might cause a loss of normal tonotopic organisation of the primary auditory cortex (Kral et al., 2009). However, this does not mean that the spatial hearing ability is limited by stimulation of both ears at early years of age. Auditory experience plays an essential role in the processing of binaural cues (Trune, 1982). Once the neural organisation is first established, plasticity of the neurons involved in spatial hearing is known to extend to adulthood, such that the auditory system is capable of any reorganisation of different inputs (Kral et al., 2009).

Evidence from electrophysiological recordings of neural responses to speech also reveals that the longer the duration of auditory deprivation, the longer it takes to learn to benefit from cochlear implantation (Ito et al., 1993; Pelizzone et al., 1991). Ito et al. (1993) found that the activity in the auditory regions of the cortex measured through P1 waveform of nine adults with profound deafness decreased according to the duration of their deafness. Pelizzone et al. (1991) recorded the long latency evoked potential in one bilateral CI adult, where one ear was congenitally deaf and the other had acquired profound deafness at 7 years of age. The evoked potential of a long latency response reflects the activity from the various levels of cortical processing. They found that the evoked response of the acquired deaf ear was comparable to normal hearing. The congenital deaf ear, on the other hand, showed an abnormal recording, suggesting that the central auditory pathway is affected by the duration of auditory deprivation. Although this study was conducted on only one adult, its findings are supported by another study conducted on five CI adults who had at least 6 months experience with CI, where a delayed late latency response was recorded in these adults (Jordan et al., 1997). These adults showed normal latency responses, and this was more pronounced for postlingually deaf adults.

In the non-human literature it has been reported that the auditory system of animals who underwent periods of monaural occlusion during development can actually be reorganised throughout life (Kacelnik et al., 2006). It was found that experience is the main factor in driving plasticity of the binaural hearing system in adult animals, particularly at the level of the auditory cortex (Kacelnik et al., 2006). It is still, however, unknown whether the extent to which the plasticity of neurons extracting ITDs (i.e. MSO neurons) and ILDs (i.e. LSO neurons) is affected by experience. Nevertheless, these results from animals seemed encouraging with regard the role of experience with bilateral CIs. It might be possible that the auditory system of bilateral CIs users can learn, through experience, to make use of altered binaural cues in ways that could improve their spatial hearing abilities. Given that spatial hearing ability of bilateral CI children declined according to age at implantation (Peters et al., 2010; Scherf et al., 2009), it is might be possible that the role of experience may only supported with early stimulation. Grieco-Calub et al. (2008), for example, reported better spatial hearing ability for children who receive bilateral CIs at a young age than that reported for children implanted bilaterally at a later age (Litovsky et al., 2004).

A previous study with direct electrical stimulation has been conducted with the aim to compare performance across CI users with regard to auditory experience following implantation (Litovsky et al., 2010). In this study, bilaterally-synchronised research processors that provide precise ITDs and ILDs directly to a single pair of electrodes were used in order to understand the potential and limitations of electrical stimulation for restoring spatial hearing in bilateral CI users. Litovsky et al. (2010) reported better ITD sensitivity when bilateral CI adults have had access to acoustic cues early in life. In contrast, poorer ITD sensitivity is reported for CI adults with earlier onset of deafness. Sensitivity to ILD, however, was found to be less affected by early deprivation (Litovsky et al., 2010). It is not clear why sensitivity to ILD is less affected by early deprivation than ITD. However, Litovsky et al. (2010), point to the role of potential training and experience. Previous studies on perceptual learning in normal-hearing listeners suggest a greater influence of training and experience on ILD sensitivity than on ITDs (Rowan, 2006; Wright and Fitzgerald, 2001). One might, therefore, expect that bilateral CI users would be able to make a better reorganisation of sensitivity to ILD after a period of auditory experience than for ITD. However, given that clinical speech processors preserve ILD more accurately than ITD, it seems that the bilateral CI users are trained in their everyday life with ILDs, but not ITDs.

Although the above studies highlighted the considerable effect of experience on the plasticity of the auditory system, it is still not clear whether plasticity can adapt to interaural differences introduced by the lack matching of inputs at the two ears. Difference in either anatomical positioning of electrode array in the cochlea and/or the insertion depth of electrode arrays between ears might result in differences in the place of stimulation across ears. Given the tonotopic organisation of the cochlea and cross-correlation models of spatial hearing, mismatch in the stimulation place at the two ears may mean that ITDs and ILDs in a certain frequency channel are delivered to non-corresponding places in the two cochleae (Long et al., 2006). Colburn et al. (2006) reported that the ability of normal-hearing listeners to detect ITD and ILD can actually be impaired when the signals at each ear differ in frequency. With direct stimulation to a pair of electrodes, it was found that the sensitivity to ITD increases with decreasing mismatch in placement between the two ears (Poon et al., 2009), such that highest sensitivity occurred nearest the pitch-matched pair (Long et al., 2006; Poon et al., 2009). Long et al. (2006) suggest that ITD sensitivity is only affected by place mismatches of above 2 millimetre (mm) interaural range along the cochlea. Sensitivity to ILDs, on the other hand, was found to be not significantly reduced with increasing mismatch in placement between the two ears less (Kan and Litovsky, 2014). There is ample evident that the plasticity can adapt to shifts in pitch in CI adults (Reiss et al., 2007). However, it remains unclear whether the plasticity can also adapt to shifts in place of stimulation.

Another factor limiting the performance of bilateral CI users is the restricted availability of binaural cues by the current speech processors. As mentioned earlier, the ITDs in the fine structure are discarded by the speech processing strategies in clinical CI processors. Although the ITDs in the envelopes are presented by the CI processors, this provides rather variable and unreliable cues for spatial hearing, because the processors have independent sampling clocks (van Hoesel, 2004). The accuracy with which ILDs are represented in the signal delivered by bilateral CIs is limited by the asymmetric activation of AGCs and compression settings. Sensitivity to binaural cues with bilateral CIs is further reduced by the mismatch in place of stimulation between the two ears. The effect of such limitations on ITD and ILD sensitivity was also examined using direct stimulation at a single pair of electrodes. Early studies demonstrated that electrical stimulation at both ears could lead to a single fused auditory precept, indicating an ability of bilateral CI users to make use of ITD and/or ILD cues (Lawson et al., 1998; van Hoesel and Clark, 1997). While lateralisation of the single percept could be affected by ILD, lateralisation of ITD was more variable and largely dependent on the place and rate of stimulation in both ears

(Lawson et al., 1998; van Hoesel and Clark, 1997). ILD sensitivity of about 0.17 to 1 dB was reported with direct stimulation (Litovsky et al., 2010; van Hoesel, 2007). Sensitivity to ITD, on the other hand, typically ranged from 50 µ to about 500 µ (van Hoesel, 2007). Sensitivity to ITD was found to decrease with increasing mismatch in placement between the two ears (Poon et al., 2009) and/or increasing stimulation rate (van Hoesel et al., 2008). Sensitivity to ITD was found to decrease at a higher stimulation rate (Lawson et al. 1998; van Hoesel, 2007), although this higher rate is needed to improve speech perception (Loizou et al., 2009). The trend in decreased ITD sensitivity with increase in stimulation rate is likely to result from the greater spread of current along the cochlea (van Hoesel, 2012). Although few strategies with a mix of rates of stimulation have been considered (van Hoesel, 2007), they, however, did not provide significant benefit, possibly due to the effect of mismatch in the place of stimulation at the two ears (Kan and Litovsky, 2014).

Other studies measured binaural masking level difference (BMLD) in bilateral CI users in an attempt to understand the perceptual mechanisms that enable bilateral CI users to detect and understand speech in noise. BMLD refers to the difference in thresholds for the diotic condition (signal and noise are same to both ears) and dichotic condition (phase-reversal of the signal at one ear). With a directly stimulated single pair of electrodes, a substantially larger BMLD of about 9 dB was recorded for adults (Long et al., 2006) and 6.4 dB for children (Van Deun et al., 2009) when shifting the phase of a 125 Hz sinusoid (ITD=4 ms) in narrowband (50 Hz) diotic noise. These BMLDs are within the range of BMLDs seen in normal-hearing listeners. Long et al. (2006) attributed the larger BMLD to the slow envelope fluctuations below 50 Hz. Recent studies by Lu et al. (2011) and Van Deun et al. (2011) reported, however, a much smaller BMLD of only a few dB when additional masking noise is presented to nearby electrodes. Similarly, binaural intelligibility level difference of speech interaurally delayed by 700 µs in broadband noise has not yet been demonstrated in bilateral CI users (van Hoesel et al., 2008). The findings of van Hoesel et al. (2008), Lu et al. (2011) and Van Deun et al. (2011) are likely to be due to the spread of current and channel interactions that are known in CIs, which may reduce sensitivity to binaural cues on adjacent electrodes.

Nevertheless, the findings of Long et al. (2006) and van Deun et al. (2009) are encouraging, as they show that: 1) binaural hearing can be accessed through bilateral CIs, 2) bilateral CI users can benefit from a phase delay in the envelope and that the absence of fine structure information does not seem to preclude binaural hearing and 3) possible potential benefits might be achieved when the processing between the two implants is synchronised and when the same acoustic frequency stimulates matched electrodes in the two ears. The next section reviews the principal benefits of synchronising the processing between the two implants.

2.6.5 Potential benefits of synchronised processing between two CIs

Synchronising the processing between the two ears could, in principle, deliver a more accurate representation of binaural cues than the traditional processors which are independent at the two ears. Given that the fine structure ITD cues are discarded by the current speech processing strategies, the use of synchronised stimulation between the two ears might only be of benefit for envelope ITDs and ILDs. As noted in the previous section, the use of unsynchronised sampling clocks in the two ears leads to variable and unreliable envelope ITD cues for spatial hearing. One might expect that synchronising the processing between two ears may improve sensitivity to ITD in the envelope. However, this may not be the case given the fact that the bilateral CI users already assigned little weight to envelope ITDs. Previous studies have demonstrated that bilateral CI users, including those who showed close to normal envelope ITD thresholds, weighted envelope ITDs low, and relied on ILDs for spatial hearing (Grantham et al., 2007; Seeber and Fastl, 2008). The small weight of envelope ITDs for localisation has also been reported for normal-hearing listeners. Localisation ability of normal-hearing listeners is strongly dominated by fine structure ITD for sounds containing low frequencies (Smith et al., 2002). For sounds without low frequencies, it has been demonstrated that ILDs on high-frequency sounds dominate localisation performance with little or no contribution of envelope ITDs (Macpherson and Middlebrooks, 2002). Although the results of Long (2006) indicate that bilateral CI users can exploit ITDs in the envelope, this effect was only apparent at the level of a single pair of electrodes.

It is possible that a great benefit from synchronisation in stimulation can be obtained when the fine structure ITDs are encoded by the CI signal processing strategies. However, van Hoesel (2004) reported only small BMLDs of about 1.5 to 2 dB when shifting the phase of a 500 Hz sinusoid (ITD=1 ms) in narrowband (500 Hz) diotic noise, even when using a research strategy which preserves fine structure ITDs (Peak Derived Timing, PDT). In addition, previous studies with direct stimulation to a single pair of electrodes have demonstrated that the sensitivity of bilateral CI users to ITDs was typically not reliable and greatly dependent on the place and rate of stimulation in each ear (Poon et al., 2009; van Hoesel, 2007). The fact that the binaural intelligibility level difference of speech has not been demonstrated in bilateral CI users to date (van Hoesel et al., 2008) may highlight the role of channel interactions from the spread of current when multiple electrodes are stimulated with speech. Indeed, Lu et al. (2011) and Van Deun et al. (2011) reported that the BMLDs substantially reduced from 9 dB to only a few dB after the inclusion of adjacent electrodes. Lu et al. (2011) also reported the BMLD was significantly and negatively correated with the degree of channel interactions as estimated from auditory nerve evoked potentials. Taken together, findings of the above studies highlight the importance of stimulating similar places along the cochlea with the same acoustic frequency information using the most appropriate stimulation rates and the role of channel interaction in manifestation the BMLDs. If the above issues are considered for the engineering of CI signal processors, the use of synchronised stimulation between the two ears might be of full benefit for ITDs.

With regard to ILDs, asymmetric activation of non-linear processing, such as AGC and compression between two ears, may affect ILD sensitivity for bilateral CI users (van Hoesel, 2002). Although Bauer et al. (1966) reported that the auditory system might adapt to altered ILDs introduced by the mismatched loudness between the two ears, there is no such evidence with regard to the asymmetric activation of non-linear processing. A better ILD sensitivity could be achieved if the processing of the AGC and compression settings between the two ears were synchronised. There is some evidence to suggest that the synchronised processing between the two ears might be of benefit for bilateral CI users. Studies with direct stimulation showed that ILD sensitivity of bilateral CI users was typically less than 1 dB, and that it is not significantly different as a function of mismatch in place of stimulation between ears (Kan and Litovsky, 2014; Litovsky et al., 2010; Poon et al., 2009). Grantham et al. (2008) also reported better ILD thresholds when AGCs are disabled compared to when they are activated, due to the random ILDs introduced by asymmetrical compressions. Evidence from hearing aid literature also supports the benefit of synchronisation of processing between ears for ILDs. It has been demonstrated that that synchronising the compressions at the two ears, through a wireless communications link, may improve spatial hearing ability for bilateral hearing aid users. Two previous studies by Kreisman et al. (2010) and Sockalingam et al. (2009) assessed spatial hearing ability with wirelessly linking the processing at the two ears including volume controls, signal processing such as noise reduction and compressions. Kreisman et al. (2010) and Sockalingam et al. (2009) both reported better performance with linked compression than unlinked compression with regard to sound quality, localisation and speech perception. Schum and Hansen (2007) measured the ILDs from Knowles Electronics Manikin for Acoustic Research (KEMAR) with bilateral hearing aids for noise presented at 90° and reported significantly larger ILDs with synchronised compressions (mean ILD= 6.5 dB) than with independent compressions (mean ILD= 2.5 dB). Taken together with the fact that bilateral CI users relied on the ILDs for spatial hearing, it appears that the use of synchronisation in processing between the two ears can be of benefit for ILDs.

2.6.6 Progress of synchronised processing with bilateral CIs

In 1998, Lawson and colleagues assessed the benefits that could be obtained by using synchronised processors under the control of a single speech processor. They reported that a bilateral CI user was able to detect ITDs as small as 150 µs for single pairs of electrodes. The CI user was also able to identify the ear receiving the louder stimulus for the smallest differences in level available from her implanted device. Although the ITD sensitivity of the bilateral CI user was still poorer than that determined in normal-hearing listeners, it shows that technical issues related to the independent processing of two speech processors are restricting the binaural benefits in CI users, and that controlling bilateral electrode arrays by a single processor might enhance ITD and ILD sensitivity.

The concept of controlling two electrodes by a single processor was applied recently in a new bilateral CI system, called Digisonic® SP Binaural (DSPB) implants. This system aims to improve binaural cues, and thus hearing, through synchronised processing of the acoustical inputs using a single speech processor and two microphones linked via a connection cable (Figure 2.12). In such a system, the speech processor receives signals from both microphones and then processes it simultaneously in two signal processing lines. Information from the right microphone is then sent to the right electrode array and the information from the left microphone is sent to the left electrode array. Each electrode array comprises 12 active electrodes along the cochlea. Unlike the standard bilateral CIs, where the stimulation is performed within a single electrode array, the synchronised CI system uses a sequential stimulation between the two electrode arrays, such that stimulation is performed from electrode EL of the ipsilateral electrode array to electrode EL+1 of the contralateral electrode array. It works as if the device was made of a single electrode array comprising 24 electrodes, where odd electrodes (EL1, EL3,…,EL23) correspond to the 12 electrodes of the ipsilateral electrode array and even electrodes (EL2, EL4,…,EL24) correspond to the 12 electrodes of the contralateral electrode array. This system uses Main Peak Interleaved Sampling (MPIS) strategy which combines peak extraction (i.e. *n*-of-*m*) and sequential stimulation (i.e. CIS). The stimulation is timed synchronously at a fixed time of about 15 µs (Figure 2.12).

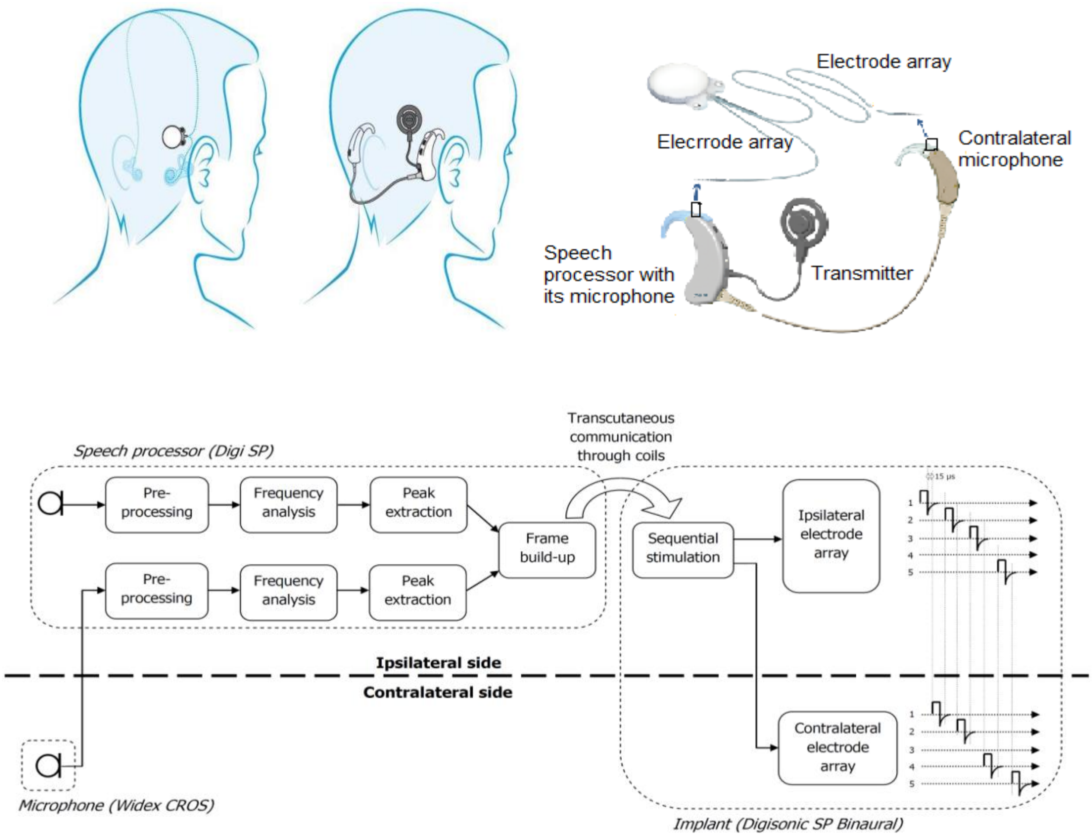


Figure 2.12: Schematic illustration of the synchronised bilateral CIs system (upper panel) and the speech processing and the electrical stimulation with that system (lower panel).

Given the way that the processing between the two ears is synchronised in this new bilateral CI system, it is unlikely that this system would provide more benefits for bilateral CI users than the conventional processors which are independent at the two ears. Although the speech processor in this system processes the sounds from both ears synchronously in time, it still processes the sound from each ear independently in two signal processing lines. This means that the compressions in the two signal processing lines, for example, will be processed independently, similar to that with the conventional bilateral CIs. As with synchronised bilateral hearing aids, a synchronised system in which the input received at one ear is shared with the other ear is needed to better ILD sensitivity. With regard to ITDs, there is also unlikely to be benefit with the new system over the conventional CIs. The random envelope ITD experienced with two independent processors is replaced with a fixed ITD, and most importantly, the fine structure ITD is also not encoded by this system. Although one might expect that synchronising the pulses between two ears may maintain envelope ITDs more accurately, this may, however, not lead to an expectation of better performance with this system, given that it appears the bilateral CI users already assign little weight to envelope ITDs (Grantham et al., 2007; Seeber and Fastl, 2008). Taken together, this system of bilateral CIs seems unlikely to provide benefits for spatial hearing over the traditional bilateral CIs.

At the start of this research project and to this researcher's knowledge, no study has been conducted on spatial hearing with such a CI system. As will be pointed out in the introductory sections of Chapters 7 and 8, two recent studies measured sound localisation and speech perception in noise with the users of the synchronised CI system (Bonnard et al., 2013; Verhaert et al., 2012). These studies reported that adults with synchronised bilateral CIs performed similarly to users of conventional bilateral CIs on sound-source localisation and speech perception in noise. Although these findings may support the theoretical considerations mentioned earlier, there are several limitations with these studies that may have influenced their conclusions. Table 2.5 summarises the results as well as the limitations of these studies. One main limitation of the two studies is that, as with most localisation studies, the way the localisation data of their subjects was analysed seems inappropriate. Neither study took into account the chance range, assuming the appropriate guessing behaviours (see Section 2.6.1 for more details). It is, therefore, not clear whether the synchronised bilateral CI subjects can localise sounds at better than expected from guessing. It is also not clear whether the localisation ability by the synchronised bilateral CIs subjects was based on binaural or monaural cues, given that level of the stimulus was kept constant in their studies. As mentioned in Section 2.6.1, there were a few unilateral CI users who could localise sounds at better than chance, based solely on the use of monaural cues (Grantham et al. 2008; Nava et al. 2009). It is, therefore, of great interest to consider whether the ability of users of synchronised bilateral CIs, particularly, to localise sounds is based on binaural cues, rather than monaural cues. With regard to speech perception in noise, neither of the two studies reported SRM. In addition, both studies reported speech perception results as the percentage of correct responses, using a fixed SNR. This may complicate the comparison between the results of the synchronised CI users to those in the published studies on conventional bilateral/unilateral CI users or normal-hearing listeners that have often reported results in terms of dB using an adaptive procedure.

Table 2.5: Results of studies on spatial hearing ability with synchronised bilateral CIs for sound source localisation and speech perception in noise.

Task	Methods	Results	Limitations
Sound-source localisation	**Verhaert et al. (2012)** Set-up: five loudspeakers between +/-90° at 45° intervals. Stimulus: broadband noise fixed at 65 dB SPL.	• Mean RMS with bilateral condition=35°. • Mean RMS with unilateral condition=77.5°.	• Small number of loudspeakers was used with relatively large angular separation between them. • Stimulus level was not roved, so that there is a possibility of the use of monaural level cues. • Data analysis seems insufficient, given that the chance range of the appropriate guessing behaviour was not considered. • The relative role of ITD and ILD cues in such CI system is still not investigated.
	Bonnard et al. (2013) Set-up: as above. Stimulus: word fixed at 60 dB SPL	• Mean RMS with bilateral condition =49.9°	
Speech perception in noise	**Verhaert et al. (2012)** Set-up and stimulus: words presented at 0° azimuth and noise at the side of better ear while listening bilaterally and unilaterally.	• Squelch effect of 13.6%, head shadow of 12.0% and summation of 14.0%	• While binaural benefits are widely reported in terms of dB for CI users, these studies reported the percentage of correct responses. • Fixed SNR was used, though the adaptive SNR is known to have advantage over the fixed SNR. • SRM was not reported.
	Bonnard et al. (2013) Set-up and stimulus: words at 0° azimuth and noise was presented simultaneously from five loudspeakers at -90°, -45°, 0°, 45° and +90°.	• The percentage of correct words=55.7%	

2.7 Research objectives

Bilateral cochlear implantation can lead to better ability to localise sources of sounds in the horizontal plane and to better perceive speech in the presence of background noise. This ability is, however, still worse than that of normal-hearing listeners. The discrepancy between bilateral CI users and normal-hearing listeners is thought to partly represent technical limitations in the current speech processors and implants which hinder the perception of ITD and ILD cues. One such limitation is the independent operation of both speech processors. Having two independent and unsynchronised speech processors might introduce differences in processing between the two sides, which distort binaural cues. Evidence from studies with direct stimulation indicates that synchronisation of stimulation at both ears can support binaural hearing for CI users (Lawson et al., 2001; Litovsky et al., 2010; Lu et al., 2010; van Hoesel et al., 2008).

With the aim of improving binaural hearing with bilateral CIs, a new bilateral CI system has been introduced, in which the processing of acoustical inputs from both ears is synchronised by using a single speech processor and two microphones. Prior to starting this project and to this researcher's knowledge, no study on binaural benefits with this kind of cochlear implant has been conducted. However, two studies have been published over the time span of this project (Bonnard et al., 2013; Verhaert et al., 2012). These studies reported that adults with synchronised bilateral CIs performed similarly to users of conventional bilateral CIs on sound localisation and speech perception in noise. However, there are several limitations with these studies that may have influenced their conclusions. For example, the way the localisation data of their subjects were analysed does not help to determine whether the subjects can localise sounds at better than guessing. It is also not clear whether their localisation ability is based on interaural cues or monaural cues introduced by the head shadow, because the level of the stimulus was kept constant and thus they might able to make use of monaural level cues.

The current project, therefore, aims to address the question: do synchronised bilateral CI users experience spatial hearing benefits? Specifically, does the synchronised bilateral CI system provide users with an ability to localise sounds on the horizontal plane, perceive speech in noise and perform in everyday listening situations? Given that few unilateral CI users can localise sounds at better than unbiased guessing (Grantham et al. 2008; Nava et al. 2009), it is of great interest to consider whether the ability of users of synchronised bilateral CIs, particularly, to localise sounds is based on binaural cues, rather than monaural cues. Closely related to this is the additional question: could this form of synchronisation provide further advantages in spatial hearing ability over conventional bilateral CIs? It is important to verify whether the bilateral synchronisation of auditory inputs with this CI system can provide any advantages in clinical practice.

Given that the current policy in the UK is to offer only a single CI for severely-to-profoundly deaf adults and that the synchronised bilateral CIs stimulate both ears for the cost of one implant, the finding of this research may have relevance to clinical populations on whether synchronised bilateral CIs can be considered an alternative option for deaf adults.

The aims of this thesis are, therefore, to:

1. Design a suitable methodology for investigating spatial hearing abilities of hearing-impaired listeners, particularly CI users.

2. Gain insights into some problems associated with the localisation data analysis and their implications for interpretation of results.

3. Explore spatial benefits that might be provided by the synchronised bilateral CIs through three tasks: sound-source localisation, speech perception in noise and self-report questionnaire.

4. Evaluate the relative contribution of ITD and ILD in sound localisation and speech perception of synchronised bilateral CI users.

5. Determine whether the spatial benefits associated with the synchronised bilateral CIs are based on binaural cues, rather than monaural cues. In other words, whether they provide any advantages over unilateral CIs.

6. Compare spatial benefits with the synchronised bilateral CIs to those reported previously from conventional bilateral CIs.

Chapter 3: General Methods

3.1 Introduction

The first aim of the project was to design a suitable methodology for investigating spatial hearing abilities of hearing-impaired listeners, particularly cochlear implant (CI) users. In the present study, spatial hearing benefits were investigated in three domains: horizontal sound-source localisation, speech perception in noise and the subjects' own report of functions in daily life.

Sound-source localisation on the horizontal plane was measured by presenting signals from different locations in the free field. The contribution of interaural time and level differences (ITD and ILD) to sound localisation performance was also investigated by examining localisation ability with signals containing either mainly ITD or ILD cues, respectively. Previous studies have investigated the effect of stimuli on localisation performance with bilateral CIs. Grantham et al. (2007) and Seeber and Fastl (2008), for example, assessed localisation performance of bilateral CI users with low-pass noise, slow-onset noise and high-pass noise in order to examine the relative contribution of fine structure ITD, envelope ITD and ILD cues, respectively. In a study conducted in our laboratory by Verschuur et al. (2005), the relative contribution of ITD and ILD cues in localisation was also examined. However, on examining the methodology used in Verschuur et al.'s study, it was found that the proposed stimuli did not well characterise the role of ITD and ILD cues in localisation. The stimuli used previously in our laboratory consisted of noise or tone bursts that provided a combination of ITD and ILD cues, and thus the relative contribution of either ITD or ILD cues could not be well determined. To address this limitation, different stimuli were developed in an attempt to better characterise of the role of ITD and ILD cues.

The effects of spatial separation of target speech and interfering noise for speech perception were also investigated. The speech material needed to 1) be familiar and suitable for all participants, 2) be used without measuring learning effect, and 3) enable differences in performance that result from binaural benefit to be detected. Speech materials typically used in the UK such as the Bamford-Kowal-Bench (BKB) or Automated Toy Test (ATT) were deemed not well-suited to use in the current project (see Section 3.4.2). The Telephone Triple Digits Test (TDT) was therefore chosen to measure spatial speech perception benefits for CI adults in the current research project. These benefits were determined using an adaptive procedure for estimating unilateral and bilateral speech perception thresholds (SRTs) for different spatial configurations of speech and noise.

In addition to the SRT measurements, listening effort, which refers to the attention and cognitive resources required to understand speech, was also estimated in the current project. It is well known that a significant amount of speech understanding involves cognitive processes (Fraser et al., 2010) and therefore listening effort might need to be considered as an important variable when qualifying the possible benefits of spatially separated speech and noise. Previous studies showed that listening with two ears can potentially provide listeners with more ease of listening (Dunn et al., 2011; Noble et al., 2008). Dunn et al. (2011), for example, found that bilateral CI users had better speech perception thresholds (SRTs) than the unilateral CI users while attending to other simultaneous tasks, such as when visual input was added. Noble et al. (2008) also reported a significantly lower self-rated listening effort for bilateral CI users than for unilateral CI users. Both studies concluded that listening with two CIs might possibly help to separate the attention between speech and noise. It has also been previously reported that much more listening effort is required to understand speech when the auditory environment is complex (Koelewijn et al., 2015 and 2012; Zekveld et al., 2011). Koelewijn et al. (2012), for example, reported much more listening effort, as measured through pupil dilation and a subjective scale, for perceiving speech in the presence of another talker than in the presence of stationary noise. The additional listening effort for speech perception in a single-talker masker has been interpreted to be due to the effect of informational masking (Koelewijn et al., 2012). Given that the amount of informational masking generally tends to be reduced for spatially separated target speech and masker noise (Colburn et al., 2006), the above results may also suggest that the listening effort required to understand speech for spatially separated speech and noise might be lower than for co-located speech and noise. Therefore, the listening effort was taken into consideration in the current project when determining the possible benefits of spatially separated speech and noise.

Functioning in daily life was also examined through a self-report questionnaire. The Speech, Spatial and Qualities of Hearing Scale (SSQ) (Gatehouse and Noble, 2004) was used to gain richer information regarding the functioning of CI users across a wide range of functions in real-world situations. Outcomes from such a questionnaire were intended to investigate how the CI users were coping in everyday life, and how these abilities experienced in everyday life related to their performance on psychoacoustic measures.

This chapter presents a description and justification of the experimental methods and methods of analysis used in all the experiments described in subsequent chapters. Sound-source localisation results for normal-hearing listeners are presented in Chapter 4, for unilateral CI users in Chapter 6, and for synchronised bilateral CI users in Chapter

7. Benefits for speech perception in noise are presented for normal-hearing listeners in Chapter 5 and for both unilateral and synchronised bilateral CI users in Chapter 8. Outcomes derived from the SSQ are described in Chapter 9 for unilateral and synchronised bilateral CI users as well as normal-hearing listeners.

3.2 General Methods

Testing was performed in a small anechoic chamber of the Institute of Sound and Vibration Research at the University of Southampton; the dimensions of the chamber were 4.5 metres (m) wide, 4.5 m long and 3 m high. The walls, floor and ceiling of the chamber were covered with open-celled foams, which eliminated reflections above 250 Hz. The chamber had an A-weighted ambient background noise level of 17 dB. A closed-circuit television (CCTV) with a microphone was placed in the chamber, thus allowing the monitoring of the participant at all times and passing on to the experimenter any queries or concerns the participant may have had during testing. The experimental set-up in the anechoic chamber is presented in Figure 3.1.

Figure 3.1: Experimental set-up in the anechoic chamber.

3.3 Outcome measure 1: Sound-source localisation

3.3.1 Setup

Localisation abilities were tested using the loudspeaker array shown in Figure 3.1. The array consisted of 11 loudspeakers (Celestion AVS101) placed in a 180° horizontal arc and separated by 18°, with the centre loudspeaker at 0° azimuth. All loudspeakers were 1.5 m from the approximate centre of the head and were at ear height of 1.2 m, which is the approximate height of the ears of a typical adult when seated in a chair. The loudspeakers were designated by a letter, A to K, from left to right. Although the participants' heads were not controlled, a small mirror was placed above the central loudspeaker and participants were instructed to try to keep their head directed towards the mirror in order to minimise head movement. This method was used previously by van Hoesel and Tyler (2003), who used a marker placed on the frontal loudspeaker to minimise head movement.

Loudspeakers were connected to a custom solid-state switchbox driven by an external Sony STR-DB790 amplifier to feed the appropriate loudspeakers. The amplifier was then connected to an external Creative Extigy sound-card and a computer with custom software. The computer and the soundcard together with the switchbox and amplifier were placed in a control room adjacent to the test room (Figure 3.2). A touch screen was placed in front of the participant in the test room and was connected to the computer in the control room. The whole localisation test was managed by the customised software, which was developed by Dr. Mark Lutman[4]. The actual locations of sound sources and the participants' responses were recorded automatically by the software. The testing environment was the same as that used in earlier studies by Buhagiar et al. (2004) and Verschuur et al. (2005).

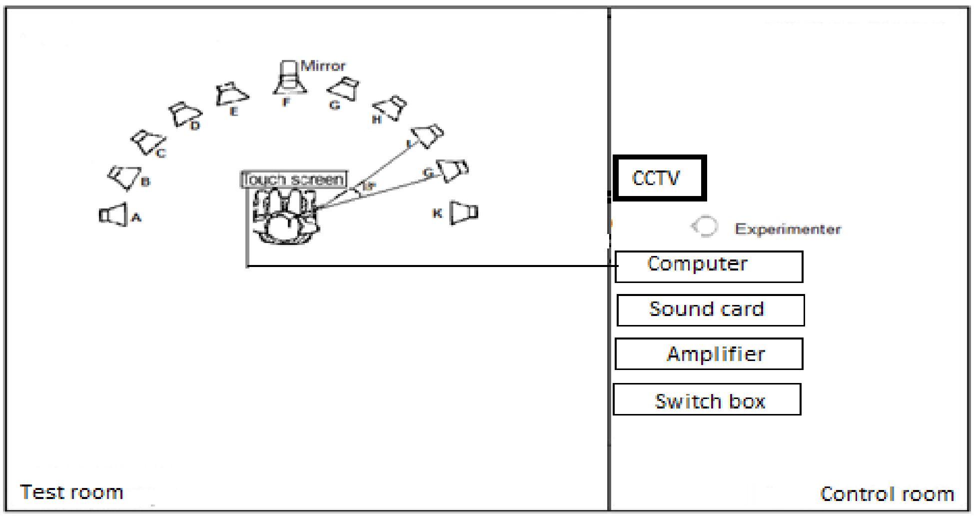


Figure 3.2: Set-up for sound localisation experiment.

[4] The localisation rig used in our laboratory is restricted to playing sound from a single loudspeaker at a time. Adequate temporal synchronisation of sound presentations from several loudspeakers was subsequently not possible.

3.3.2 Stimuli

As mentioned in Section 2.3.1, horizontal localisation in normal-hearing listeners is based primarily on the use of fine structure ITD cues for signals below about 770 Hz and ILDs for higher frequency signals (Moore, 1995). In CI users, the fine structure ITD cues are discarded by the signal processing strategies that are commonly used in CIs, and therefore, the ITDs in the envelopes of signals should be considered.

In order to gain an insight into the relative contribution of ITDs and ILDs in localisation performance, different stimuli with different combinations of binaural cues were used. Broadband stimuli, namely speech and pink noise, were used in this project to allow both ITD and ILD cues to be used. The same stimuli have been used previously in our laboratory with normal-hearing listeners and hearing aid users (e.g. Lutman and Payne, 2002) and CI users (e.g. Buhagiar et al., 2004; Verschuur et al., 2005). The speech stimulus was a one-second sample of a male voice saying the sentence ‘’Where do I speak from’’. The pink noise, on the other hand, consists of four 150 millisecond (ms) pink noise pulses (0.25 to 10 kHz) with 10 ms rise-fall times, and a 50 ms inter-pulse interval. Both speech and pink noise stimuli include strong ITD and ILD cues as well as spectral cues. They also provide a link to the existing literature. Other added values of the speech stimulus are the strong presence of envelope ITD cues, and the fact that listeners are familiar with localising speech in their everyday life (i.e. high face validity).

Since the previous stimuli used in our laboratory have only provided a mixture of binaural cues, the role of either ITD or ILD cues in localisation has not been well characterised. This shortcoming was addressed in the present study by creating different stimuli that reduced, in turn, each of the binaural cues: fine structure ITDs, envelope ITDs and ILDs. A description of these stimuli is presented in Table 3.1.

Table 3.1: Characteristics of newly developed stimuli.

Test stimulus	Previous stimuli used in our laboratory	Rationale for change
Low-pass pink noise Pink noise filtered with a low-pass filter at 1 kHz with a slope of 15 dB/octave, and with 10 ms rise-fall times.	**Tone bursts** Four 1 kHz beeps of 500 ms duration with gaps of 500 ms and 40 ms rise-fall times.	• Tone bursts of 1 kHz include ITD cues as well as ITD on envelope onset and offset. • The new low-pass pink noise stimulus puts more emphasis on fine structure ITD cues. It includes strong ITD cues and weak ILD cues.
High-pass pink noise Pink noise filtered with a high-pass filter at 2.5 kHz with a slope of 15 dB/octave, and with 10 ms rise-fall times.		• No stimulus containing mainly ILD cues has been used previously in our laboratory. • The new high-pass pink noise includes strong ILD cues and weak envelope ITD cues.
High-pass pink noise bursts Four pink noise bursts of 10 ms (high pass at 2.5 kHz) with 1 ms rise-fall times and a gap of 190 ms.	**Transient** White noise burst of 10 ms generated though reverberation simulation.	• Transient stimulus includes ITD cues as well as ITD on envelope onset and offset. • The new high-pass pink noise burst stimulus emphasizes ITD on envelope onset and offset.

All stimuli were generated digitally at a sampling rate of 44.1 kHz, using Adobe Audition software. Each stimulus was created as a waveform file and presented from one of the 11 loudspeakers. Stimuli were presented at a nominal listening level, which is 65 dB SPL (A-weighted). The overall level of each stimulus was roved randomly from trial to trail within the range of $\pm$ 4 dB, with the intention to minimise the use of monaural level cues that might provide reliable cues to location (Byrne et al., 1992). The spectral properties of the stimuli were fixed. The spectra of the stimuli are shown in Figure 3.3, which was generated using a Fast Fourier Transform algorithm.

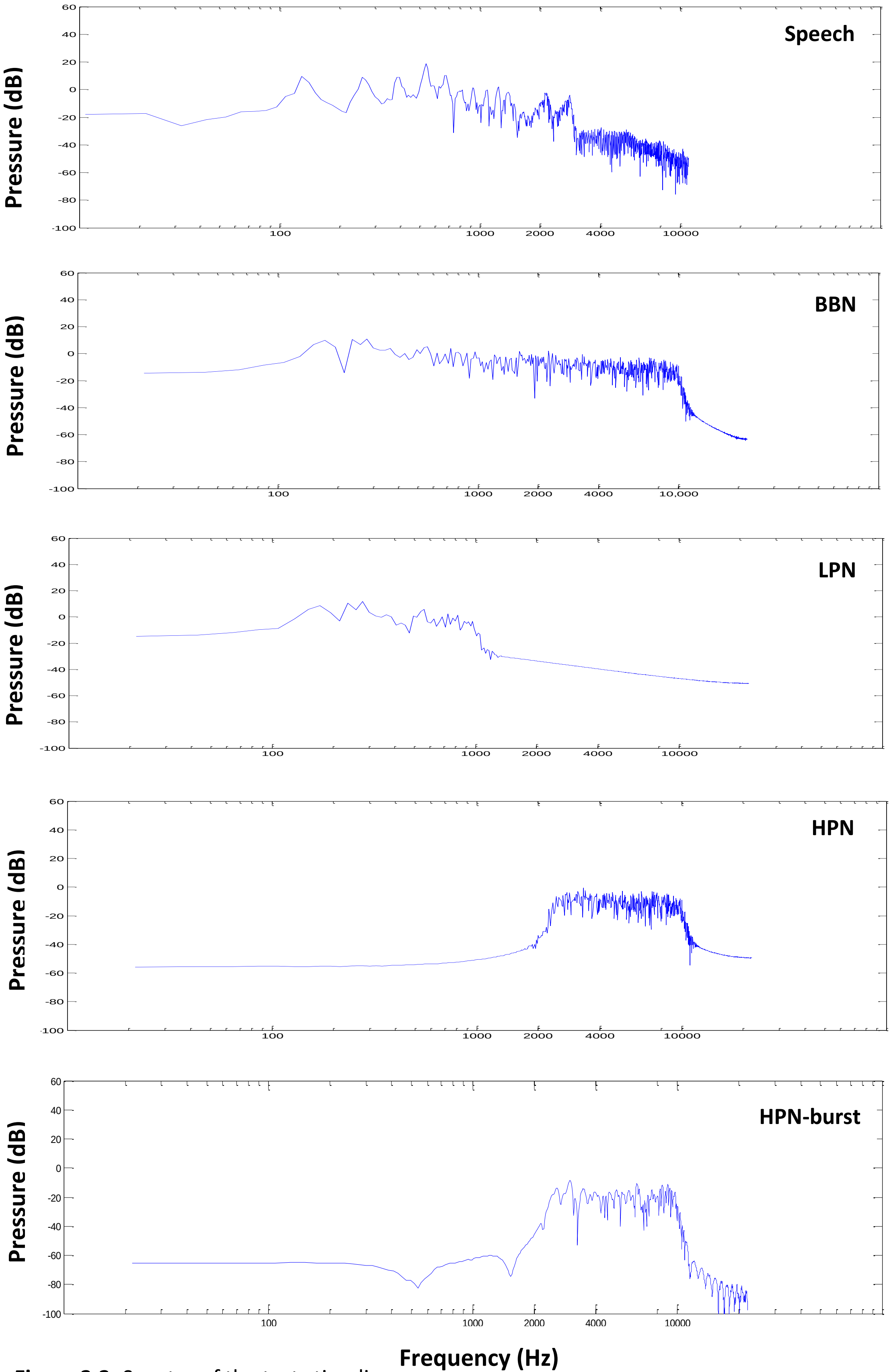


Figure 3.3: Spectra of the test stimuli.

3.3.2.1 Analysis of ITD and ILD cues

The content of ITD and ILD cues in the stimuli used in the current study can be evaluated by means of convolving the test stimuli with a head-related transfer function (HRTF). In this study, the content of ITD and ILD cues in the broadband noise stimulus were evaluated using a set of HRTFs that were previously measured with a microphone placed either in-the-ear at the tympanic membrane (TM) or above-the-ear, like behind-the-ear (BTE) hearing aids at both ears of a human head and torso simulator (Kayser et al., 2009). Evaluating the contents of the ITD and ILD cues at the two different microphone positions would help to evaluate the effect of the CI microphone placement behind the ear on the stimuli for CI users.

The HRTFs that were measured at the Natural Science Campus of the University of Oldenburg were used in the current study, with permission from the publisher. The HRTFs can be downloaded electronically from http://medi.uni-oldenburg.de/hrir/ and a full description of the HRTF database can be found in in the study of Kayser et al. (2009). The current study only used the HRTFs that were recorded in an anechoic chamber and were measured for a distance of 0.8 m between an artificial head and torso simulator and six different azimuths at -90°, -75°, -55°,-35°,-20° and 0°.

Results from the microphones at the TM (solid line) and BTE hearing aid (dashed line) for the different azimuths are shown in Figure 3.4, for the ITD measurement, and Figure 3.5, for the ILD measurement. The ITDs were determined by calculating the delay in cross-correlating the stimulus from both ears. The ILDs were calculated as the difference in the root mean square power between the signals at the both ears.

Figure 3.4 shows that the ITDs are generally larger for the lower frequencies than for higher frequencies, for both the TM and the BTE hearing aid microphone measurements. This result is consistent with other studies, which suggest that ITDs are frequency dependent, where ITDs were found to be larger for low frequencies than for high frequencies (Kuhn, 1977; Wightman and Kistler, 1989). The ITDs measured from TM microphones and the BTE hearing aid microphones are in good accordance, suggesting that the CI microphone placement behind the ear does not affect ITD cues. The ITDs of both the TM and BTE hearing aid measurements increased as the sound source moved from the front (0°) to the side (-90°), although the monotonic ITD increase was less apparent for azimuths beyond about -55°.

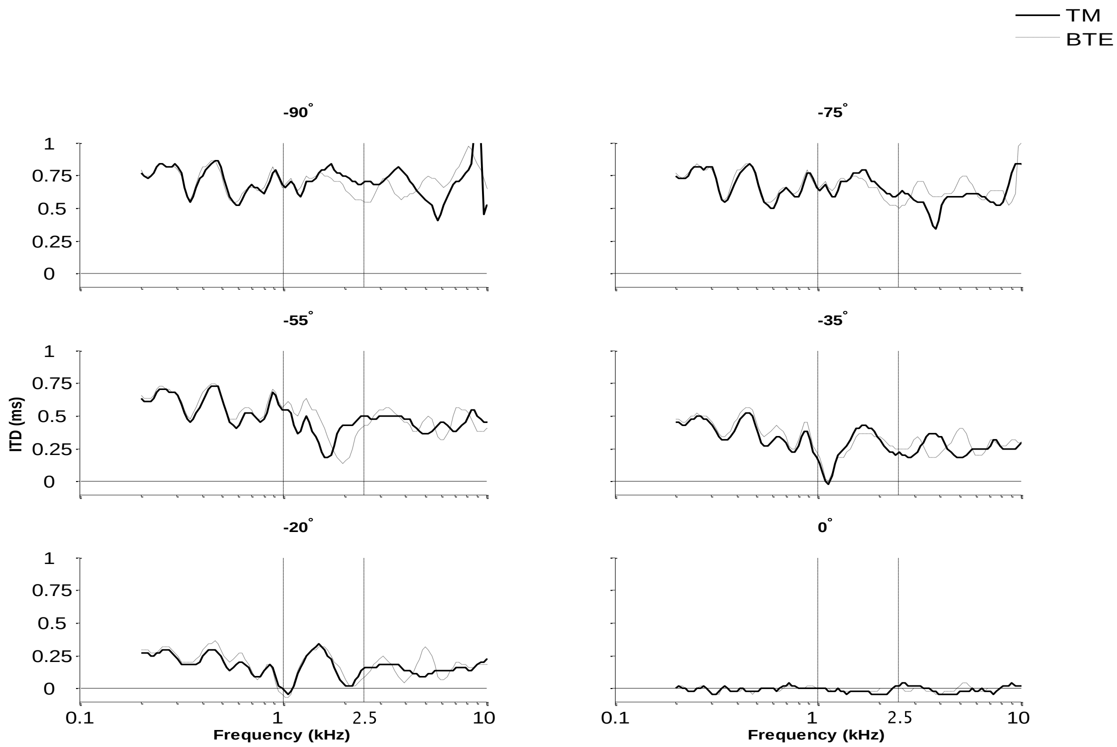


Figure 3.4: ITDs calculated from the HRTFs for the in-the-ear microphones at the tympanic membrane (TM, solid line) and the pair of the behind-the-ear hearing aid microphones (BTE, dashed line) for different azimuth angles from front at 0° to left side -90°. The frequencies of 1 kHz and 2.5 kHz are indicated by the vertical lines.

With regard to the ILDs, Figure 3.5 shows that the ILDs are larger for the higher frequencies than for lower frequencies. This can be explained by the effect of head shadow, which mostly affects frequencies above about 1500 Hz (Moore, 1995). For frequencies lower than 1 kHz, ILDs are generally lower than 5 dB, which seems unlikely to serve as a reliable localisation cue. However, they might provide some information for azimuths between 0° and 55°, where a monotonic increase with azimuth can be observed. For frequencies above 1 kHz, a strong monotonic increase of ILDs with azimuths between 0° and 55° can be observed for both the TM and BTE hearing aid measurements. The measured ILD cues from TM and the BTE hearing aid microphones showed a similar behaviour up to a frequency of about 3 kHz. The ILDs of the higher frequencies, however, were greatly suppressed by the BTE hearing aid microphones' placement, possibly due to the absence of the effects of the pinnae and the ear canals (i.e. spectral cues) that were available for the TM microphone measurements.

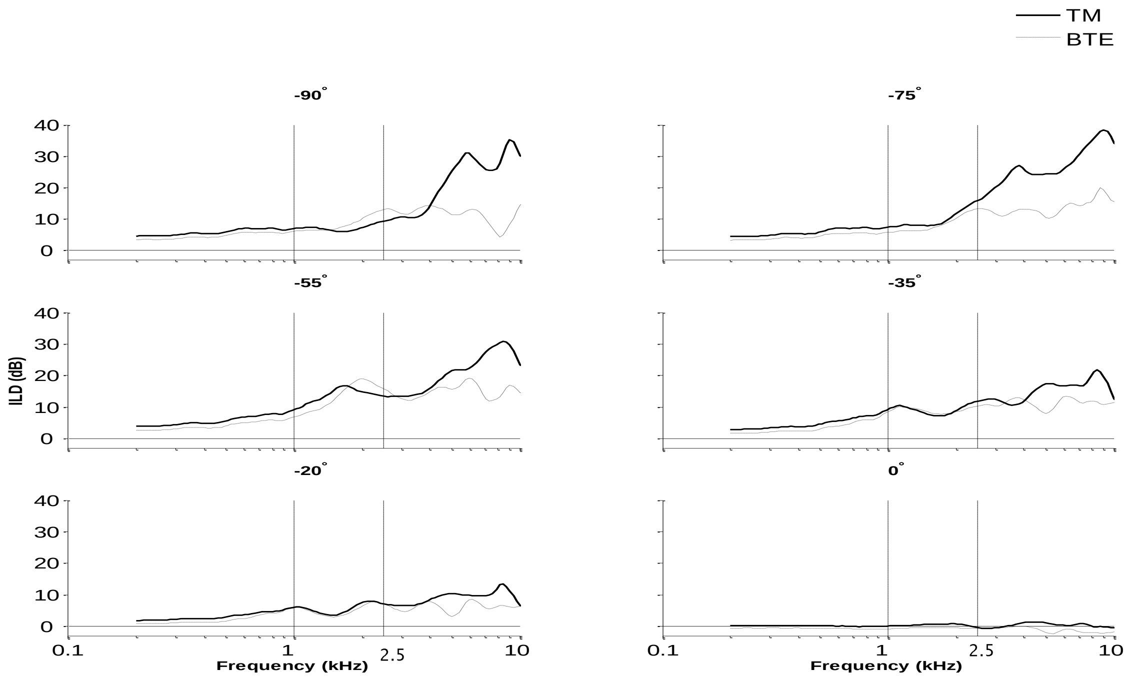


Figure 3.5: ILDs calculated from the HRTFs for the in-the-ear microphones at the tympanic membrane (TM, solid line) and the pair of the behind-the-ear hearing aids microphones (BTE, dashed line) for different azimuth angles from front at 0° to left side -90°. The frequency of 1 kHz and 2.5 kHz are indicated by the vertical lines.

The above analysis generally indicates that it is difficult to have a stimulus that only contains ITDs or ILDs. For frequencies below 1 kHz, a strong ITD cue was available, whereas the ILD cue reached a minimum. The ILDs improved with higher frequencies, whereas the ITDs did not change at higher frequencies. Placing the microphone above-the-ear instead of in-the-ear results in a decrease in ILD of the high frequencies, possibly due to the absence of the pinnae and the ear canal effects.

3.3.3 Calibration

A sound level meter (Brüel and Kjaer 2260) and microphone (Brüel and Kjaer 4189) were used to calibrate the output of the loudspeakers. The sound level meter was set to the frequency weighting (A), fast RMS, and was placed on a tripod in the position of the centre of the participant's head (i.e. the microphone was 1.2 m high and 1.5 m from each loudspeaker). Calibration consisted of the following stages, which were conducted once before the start of the experiment:

1. A calibration noise was generated in Adobe Audition, which consisted of a pink noise burst lasting 30 seconds. This noise was only presented from the central loudspeaker at 0° azimuth. The sound level meter was positioned with the

microphone facing forwards. The sound level of the noise was adjusted via the amplifier volume control until the sound level meter gave a reading of 70 dB (A).

2. The calibration noise was then run through each loudspeaker to ensure that each of the 11 loudspeakers gave an equal sound level. The sound level meter was positioned with the microphone facing upwards. The output of each loudspeaker was recorded using the sound level meter. Software adjustment was then performed, based on the attenuation factors, to enable the outputs of the 11 loudspeakers to be equalised within ±0.5 dB.

3. Each of the above five stimuli was presented from the central loudspeaker. The sound level meter was positioned with the microphone facing forwards. The level of each stimulus was adjusted via the amplifier volume control until the sound level reached 65 dB (A).

It was noticed during calibration that for all stimuli, except speech, an audible hissing noise of 28 dB (A) existed during the inter-pulse intervals of the stimulus. This hissing was still apparent even when the stimuli were listened to through Audible Audition. The only possible source of such distortion was the software-hardware interaction used for this experiment, which is quite old, and it was not possible to do anything about this.

The output of the loudspeakers was also checked on a daily basis, by measuring the sound level of each type of stimulus from the central loudspeaker, while the amplifier volume control was set based on stage 3.

3.3.4 Procedure

During testing, participants were seated in the centre of the array, facing the central loudspeaker, as shown in Figure 3.1. Participants were instructed to keep their heads directed towards the mirror while the stimulus was presented, to minimise head movement. Their head movements were also monitored by the experimenter, via CCTV. The experimenter was seated in the control room and monitored the participants through CCTV.

A run consisted of the presentation of the stimulus 33 times, 3 times from each of the 11 loudspeakers in a random order. Each run used a single stimulus. A complete set of five runs, one run for each stimulus, was conducted for each participant. The order of stimulus was varied between participants to minimise any order effect. After about 5-

10 min break, the five runs were repeated once more, in reverse order. Thus, for each participant and for each stimulus, there were 66 responses.

Participants were instructed to identify the loudspeaker the sound came from, after each stimulus presentation, using a touch screen with an image of the loudspeaker array and clicking on the letter corresponding to the loudspeaker. Participants were instructed to guess if they were unsure of where the sound came from. The response was automatically registered by the testing software. No repeats were allowed and no feedback was given.

Before starting testing, practice trials were presented for each participant, to familiarise the participant with the task. Practice was terminated when the participant was fully familiarised with the task, upon the judgment of the experimenter. Practice typically included speech stimulus presentations from each of the 11 loudspeakers.

3.3.5 Analysis

3.3.5.1 Overall localisation error

Analysis of localisation ability is based on the deviation in degrees between the actual locations of sound sources and locations identified in the responses. Overall localisation error is frequently expressed as either a mean absolute error (MAE) (Searle et al., 1976) or a root mean square error (RMS) (Hartmann, 1983).

The MAE for a particular loudspeaker, K, was calculated as the average of the absolute values of the errors, which are the differences between the actual loudspeaker location of sound source and that identified in the listener's response. The average MAE across all the loudspeaker locations was then calculated for each stimulus (Equation 3.1). The MAE error is often used in our laboratory as a measure of localisation performance for normal-hearing listeners and hearing aid users (e.g. Lutman and Payne, 2002) and CI users (e.g. Buhagiar et al., 2004; Verschuur et al., 2005).

In the RMS error for K loudspeaker, the errors (i.e. differences between the actual loudspeaker location of sound source and that identified in the listener's response) are each squared before being averaged, and then the square root of that average is taken. The average RMS error across all the loudspeaker locations was then calculated for each stimulus, which is labelled by $\overline{D}$ in this thesis (Equation 3.2). The RMS error is widely used to analyse localisation performance (e.g. Grantham et al., 2007; van Hoesel and Tyler, 2003).

$$\mathrm{MAE} = \frac{1}{n}\sum_{k=1}^{n}\left(\frac{\sum_{\mathrm{i}=1}^{T_k}(\,|r_i-k|)}{T_k}\right) \qquad (3.1)$$

$$\overline{\mathrm{D}} = \mathrm{RMS} = \frac{1}{n}\sum_{k=1}^{n}\sqrt{\frac{\sum_{i=1}^{T_k}(r_i-k)^2}{T_k}} \qquad (3.2)$$

where *K* is the particular loudspeaker and there are a total of *n* loudspeakers, r_i is the listener's response to the *i*th trial on which loudspeaker *K* is presented and there are a total of T_k of trials.

Based on Equations 3.1 and 3.2, the RMS error always gives a relatively large weight to large errors, whereas the errors are weighted equally in the average MAE. For this reason, the MAE is considered of greater use with children, so that the large errors that might be attributed to their short instances of inattentiveness would not largely weight their localisation performance. The RMS may be preferred for use with adults, as it better reflects the underlying causes that limit localisation ability of a listener (see the next section for more details).

Previous studies have often compared the MAE or RMS error of an individual to a single value that would be obtained by a subject responding randomly (i.e. chance level). However, the likelihood that an individual error is based on guessing has been largely ignored. Only the studies by Grantham et al. (2007; 2008) have reported a method to achieve this by estimating the 95% confidence range expected from unbiased guessing. Chance performance in this research project was determined by the 99% confidence range expected by a defined model of guessing, using a computer simulation (see Section 4.2).

3.3.5.2 Random error ($\bar{s}$) and constant error ($\bar{C}$)

While the MAE and RMS error are useful in reflecting overall localisation error, they do not provide the underlying causes of that error. Therefore, the following error measures introduced by Hartmann (1983) were also used to describe localisation ability in this project.

The overall $\bar{D}$ error can be partitioned into two components: random error ($\bar{s}$) and unbiased constant error ($\bar{C}$). Random error reflects variability in the listener's responses to a particular sound source and is calculated by computing the standard deviation of the listener's responses to a particular sound source averaged across all loudspeakers (Equation 3.3). Constant error ($\bar{C}$), on the other hand, measures the magnitude of response bias across all loudspeakers. It estimates the RMS deviation of the average response from the actual sound locations (Equation 3.4). The distinction between $\bar{D}$ and $\bar{C}$ is that $\bar{D}$ measures the differences between the listener's responses to a sound source and the actual source location, whereas $\bar{C}$ measures the difference between the listener's average responses and the actual source location.

$$\bar{s} = \frac{1}{n}\sum_{k=1}^{n}\sqrt{\frac{\sum_{i=1}^{T_k}(r_i - R_k)^2}{T_k}} \qquad (3.3)$$

$$\bar{C} = \frac{1}{n}\sum_{k=1}^{n}\sqrt{\frac{\sum_{i=1}^{T_k}(R_k - k)^2}{T_k}} \qquad (3.4)$$

where *K* is the particular loudspeaker and there are a total of *n* loudspeakers, r_i is the listener's response to the *i*th trial on which loudspeaker *K* is presented and there are a total of T_k of trials and $R_k$is the mean response for a given *k* loudspeaker.

The relationship between these measures can be defined as:

$$\bar{D}^2 = \bar{C}^2 + \bar{s}^2 \qquad (3.5)$$

Another useful measure is the signed constant error ($\bar{E}$), which indicates the side of the overall bias to the right or the left. The signed constant error can be calculated by taking the arithmetic average of the signed deviation of the mean responses from the actual locations (Equation 3.6).

$$\bar{E} = \frac{1}{n}\sum_{k=1}^{n}\left(\frac{\sum_{i=1}^{T_k}(R_k - k)}{T_k}\right) \qquad (3.6)$$

where *K* is the particular loudspeaker from a total of *n* loudspeakers, R_k is the mean response for a given *k* loudspeaker and T_k is the number of presented trials.

For each participant and for each stimulus, the errors, including overall error (MAE and $\bar{D}$ error), random errors ($\bar{s}$), and the unsigned and signed constant error ($\bar{C}$ and $\bar{E}$) were all reported across all the 11 loudspeakers.

3.4 Outcome measure 2: Speech perception in noise

3.4.1 Setup

Part of the hardware used in this experiment was the same as that for the localisation experiment: a laptop with custom-made MATLAB software and an external Creative Extigy sound-card were connected to three loudspeakers (Celestion AVS101) at 0°, +90° and -90°, via a small switch box. The level of the stimulus was controlled through an Ariston AX-910 amplifier. The touch screen was placed in front of the participant in the test room and was connected to the laptop in the control room, such that the experimenter could control the test from the control room.

3.4.2 Stimuli

Stimuli used in this project consisted of target speech and masker noise. Targets were the Telephone Triple Digits Test (TDT). The TDT is based on the English Number Perception in Noise test developed by Hall (2006). It involves digits from 0 (pronounced 'oh') to 9, with the exclusion of number 7, as it has two syllables, being played to the participant in sets of triplets. The masker was steady white noise that had the same long-term average spectrum as the digits (Figure 3.6).

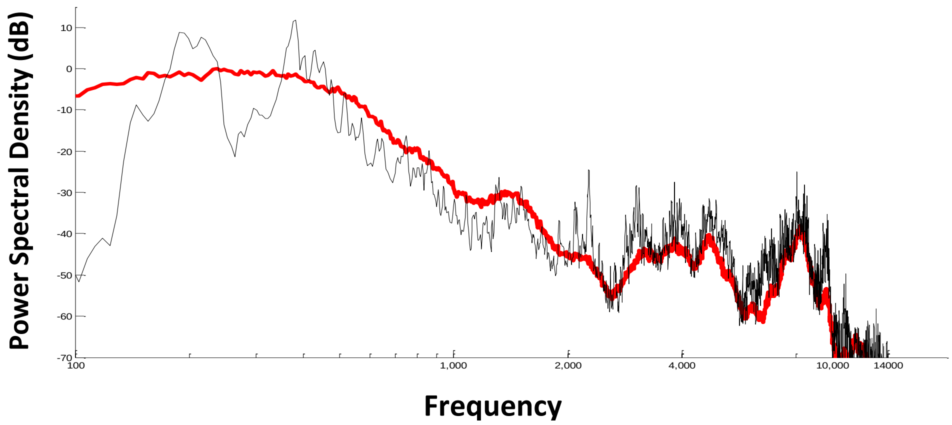


Figure 3.6: The spectra of the long-term average speech spectrum of the TDT (black line) and the speech-shaped noise (red line).

The main reason for choosing this particular speech test was its suitability for all users of the synchronised bilateral CIs. Some adults with the synchronised bilateral CIs had scores of less than 70% for testing in quiet using Bamford-Kowal-Bench (BKB) sentences, meaning that they were not able to undertake BKB testing in noise. The Automated Toy Test (ATT) was also deemed not as well-suited to the CI adults as the TDT. Another added value of the TDT is that it does not require good English to perform the test, and therefore, can be readily administered for non-native English listeners.

Targets were presented nominally at a level of 65 dB SPL (A-weighted), so that the level of presentation was similar for both localisation and speech perception tasks. The level of noise was varied adaptively using a standard adaptive procedure (see Section 3.4.4). One advantage of the adaptive procedure over the fixed signal to noise ratio (SNR) is that the adaptive procedure is targeting the predetermined performance level on the psychometric function and thus avoiding the occurrence of ‘‘ceiling’’ and ‘‘floor’’ effects that may occur if a fixed SNR is used (Leek, 2001; Liu and Eddins, 2012). The level of targets rather than the noise was fixed here, in order to make the test easier for CI users. All stimuli were generated digitally at a sampling rate of 44.1 kHz that was used also for the localisation task. The MATLAB code was written by Dr Daniel Rowan.

3.4.3 Calibration

The noise was calibrated daily at a level of 65 dB (A) by placing the sound level meter as described in Section 3.3.3 and checking its reading when playing the noise from the central loudspeaker. Also with this experiment, a hissing noise of 21.6 dB (A) from the loudspeakers was noticed when no speech or noise were played during test. No compensation, however, was made for that.

3.4.4 Procedure

During testing, participants were seated in the centre of the array, facing the central loudspeaker. Participants were instructed to keep their heads directed towards the mirror while the stimulus was presented to minimise head movement. Their head movements were also monitored by the experimenter via CCTV. The experimenter was seated in the control room and monitored the participant through CCTV.

The digits were always presented from the central loudspeaker at 0° azimuth. The noise was played from one of three locations: front (0º, the same loudspeaker as the digits), right (+90º) or left (-90º) of the participant. In each run of trials, noise was presented from one location, so that the location of noise either at 0°, +90° or -90° was fixed during the run. Three runs, one at each noise location, were included within a single block. Three blocks were administered for normal-hearing listeners and only two blocks for CI users, in order to minimise the possibility of the participant being tired at the end of test. A set of 9 runs was completed by normal-hearing listeners and 6 runs by CI users. The above arrangement was tested when listening with both ears for normal-hearing listeners and synchronised bilateral CI users (i.e. bilateral listening mode) and with one ear for unilateral CI users.

It was also necessary to test normal-hearing listeners and synchronised bilateral CI users listening with one ear, in order to measure the spatial benefits for speech perception. Normal-hearing listeners were tested listening with one ear only using the similar arrangement (three blocks, each consisting of three runs). An earplug (E.A.R Soft) and earmuff (Peltor Optime III) were used to block the non-listening ear in the monaural listening mode. The ear canal of either the left or right ear (chosen at random) was plugged and then covered with the muff. The synchronised bilateral CI users were tested listening unilaterally with right CI only and left CI only. For each unilateral listening mode, two blocks were completed, in which each block consisted of two runs, one run when the noise presented at front and the other run when the noise presented at the contralateral side of their activated implant.

Table 3.2 summarises the full measurements for speech perception obtained for the normal-hearing listeners and CI users. After each block, about 5-10 min break was given for each participant. During the break, the participant was engaged in a conversation when switching between listening modes, in order to allow brief acclimatisation to the new listening condition. The order of noise location within each block and listening mode was counterbalanced using the Latin square design.

Table 3.2: Overview of the measurements for speech perception obtained for the normal-hearing listeners, synchronised bilateral CI users and the unilateral CI users.

Noise location	**Normal-hearing listeners**		**Synchronised bilateral CI users**			**Unilateral CI users**
	Both ears	one ear	Both CIs	Right CI	Left CI	
Front (0°)	3	3	2	2	2	2
Right (+90°)	3	3	2	-	2	2
Left (-90°)	3	3	2	2	-	2

Prior to each run, participants were familiarised with the locations of loudspeakers where the digits and the noise would be heard. Participants were instructed to identify all three digits in the triplet and to ignore the noise as much as possible. They were asked to respond by pressing the three keys that correspond to what they heard, in the correct order on the touch screen provided. They were encouraged to guess when they were not sure of what they had heard. Participants' responses were only scored correct if all three digits in the triplet were identified correctly in the same order, and were automatically registered by the testing software. No repeats were allowed and no feedback was given. Before starting testing, practice trials were presented for each participant, to familiarise the participant with the task. Practice, which typically included one run with the noise location at the front, was terminated when the participant was fully familiarised with the task, upon the judgment of the experimenter.

A speech reception threshold (SRT) was determined for each run. The adaptive procedure was used to estimate SRTs. The level of noise was initially presented at 70 dB SPL and continued to increase until the participant responded incorrectly. Subsequent levels were determined following a two-down/one-up adaptive rule where the signal to noise ratio was decreased following two consecutive correct responses and increased following a single incorrect response. The step sizes used were, respectively, 8 dB and 4 dB for the first and second reversals, and 2 dB for the remaining eight reversals. The SRT was calculated based on the average level presented in the last eight reversals, with a theoretical asymptote of 71%.

In addition to the SRT measurements, listening effort, which refers to the attention and cognitive resources required to understand speech, was also considered in this project. It is well known that a significant amount of speech understanding involves cognitive processes (Fraser et al., 2010). Previous studies showed that that listening with two ears might possibly help to separate the attention between speech and noise (Dunn et al., 2011; Noble et al., 2008). This might suggest that the attention necessary to separate speech and noise would be lower for spatially separated speech and noise than for co-locating speech and noise. It is possible that participants might experience less listening effort when speech and noise are spatially separated than when they are co-located. It is therefore important to take into consideration listening effort when determining the possible benefits of spatially separated speech and noise for CI users.

Listening effort was measured using a subjective listening effort scale and objective response time. Participants were asked to rate their listening effort required to understand speech on a scale ranging from 1 (‘‘Extreme effort’’) to 7 (‘‘No effort at all’’). The scale is currently used at the University of Southampton Auditory Implant Service (USAIS) centre, and it is presented in Appendix A.1. The response time required to determine the SRT for each run was also measured based on the calculations implemented in MATLAB code written by Dr Daniel Rowan. Subjects were unaware that the response time was calculated. These measures of listening effort were administered once the SRTs were determined for noise at 0°, +90° or -90° for normal-hearing listeners and synchronised bilateral CI users listening bilaterally and for unilateral CI users. Thus, two measurements of listening effort are obtained for each noise location for CI users, and three measurements for normal-hearing listeners.

3.4.5 Analysis

3.4.5.1 SRTs in noise

For each noise location and listening mode, three SRTs, in dB SNR, were obtained for each of the normal-hearing listeners and two SRTs for each of the CI users. These SRTs for each participant were averaged to give a final SRT for each noise location and listening mode.

3.4.5.2 Spatial benefits

Spatial benefits for speech perception including spatial release from masking (SRM), binaural squelch, head shadow and binaural summation were calculated for each participant. These benefits were measured by comparing SRTs for different noise locations and listening modes, as illustrated in Figure 2.6. A detailed description of these benefits was presented previously in Section 2.3.2.

3.4.5.3 Listening effort benefits

The scores of listening effort and response time for each noise location were first averaged to give a final score and response time for each noise location. The benefit in terms of the listening effort was expressed as the difference in the listening effort required in conditions with spatially separated versus spatially co-located speech and noise. The difference in the score and response time between when speech and noise were co-located and spatially separated was calculated. Positive values indicate lower listening effort (i.e. higher/better listening effort score and faster response time) being required to understand speech when speech and noise were spatially separated (i.e. benefit).

3.5 Outcome measure 3: Self-report questionnaire

Although sound-source localisation and speech perception in noise are used to measure spatial hearing benefits, these measures only reflect limited areas of the benefits and do not necessarily reflect the ability for listening in everyday life situations. Therefore, another way of assessing the benefits, by means of a self-report method, is used. In the self-report method, it is possible to get richer and more predictive information for spatial benefits in real-life situations and more understanding of how participants are coping in everyday life. In addition, it helps to determine to what extent the performance in laboratory tests relates to functioning in everyday life.

A self-report questionnaire, named the Speech, Spatial and Qualities of Hearing Scale (SSQ) (Gatehouse and Noble, 2004) was used. The SSQ covers a wide range of functions, with some emphasis on functions that are assumed to depend on binaural hearing. The SSQ is a 50-item scale that covers three main subscales that measure hearing for speech (14 questions), spatial hearing (17 questions) and qualities of hearing (19 questions). The SSQ was sent in advance to participants to complete prior to testing, in order to ensure that their rating was not affected by their performance on psychoacoustic measures (i.e. sound localisation and speech perception). They were asked to rate their experience in everyday life using a horizontal visual-analogue scale (VAS) on a 10-point scale from 0 (‘‘not at all’’) to 10 (‘‘perfectly’’). The SSQ is included in Appendix A.2.

The scores of each of the three subscales (i.e. speech, spatial and qualities) were averaged for each participant, with higher average value representing greater ability. To gain a better understanding of participants’ functioning in everyday life, the average of a set of smaller subscales, as described by Gatehouse and Akeroyd (2006,) was also reported. The speech subscale was divided into four sections: speech in quiet, speech in noise, speech in speech contexts, and multiple speech-stream processing. The spatial subscale was divided into two sections: localisation, and distance and movement. The qualities subscale was divided into four sections: sound quality and naturalness, identification of sound and objects, segregation of sounds, and listening effort. The assignment of individual SSQ items to each of the smaller subscale labels is given in Table 3.3. The correlations between the self-rated abilities on SSQ and binaural benefits for localisation and speech perception in noise were also calculated.

Table 3.3: The individual SSQ items to each of the subscale labels.

	SSQ subscale label	Contributing items
Speech	Speech in quiet	Speech items 2 and 3
	Speech in noise	Speech items 1, 4, 5 and 6
	Speech in speech contexts	Speech items 7, 8, 9 and 11
	Multiple speech-stream processing and switching	Speech items 10, 12 and 14
Spatial	Localisation	Spatial items 1, 2, 3, 4, 5, 6 and 7
	Distance and movement	Spatial items 8, 9, 10, 11, 12, 13, 15, 16 and 17
Qualities	Sound quality and naturalness	Qualities items 8,9,10,11 and 12
	Identification of sound and objects	Qualities items 4,5,6,7 and 13
	Segregation of sounds	Qualities items 1,2 and 3
	Listening effort	Qualities 14, 18 and 19

3.6 Conclusions

In summary, a full description and justification of the experimental methods and methods of analysis used in this research project were presented. In order to evaluate the above methodology which was designed to assess spatial hearing abilities with CIs, the spatial hearing abilities of normal-hearing listeners were first tested for sound-source localisation (Chapter 4) and speech perception in noise (Chapter 5). The results of normal-hearing listeners were intended to ensure that the above methods produced reasonable results and no further refinements were needed. They were also intended to interpret the results of CI users.

Chapter 4: Reference data on sound-source localisation

4.1 Introduction

One of the main aims of this project was to assess spatial hearing abilities that might be provided by the synchronised bilateral cochlear implants (CIs). Sound-source localisation in the horizontal plane was one of the potential measures of spatial hearing benefits that were used in this project. In this measure, the ability of a listener to identify which loudspeaker, from a surrounding arc of loudspeakers, the sound came from was assessed. As noted in Section 2.2.1, the binaural cues, including interaural time and level differences (ITD and ILD) that underlie humans' ability to localise sounds in the horizontal plane can only be determined through binaural hearing. Thus, bilateral implantation may give users the potential to take advantage of binaural hearing which could improve the ability of CI users to localise sound sources.

Sound-source localisation has been extensively studied with bilateral CI users (e.g. Grantham et al., 2007; Seeber and Fastl, 2008; van Hoesel and Tyler, 2003; Verhaert et al., 2012; Verschuur et al., 2005). All the above studies show significant improvement in localisation performance when using two implants compared with only one. Results from studies that investigated the contribution of binaural cues to localisation with bilateral CI users consistently showed that bilateral CI users predominantly relied on ILD for localisation. Grantham et al. (2007) and Seeber and Fastl (2008), for example, assessed localisation performance of bilateral CI users with low-pass noise, slow-onset noise and high-pass noise in order to examine the relative contribution of fine structure ITD, envelope ITD and ILD cues, respectively. Both studies showed that localisation performance of bilateral CI users was better for high-pass noise than for the others, suggesting the role of ILD in the high-frequency sounds. Verschuur et al. (2005), from our laboratory, also studied the effects of type of stimulus on localisation performance in bilateral CI users. However, they used noise bursts and tone bursts, which seem to provide a combination of ITD and ILD cues. Thus, the relative contribution of either ITD or ILD cues in localisation of bilateral CI users may not have been well characterised. As a result, the research team decided to develop new stimuli with the aim to better characterise of ITD and ILD cues, which were presented in Table 3.1, above. These stimuli were intended to provide better insights into the relative contributions of ITD and ILD to localisation for the synchronised bilateral CI users.

Before assessing localisation performance of CI users with the new stimuli, it was necessary in the first place to ensure that these new stimuli produced what was anticipated from previous studies on normal-hearing listeners. For example, it was established that localisation performance of normal-hearing listeners deteriorates as the bandwidth of the sounds decreases and that localisation performance of high-frequency sounds is worse than low-frequency sounds (Bogaert et al., 2006; Middlebrooks, 1992). This can be explained as being due to the limited availability of ITDs and ILDs and spectral cues in the narrowband sounds compared to the broadband sounds. As the bandwidth of a sound deceases, the opportunity to compare information across frequency bands becomes limited and thus the quantity of available localisation cues decreases. The periodic nature of the pure tones makes phase leads and lags indistinguishable, leading to ambiguity in the interaural phase differences (IPDs), particularly for high frequencies (Wightman and Kistler, 1993). Localisation performance, using the same methodology and stimuli used with CI users, was therefore first assessed with normal-hearing listeners, to ensure that the localisation method of this project did not need any refinements.

It is also necessary to deal with a number of uncertainties in the interpretation of localisation performance that were raised previously in Section 2.6.1. Most localisation studies compared overall localisation error to a chance level, which is calculated, explicitly or implicitly, assuming unbiased guessing. Here, two issues should be taken into consideration when reporting localisation performance. The first issue is that the overall localisation error is often compared to a single value that represents chance level. Comparing the observed localisation ability to a single value might, however, lead to an inappropriate conclusion. Statisticians usually use a range (i.e. confidence interval) in order to differentiate correct scores from chance, and thus a probable range of errors occurring by guessing should be considered when reporting listener's localisation ability.

The second issue is that chance performance is often estimated assuming unbiased guessing. Such an assumption, however, may also lead to an inappropriate conclusion when a different guessing behaviour actually occurs. For example, the responses of a person who is biased in guessing might be treated as actual localisation ability rather than the biased guessing. It is, therefore, necessary to take into consideration the appropriate guessing behaviour of a listener when calculating chance range. Given that the application of the two issues mentioned above has been largely ignored when analysing localisation ability, a computer simulation was performed to clarify the significance of these issues and their impact on the conclusions drawn in the existing literature.

This chapter presents a computer simulation to deal with the chance range expected from different patterns of guessing, including unbiased and biased guessing (Section 4.2). It then presents localisation performance of normal-hearing listeners with different types of stimuli, with the aim of ensuring that the localisation set-up and stimuli used in this project produced reasonable results and that the method did not need any further refinements (Section 4.3). The results from the normal-hearing listeners were also intended to help to interpret the results of the CI users.

4.1.1 Summary of objectives

The objectives of this study were to:

1. Clarify the significance of the two issues raised above with the current interpretation of localisation performance, including chance range (rather than chance level), calculated with the assumption of different patterns of guessing behaviour (rather than just unbiased guessing).

2. Evaluate the methodology designed to assess localisation performance with the synchronised bilateral CIs and ensure that it produced reasonable results.

4.2 Localisation performance analysis: revisited

Several studies have assessed localisation ability by comparing the localisation error of one individual to the value expected from guessing (i.e. chance level). For example, benefits from bilateral implantation have often been investigated by comparing the localisation ability of bilateral CI users listening through both implants to either the ability of those users when listening with only one of the implants (e.g. Grantham et al., 2007; van Hoesel and Tyler, 2003; Verschuur et al., 2005) or to the ability of unilaterally implanted users (Buhagiar et al., 2004; Grantham et al., 2008). The results show significant improvement in localisation performance when using two implants, where the bilateral performance is often better than chance levels. However, the better than chance level shown by the bilateral CI users may not necessary indicate that they can localise sounds, for two reasons.

First, comparing the observed localisation ability to a single value might lead to an inappropriate conclusion. To be more certain that chance is not the basis of observed localisation ability, a probable range of errors occurring by guessing should therefore be calculated. The overall localisation error of an individual needs to be below the chance range in order to be confident, for a given level of confidence, that this error did not reflect guessing. Although the chance range has been reported previously for psychophysical studies (Moulton, 2000), its application in localisation studies has been largely ignored. Only two studies that the researcher is aware of have considered the chance range when analysing localisation ability, where the chance range was estimated as 95% of the errors (Grantham et al., 2007; 2008). However, Grantham et al. (2007; 2008) always assumed unbiased guessing when calculating chance range, which may cause misinterpretation of localisation performance. Assuming unbiased guessing may lead to an inappropriate conclusion when a different guessing behaviour actually occurs. Without considering the appropriate guessing behaviour, the responses of a person who is biased in guessing might, for example, be erroneously treated as actual localisation ability rather than guessing behaviour. This is the second issue that should be taken into consideration when interpreting listener's localisation performance.

To illustrate the second issue, the responses given by a bilateral CI subject from van Hoesel and Tyler (2003) are displayed in Figure 4.1; van Hoesel and Tyler (2003) reported an overall localisation error of about 30° for this subject while listening with the right implant only (chance level for their set-up was 50°). They suggested that the lower overall error achieved by this subject may have resulted from the ability to use monaural spectral and/or level cues. Examination of the pattern of responses given by that subject, however, indicates that the better than chance level by that subject reflects a consistent biased guessing rather than localisation ability. The smaller overall error of 30° reported for the right implant reflects a bias towards the frontal loudspeakers, whereas the larger error of 60°, reported for the left implant reflects a bias towards the left-most loudspeaker. It is therefore necessary to deal with the most appropriate model of guessing behaviour when reporting localisation ability in order to meaningfully interpret localisation error. Alternatively, scores of bias (i.e. constant error) and variability in response (i.e. random error) need to be reported. Given that the overall $\bar{D}$ error is composed of both constant and random errors, scores of such errors are intended to help determine the main reason underlying the overall localisation error. Although Hartmann (1983) introduced all these error measures many years ago, most localisation studies have still ignored the need to use such errors.

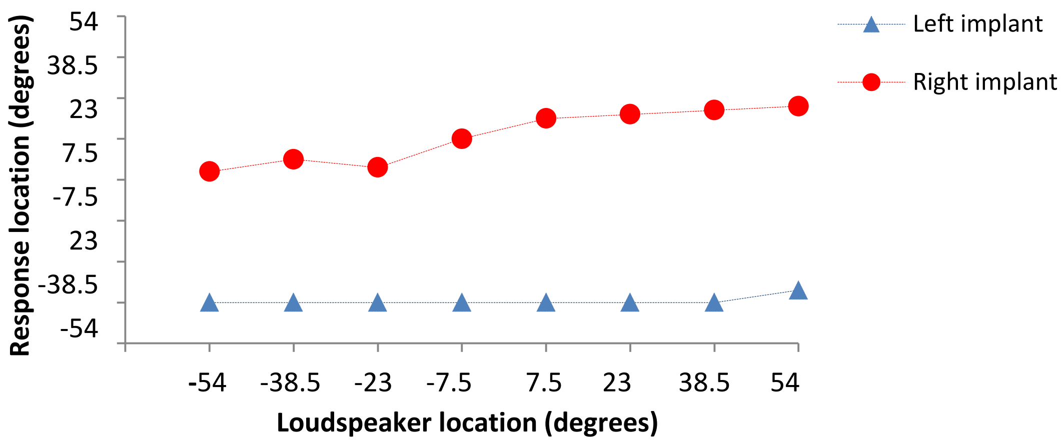


Figure 4.1: Results from van Hoesel and Tyler (2003) for a bilateral CI subject when listening with right implant only (red circle) and with left implant only (blue triangle). The mean response locations were plotted as a function of actual loudspeaker locations. In their set-up, eight loudspeakers were extended from -54° (loudspeaker 1) to 54° (loudspeaker 8) at 15.5° intervals. This figure was redrawn from Figure 2 in their article.

In order to clarify the significance of the above mentioned issues and their impact on the conclusions drawn in the existing literature, a computer simulation was performed to calculate the expected chance range assuming different patterns of guessing behaviours.

4.2.1 Computer simulations

MATLAB software (The Mathworks Inc.) was used to model different patterns of guessing behaviours. The simulation model consists of input, processing and parameters and output (Figure 4.2). The MATLAB code was written by Dr Daniel Rowan.

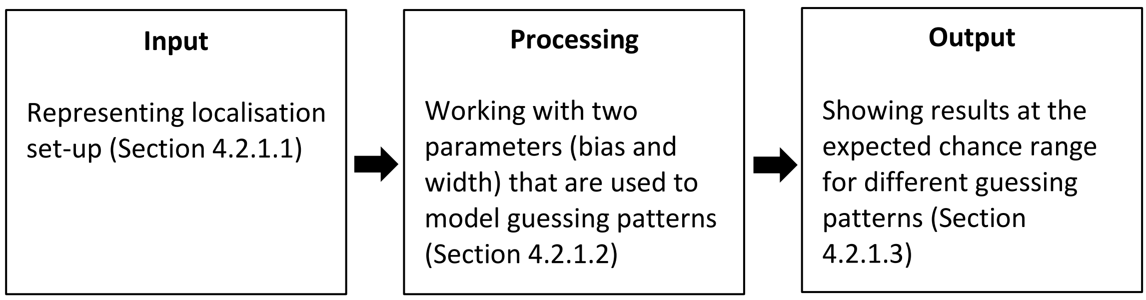


Figure 4.2: Overview of simulation.

4.2.1.1 Input

Sound-source localisation is often measured by presenting sounds from different loudspeakers and asking the listener to determine where a sound comes from. A horizontal localisation set-up consists of a number of loudspeakers (*n*), positioned in the frontal horizontal plane, symmetrically around the midline (0°), and spaced by a common angle (*A*). The sound is presented from one of *n* loudspeakers, and the subject is asked to identify the location of the sound source, this process typically being repeated for all *n* loudspeakers, usually in numerous trials (*T*).

The identical localisation set-up that was used in this project was simulated, where *n*= 11 loudspeakers, *A*=18° and *T*=6. In total, 66 responses (11 loudspeakers x 6 trials) were presented and this is the same number of responses received by real subjects for each stimulus. To estimate chance range, simulation was run on 10000 hypothetical subjects, giving an accuracy for the localisation error of approximately ±0.5° (i.e. margin error of ±2.5° for a 99% credible interval).

4.2.1.2 Processing and parameters

After each sound presentation, the responses were determined according to the modelled guessing behaviour. Two key parameters were used to define any guessing behaviour: bias (*B*), which represents a particular loudspeaker, and the width (*W*), which is the standard deviation of responses. The *W* in the simulation is the means to determine the spread of responses in azimuthal degrees around *B*.

Unbiased guessing, for example, was modelled by setting the *B* to the centre of loudspeaker array (loudspeaker number 6) and making *W* sufficiently large given the number of loudspeakers. The resulting distribution of the responses was a rectangular distribution, where the probability of responses is distributed evenly over the 11 loudspeakers, forming a near-flat line, with a zero mean value and large standard deviation. For any trial, the responses needed to be a number between 1 and 11, and any response less than 1 or greater than 11 would be ignored and the simulation would be repeated again. The histogram of the modelled unbiased guessing is shown in the left panel of Figure 4.3.

To model biased guessing, on the other hand, a Gaussian distribution was used, where its mean equals *B* and its standard deviation equals *W*. It should be emphasised here that the research team is not claiming the Gaussian distribution to be the best nor that the responses of real subjects who are biased in their responses would take the shape of Gaussian distribution. Rather, Gaussian distribution was used for the sake of convenience and illustration of the issue, and any future study that follows this should use a distribution that more accurately represents subjects' behaviour. The right panel of Figure 4.3 shows the histogram of the modelled biased guessing where the mean of the responses was always biased towards the frontal loudspeaker (*B*=loudspeaker number 6), with no variation in responses (*W*= 0°).

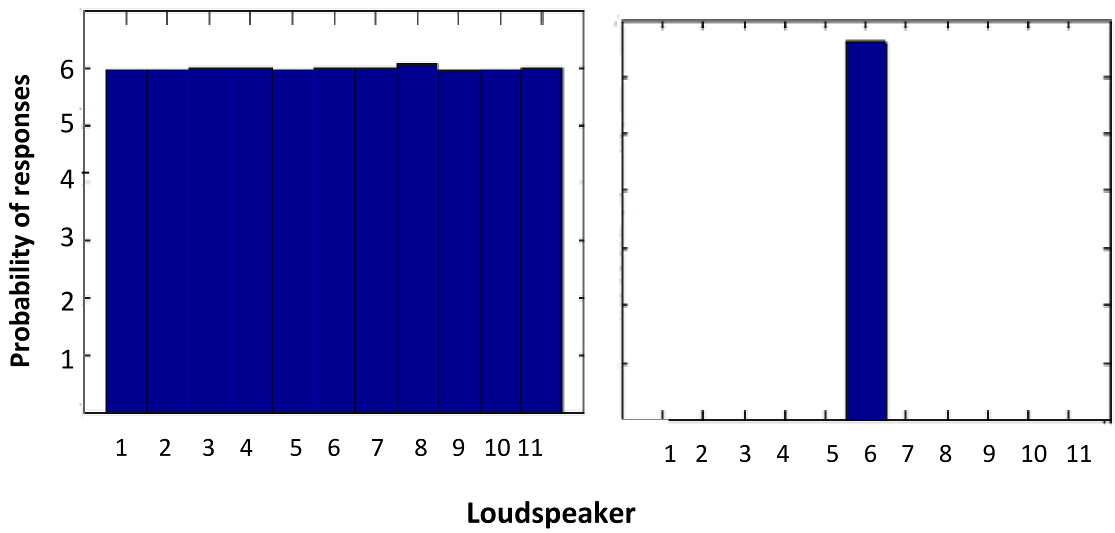


Figure 4.3: The distributions used to model unbiased guessing, in the left panel (a rectangular distribution where *B*=loudspeaker number 6 and *W*=50°), and biased guessing towards the frontal loudspeaker, in the right panel (a Gaussian distribution where *B*=6 and *W*=0°). The localisation set-up used for this was similar to that shown in Figure 3.2.

Between unbiased guessing and biased towards the frontal loudspeaker, values of *B* and *W* can be varied to model different guessing behaviours. Only the guessing behaviour that is likely to resemble the more common patterns of guessing were simulated. For example, a unilateral CI user with bilateral deafness might hear all sounds as coming from the loudspeakers on the implanted side, or from the frontal loudspeakers. An overview of these patterns of guessing is given in Figure 4.4.

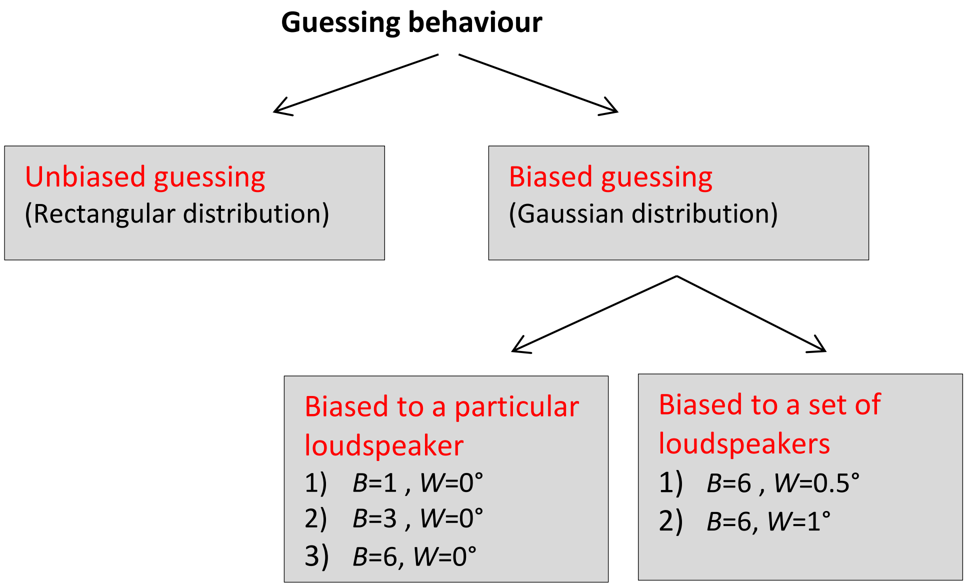


Figure 4.4: Overview of the guessing behaviours that were simulated. Values of bias, *B* (a particular loudspeaker), and width, *W* (standard deviation of responses), were adjusted to give the modelled behaviour.

4.2.1.3 Output

For each of the simulated guessing behaviours, both the expected chance level and chance range expected from guessing were calculated. Chance level and chance range correspond, respectively, to the mean and 99% credible intervals of error scores (i.e. the 0.5th and 99.5th percentiles). The chance level and range for overall error include mean absolute error (MAE) and overall root mean square error ($\bar{D}$ error) and constant and random errors were all calculated.

4.2.2 Results

The expected chance level and 99% chance range that were obtained from unbiased guessing and biased guessing are presented in this section. The aim was to demonstrate the importance of considering chance range and its dependence on guessing behaviour. Results from all the modelled guessing behaviours are summarised in Table 4.1.

Table 4.1: The expected chance level (99% chance range), in degrees, expected from different guessing behaviours for different localisation error measures: mean absolute error (MAE), overall root mean square error ($\bar{D}$ error), random error ($\bar{s}$) and constant error ($\bar{C}$).

Guessing behaviour	**MAE**	$\bar{D}$	$\bar{s}$	$\bar{C}$
Unbiased guessing	65.5 (51-79)	80 (66-94)	57 (47-66.5)	61 (43-78.5)
Biased to frontal loudspeaker at 0°	49	60	0	57
Biased to the middle loudspeaker on the right side at 54°	64	78	0	78
Biased to the endmost loudspeaker on the right side at 90°	90	106.5	0	106.5
Biased to frontal loudspeaker at 0° with few responses towards neighbouring loudspeakers (W=0.5°)	50 (46-53)	58 (54.5-61)	10 (7-13)	57 (54-60)
Biased to frontal loudspeaker at 0° with more responses towards neighbouring loudspeakers (W=1°)	51 (45-56.5)	60 (54-67)	19 (14-23.5)	57.5 (51-63)

4.2.2.1 Unbiased guessing

Figure 4.5 shows the chance level (represented by data points) and the 99% chance range (represented by error bars) expected from unbiased guessing for overall localisation error (MAE and $\bar{D}$ error). The unbiased guessing behaviour illustrates what might be observed from individuals who are, for example, bilaterally deaf, not knowing the location of the sound, and they guess randomly in an unbiased way. The distribution of this guessing behaviour has been presented previously in the left panel of Figure 4.3. To the best of this researcher's knowledge, this guessing behaviour is usually assumed to estimate chance level. The expected chance level obtained with the simulation is similar to the chance level calculated independently for each localisation error. The expected chance level for MAE of 65° was also similar to the chance level calculated in previous studies that have used same localisation set-up (Buhagiar et al., 2004; Verschuur et al., 2005).

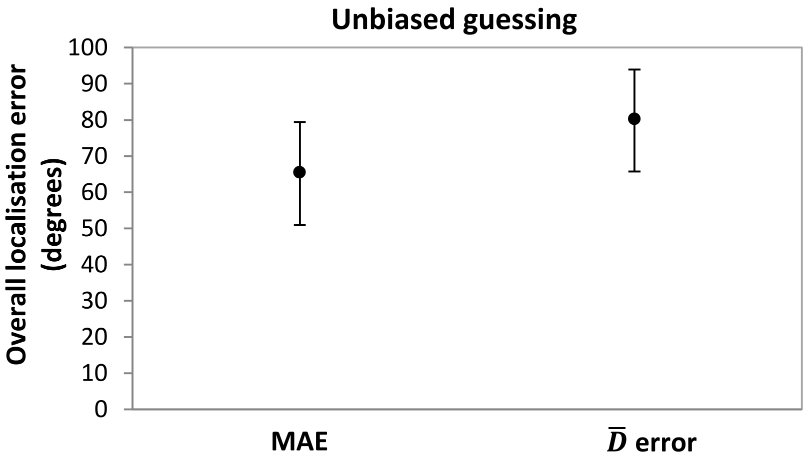


Figure 4.5: The chance level (data points) and the 99% chance range (error bars) expected from unbiased guessing for overall localisation error: mean absolute error (MAE) and overall rms error ($\bar{D}$ error). These values were computed via simulation using the localisation set-up that was used in this project (n=11 loudspeakers, A=18° and T=6 trials).

Figure 4.5 also shows, most importantly, the 99% chance range associated with unbiased guessing (represented by the error bar). For the number of trials used in this simulation, localisation error of an individual needs to be lower than the minimum end of the range (negative bar in the figure) in order to be 99% confident that this error did not reflect unbiased guessing. For the localisation set-up used, the MAE of any individual, for example, needs to be lower than 51° in order to conclude that this MAE did not reflect unbiased guessing, and any MAE within the chance range would still be the result of unbiased guessing.

To clarify the significance of chance range, the results of the simulation were compared to the those of Buhagiar et al. (2004) who used a similar localisation set-up. Figure 4.6 shows the redrawn MAE scores of each unilateral CI subject from the study of Buhagiar et al. (2004). Also shown is the chance range expected from unbiased guessing (grey area in the figure). Although the MAEs of some subjects were below the chance level, they were still within the chance range, suggesting that their overall error scores resulted from unbiased guessing. The figure also shows that the MAEs of all but five subjects (Subjects 2, 7, 9, 12 and 17), were within the chance range for unbiased guessing. Given that the MAE scores of the five subjects were better than the chance range expected from unbiased guessing, this does not, however, necessarily mean they could localise sounds. There is a possibility that the better than chance range of unbiased guessing by such subjects was achieved because they followed different patterns of guessing, where their responses were biased towards particular loudspeakers. This possibility was demonstrated via the simulation, as reported in the following section.

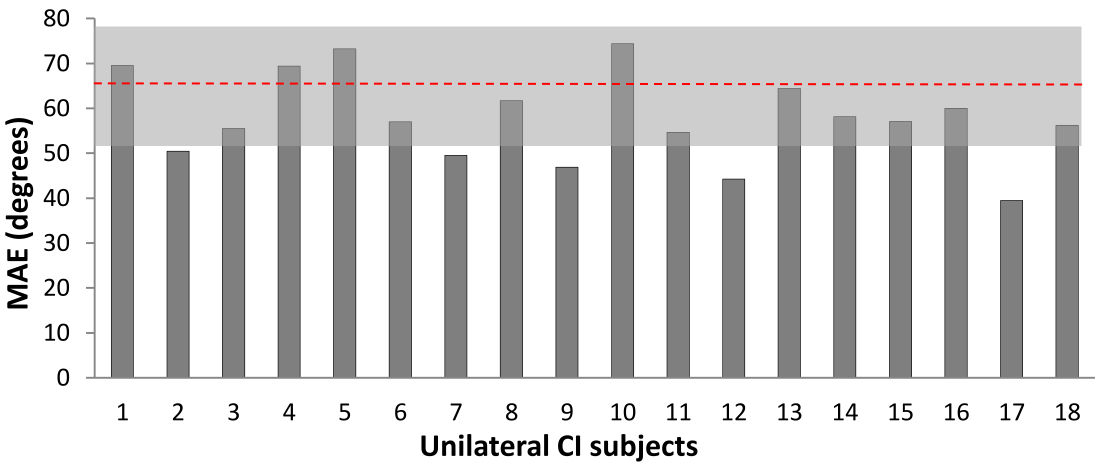


Figure 4.6: Scores on MAE for 18 unilateral CI subjects averaged across different types of stimuli from the previous study by Buhagiar et al. (2004). The grey area indicates the 99% chance range, whereas the dashed horizontal line indicates the chance level calculated assuming unbiased guessing. This figure was redrawn from Figure 3 in Buhagiar et al. (2004).

4.2.2.2 Biased guessing

Another guessing behaviour was assumed where the responses were consistently biased to a particular loudspeaker, as might occur with individuals who are, for example, unilaterally deaf and hearing all sounds to the side, and always show responses towards a particular loudspeaker on that hearing side. Biased guessing towards the frontal loudspeaker, the middle loudspeaker on one side and the end-most loudspeaker on the same side were simulated. These represent bias towards 0°, 54° and 90° for the localisation set-up used in the simulation.

The expected chance levels (data points) for the above patterns of biased guessing are displayed in Figure 4.7. Also shown is the chance range expected from unbiased guessing that was calculated in the previous section (grey area in the figure). It should be noted that no chance range (no error bars) is shown in the figure because there is no variability in responses with biased guessing towards a particular loudspeaker. Scores of random error were always 0° for such biased guessing (Table 4.1). Three categories of overall error scores are apparent in Figure 4.7. The first category shows an overall error that was worse than chance range of unbiased guessing, and this is for bias towards 90°. The second category shows an overall error that was within the unbiased guessing range, for bias towards 54°. This indicates that an overall error that is within the unbiased guessing range was not necessarily obtained by unbiased guessing, but also by bias towards 54°. The third category shows an overall error that was better than chance range of unbiased guessing, and this is for bias towards the frontal loudspeaker at 0° azimuth. Such a finding is of great importance, as it indicates that a better than unbiased guessing performance can simply be achieved by biased guessing towards the frontal loudspeaker.

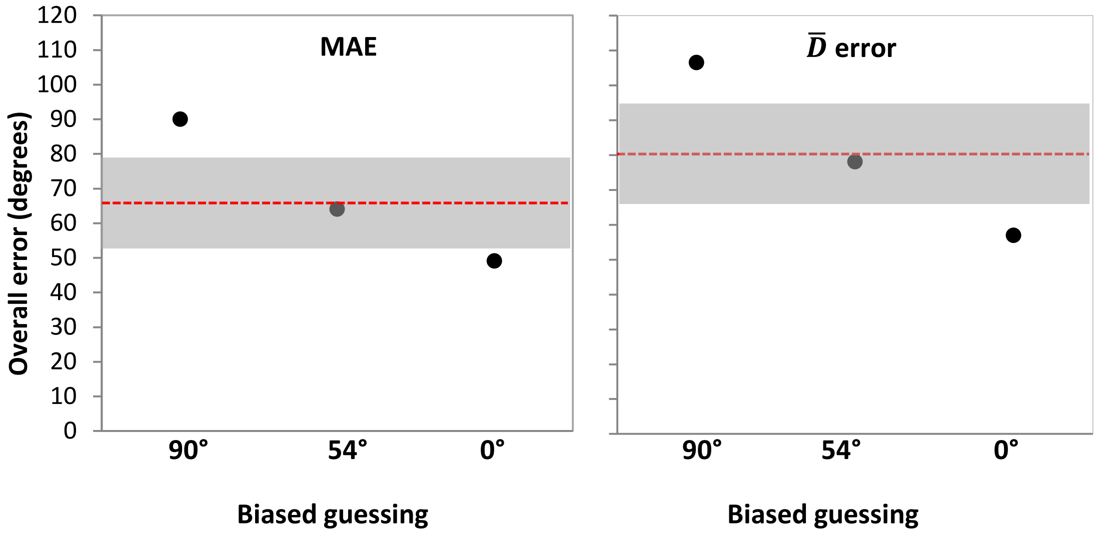


Figure 4.7: The expected chance level (data points) for biased guessing towards a particular loudspeaker for MAE (left panel) and $\bar{D}$ error (right panel). The chance level expected from unbiased guessing (horizontal line) and its chance range (grey area) are also displayed.

The better than chance range of unbiased guessing could still also be obtained when the responses were biased towards a set of frontal loudspeakers, where the average responses were biased towards 0° azimuth with some responses spread around the neighbouring loudspeakers. The histograms of this guessing are shown in the upper panel of Figure 4.8, where the spread of responses was determined by width *W*. The lower panel of Figure 4.8 shows that an overall error that is lower than chance range of unbiased guessing can be obtained when the responses are biased towards the frontal loudspeakers.

Having established that a better than unbiased guessing performance can be obtained by biased guessing towards frontal loudspeaker(s), the next question is how to determine whether the overall error by a subject reflects localisation ability or just biased guessing towards frontal loudspeakers. Two ways can help with this. The first is to consider the appropriate guessing behaviour of the subject when calculating chance range. For a subject who showed biased guessing (as shown by a bilateral CI subject in Figure 4.1.), it is necessary to compare the overall error of that subject to the chance range expected from biased guessing rather than unbiased guessing. Alternatively, scores of constant error (i.e. bias) and random error (i.e. variability in responses) should be considered. Given that the overall $\overline{D}$ error is composed of both constant and random errors, scores for such errors would help to determine the main reason underlying the overall $\overline{D}$ error.

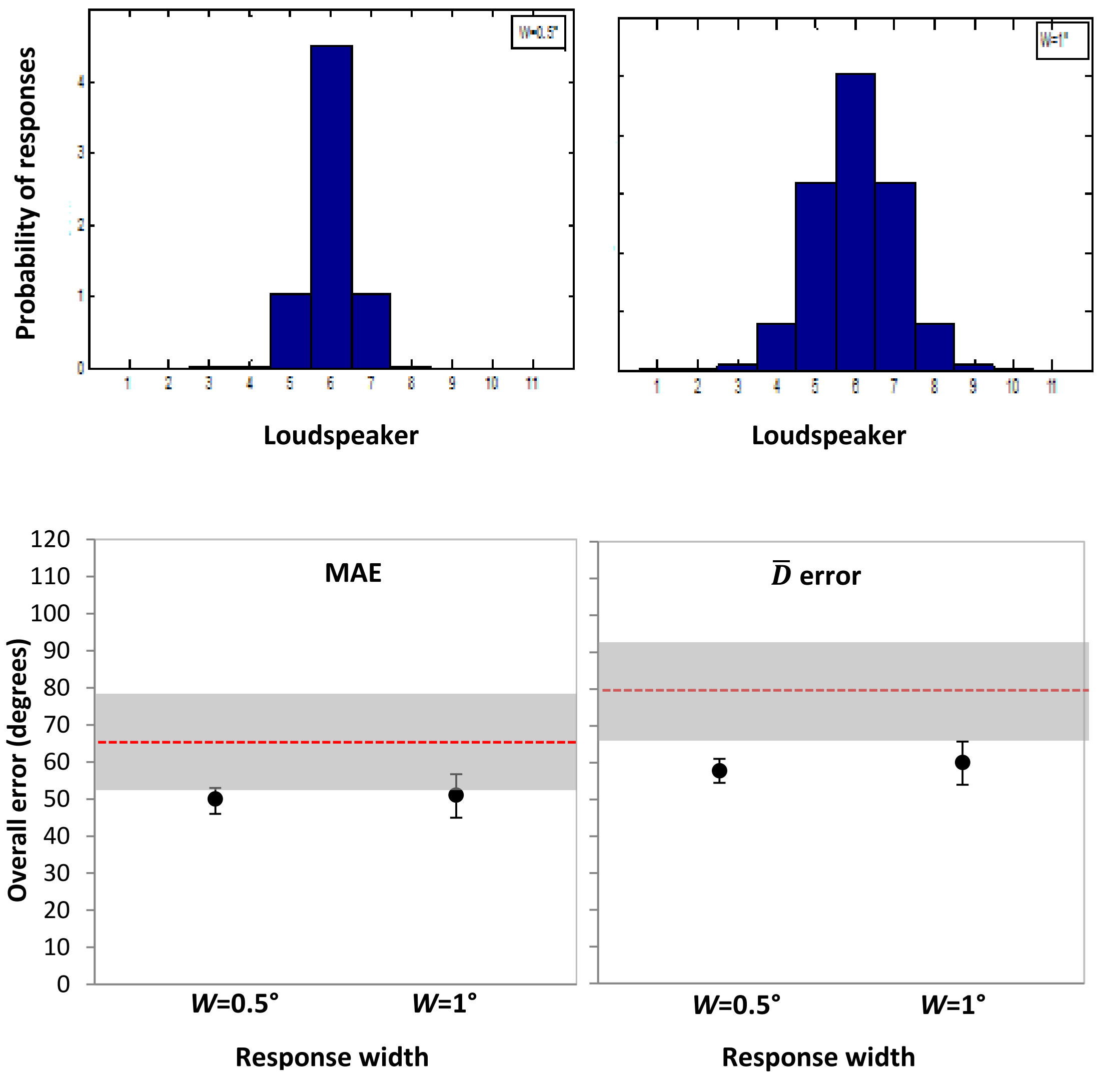


Figure 4.8: Upper panel shows the histograms of biased guessing towards different sets of loudspeakers, where *B*=6 with different values of *W* (as shown in the right-hand corner of each histogram) to determine the spread of responses. The lower panel shows the expected chance level (data points) and 99% chance range (error bars) for these biased guesses for MAE (left panel) and $\overline{D}$ error (right panel). The chance level expected from unbiased guessing (horizontal line) and its chance range (grey area) are also displayed.

Figure 4.9 displays the scores of constant error and random error for biased guessing. The figure shows that one of the characteristics of biased guessing is that it is usually associated with relatively greater constant error score and much smaller, if any, random error score. Thus, an overall error that is better than unbiased guessing performance is more likely to reflect biased guessing if the score for constant error is much greater than the random error score. Scores for constant and random error also help to differentiate whether the overall error that is within the range of unbiased guessing has resulted from unbiased guessing or bias towards 54°. Unbiased guessing is characterised by relatively large scores for both constant error and random error. However, biased guessing towards 54°, as with other biased guessing, is associated with a greater amount of constant error and smaller random error (Table 4.1).

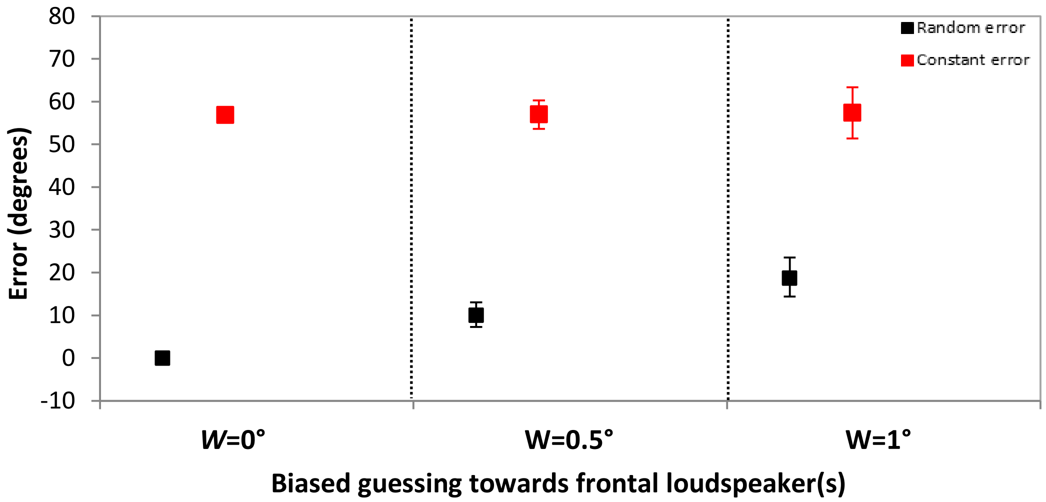


Figure 4.9: The chance level (data points) and chance range (error bars) expected from biased guessing as a function of values of *W* for random error (black data points) and constant error (red data points).

In summary, the results from the simulation show the importance of considering the chance range when reporting localisation ability. They also show how the chance range is greatly affected by guessing patterns, where a smaller error can be obtained for biased guessing towards frontal loudspeakers. These results were intended to help to analyse the localisation data in this project, in that:

- Overall localisation error of any individual would be treated as unbiased guessing if it is equal to or greater than 51° for MAE and 66° for $\overline{D}$ error (the minimum end of chance range for unbiased guessing).

- Any overall error that fell between 45° and 51° for MAE or between 54° to 66° for $\overline{D}$ error would be treated with caution, as this may reflect biased guessing towards frontal loudspeakers. In order to ascertain whether such overall error was due to localisation or biased guesses, scores of constant and random error would be observed. An overall $\overline{D}$ error that fell within the chance range of biased guessing would be considered as a biased guessing if the score of constant error was much greater than random error score.

4.3 Localisation performance of normal-hearing adults

This section presents an experiment on normal-hearing listeners with the aim to evaluate the localisation methodology used in this project, and in particular to ensure that the new developed stimuli produced what was anticipated from previous studies, as mentioned in Section 4.1.

4.3.1 Additional methods

Testing was approved by the Institute of Sound and Vibration Research Human Experimentation Safety and Ethics Committee (reference number: 4164).

4.3.1.1 Participants

Sample size calculation was conducted to determine the appropriate sample size. Prior to conducting the experiment, there was uncertainly whether the statistical analysis should be based on the original data (i.e. overall localisation error) or subsequent to a transformation of the data. A transformation is indicated when the distribution of the data is not normal. There is a reason to think that the distribution in this case might not be normal and the transformation should therefore be applied before parametric statistical analyses. Given that the smallest mean difference in overall localisation error between stimuli cannot be less than 0°, the data can be positively skewed when the spread of data was more in the positive direction than the negative direction. Lutman and Payne (2002) assessed localisation ability of 16 normal-hearing listeners with different types of stimuli and indeed found the distribution of overall error scores to be positively skewed. McManus (2008), on the other hand, found that the overall error scores from 18 normal-hearing listeners were at least normally distributed.

The primary planned analysis was an analysis of variance (ANOVA) on individual localisation error with related factors of stimulus. Ten related sample *t*-tests were used to determine whether the difference in mean localisation error between two stimuli was statistically significant. Given the number of main effects and interactions, the criterion significance level was adjusted using a Bonferroni correction during sample size calculations to 0.005 (0.05/10). Based on the original data, the mean difference in overall error scores between two stimuli was estimated to be 1.6°, and the standard deviation of this difference to be 1.5° (McManus, 2008). The sample size calculation with statistical power of 80% indicated that at least 15 subjects were required to detect differences in localisation error between stimuli (two-tailed tests, α=0.005, δ=1.6° and σ=1.5°). With the assumption of transformation of the data, a sample size of 16 subjects was indicated, as with Lutman and Payne (2002).

According to the above two assumptions on the shape of distribution, a sample size of at least 16 subjects was aimed at in the current study. They were recruited from the student population at the University of Southampton based on the following criteria:

- Have normal-hearing: this was defined as pure tone, air-conduction thresholds of 20 dB hearing level (HL) or better, bilaterally, at octave frequencies between 0.5 to 8 kHz, using a GSI-61 audiometer and TDH-39 headphones. The difference in the thresholds at any one frequency did not exceed 15 dB HL between the two ears.

- Both ears are in an otologically normal/healthy condition on the day of testing, confirmed by a health questionnaire shown in Appendix A.3, otoscopy, and tympanometry. Listeners with ear or hearing problems within the past 12 months were excluded.

- Aged between 18 to 35 years, in order to decrease the possibility of age-related hearing loss.

Taking into consideration the risk of non-compliance with testing, 20 normal-hearing adults were recruited, as opposed to the 16 subjects initially planned. The experiment was terminated after fully recruiting and testing 20 listeners, which increased the statistical power to 94%. They all had normal hearing with mean age of 25 years (10 females, 10 males). Participants were paid £10 for their participation. All participants signed informed consent forms after being provided with details about the study.

4.3.1.2 Procedure

Exactly the same set-up and procedures explained in Section 3.3 were used. In summary, subjects were seated in the centre of a lighted anechoic chamber. Eleven loudspeakers were positioned in a horizontal arc extending from -90° to +90° (Figure 3.2). After each stimulus presentation, the subject was asked to identify the loudspeaker from which the stimulus was presented by using a touch screen with an image of the loudspeaker array and clicking on the letter corresponding to the loudspeaker. Each of the five stimuli listed in Table 3.1 including speech, broadband noise (BBN), low-pass noise (LPN), high-pass noise (HPN) and high-pass noise burst (HPN-burst) was presented 66 times (11 loudspeakers x 3 trials x 2 replications). The nominal stimulus level was 65 dB SPL (A-weighted) and it was randomly roved by ±4 dB from trial to trial during testing, whereas the frequency content of the stimuli was kept constant. The test session began with practice trials, which typically included presenting speech stimulus three times from each of the 11 loudspeakers. Testing was performed in one session, which took approximately one hour. Frequent rest intervals were provided during the session.

4.3.2 Results

The localisation performance of the 20 normal-hearing subjects for different stimuli is described in this section. An overview of their localisation performance is presented in Section 4.3.2.1. Their scores on overall localisation error, and random and constant error are then reported in Sections 4.3.2.2 and 4.3.2.3.

4.3.2.1 Exploration of localisation performance

The sound-source localisation of each stimulus by the normal-hearing subjects is shown in Figure 4.10, where the mean response locations are plotted as a function of actual loudspeaker locations. Data points falling on the diagonal line represent correct responses (i.e. perfect localisation performance), points falling below the diagonal line represent responses to the left of the actual loudspeaker location and points falling above the diagonal line represent responses to the right of the actual loudspeaker location.

Figure 4.10 shows that that mean response locations generally fall along the diagonal line, for all stimuli, particularly broadband stimuli. Broadband stimuli were also associated with much small variability in responses, as represented by the error bars in the figure. Among the narrowband stimuli, it seems that localisation performance of low-pass noise was better than for high-pass noise stimuli. The mean responses of high-pass noise stimuli lie fairly close to the diagonal line for loudspeakers on azimuths between ±72°. For azimuths beyond ±72°, however, mean responses diverge from the diagonal line with responses rarely given for azimuths on +/-90°. The variability in responses was also greater for high-pass stimuli, particularly the high-pass noise burst stimulus.

The relationship between mean response locations and the loudspeaker locations was examined statistically and the results of the Pearson correlation are presented in Table 4.2. Mean response locations were found to be at least approximately normally distributed for all stimuli (Shapiro-Wilk normality test: $P > 0.05$). The results indicate a significant and robust relationship between mean response locations and the loudspeaker locations for all stimuli.

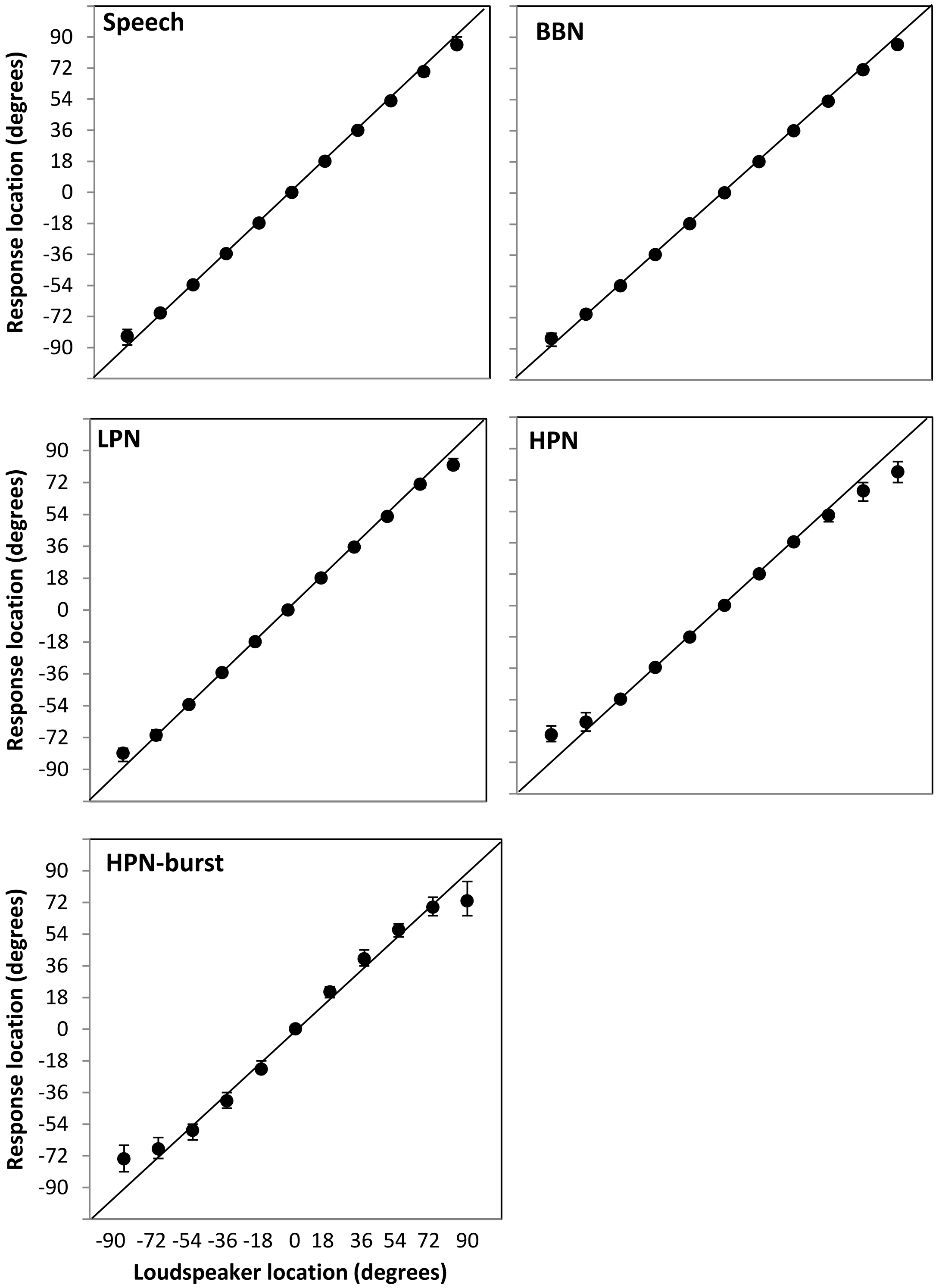


Figure 4.10: Mean response locations across all normal-hearing subjects (data points) as a function of loudspeaker location for speech, broadband noise (BBN), low-pass noise (LPN), high-pass noise (HPN) and high-pass noise burst (HPN-burst). Error bars represent the upper and lower quartiles. The diagonal line represents the perfect localisation performance.

Table 4.2: Results of the Pearson correlation between mean response locations given by the normal-hearing subjects and actual loudspeaker locations for each stimulus.

Stimulus	*r*	r^2	*P*
Speech	1.00	1	< 0.001
BBN	1.00	1	< 0.001
LPN	0.99	0.99	< 0.001
HPN	0.99	0.99	< 0.001
HPN-burst	0.98	0.96	< 0.001

4.3.2.2 Overall localisation errors

Overall localisation error, which is usually used to quantify localisation performance, is reported in this section. The overall localisation errors (MAE and $\overline{D}$ error) across all subjects for each stimulus are displayed in Figure 4.11. The grey area in the figure indicates the chance range of unbiased guessing. As indicated previously in Section 4.2.1, chance range was calculated as 99% confidence intervals of the errors by 10000 hypothetical subjects, in which the computer responds randomly to 66 trials on each subject, the same number of trials as received by the real subject. It should be noted that the overall localisation error presented in Figure 4.11 was averaged across the two replications since neither a consistent nor large difference in overall error was found between the two replications. The difference in mean overall error between the two replications for each stimulus was 1° or less.

Figure 4.11 shows four main trends. First, the overall error scores of all subjects were below the 99% chance range expected from unbiased guessing for all stimuli. The overall localisation error scores including the MAE and $\overline{D}$ error were all far below the chance range of unbiased guessing. Second, the better than unbiased guessing performance did actually reflect localisation ability by the subjects. The overall error scores by all the subjects were far below the chance range expected from biased guessing towards the frontal loudspeakers. As pointed out previously in Section 4.2.2, the chance range for biased guessing towards frontal loudspeakers was between 45° and 51° for MAE or between 54° to 66° for $\overline{D}$ error. Further support to that is the good relationship between the response locations and loudspeaker locations shown in Figure 4.10, and the smaller constant and random error scores for the subjects (see the following section).

Third, the overall error scores generally appear to be similar across broadband stimuli and low-pass noise stimulus. For example, mean $\overline{D}$ error scores of about 5.1°, 5.2° and 6.6° were found, respectively, for speech, broadband noise and low-pass noise stimuli. High-pass noise stimuli, however, tended to be associated with larger overall error scores, with mean $\overline{D}$ error scores of 9.7° and 13.4° for high-pass noise and high-pass noise burst stimuli. The variation in overall scores between subjects also seems to be greater with high-pass noise stimuli than the other stimuli.

The fourth trend shown in Figure 4.11 is the higher scores of $\overline{D}$ error compared to the MAE scores. Such a finding was expected, given the ways the MAE and $\overline{D}$ error were calculated, as described in Section 3.3.5. Calculation of MAE involves summing the absolute values of the errors, such that all errors are weighted equally in the average MAE. Calculation of the $\overline{D}$ error, on the other hand, involves summing the squared errors, so that the large errors have a relatively greater influence on the total error than the smaller errors.

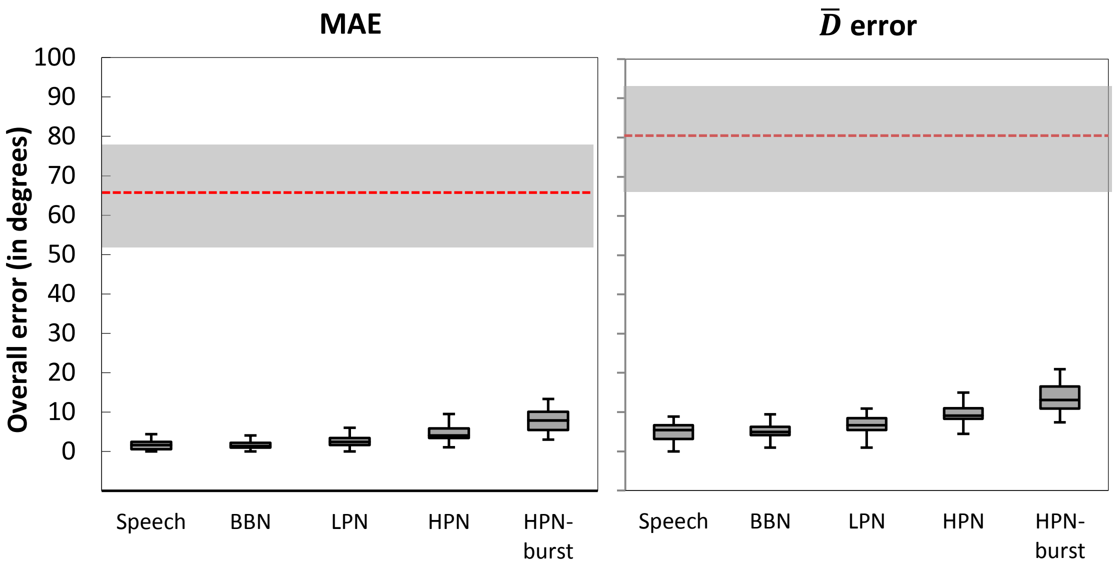


Figure 4.11: Overall localisation error (left panel: mean absolute error, MAE; right panel: overall root mean square error, $\overline{D}$ error) across all subjects for different types of stimuli: speech, BBN, LPN, HPN and HPN-burst. Each box represents the two middle quartiles (end of boxes), separated by median (horizontal line), maximum and minimum values (horizontal lines at the end of whiskers). The horizontal red line shows the chance level expected from unbiased guessing, with the grey area indicating the chance range of unbiased guessing (see Section 4.2.2.1).

Statistical analyses were conducted to examine the above trends. The results of the normality test indicated that that the distributions of MAE and $\overline{D}$ error scores of all stimuli were at least approximately normally distributed (Shapiro-Wilk normality test: $P > 0.05$). Initially, two-tailed one-sample *t*-tests were conducted on overall error scores (MAE and $\overline{D}$ error) to determine whether the scores of the normal-hearing subjects were significantly different from chance range ($P < 0.05$). The results indicated that the MAE and $\overline{D}$ error scores were significantly better than chance range of unbiased guessing for all stimuli (Table 4.3). A repeated measures ANOVA was also conducted on the MAE and $\bar{D}$ error scores with the within-subjects factor of stimulus. The effect of the stimulus was statistically significant in both MAE (F (4) =40.0, P < 0.001) and $\bar{D}$ error (F (4) =41.9, P < 0.001). To investigate the stimulus effect further, ten *post hoc* pairwise comparisons were conducted on MAE and $\bar{D}$ error scores with Bonferroni corrections. The results confirmed the above observation, in that overall localisation error with high-pass stimuli, including high-pass noise and high-pass noise burst, was significantly greater than that for each of the other stimuli (P < 0.001). High-pass noise burst stimulus was also associated with significantly larger MAE and $\bar{D}$ error scores than high-pass noise stimulus (P < 0.001). There was no significant difference between any of the other stimuli (P> 0.1).

Table 4.3: Results of two-tailed one-sample *t*-tests to determine whether the MAE and $\bar{D}$ error scores of the normal-hearing subjects were significantly different from chance (P <0.05).

Stimulus	**MAE**		**$\bar{D}$ error**	
	t	***P***	***t***	***P***
Speech	173	< 0.001	117	< 0.001
BBN	150	< 0.001	113	< 0.001
LPN	143	< 0.001	109	< 0.001
HPN	84.5	< 0.001	77.6	< 0.001
HPN-burst	62.5	< 0.001	62.2	< 0.001

4.3.2.3 Random and constant errors

In order to understand the main reason underlying the larger overall error ($\bar{D}$ error) shown by the subjects for high-pass stimuli than for the other stimuli, scores of random error ($\bar{s}$) and constant error ($\bar{C}$) are displayed in Figure 4.12. It is worth remembering that the constant error (i.e. bias) refers to the deviation of the mean responses (the data points in Figure 4.10) from the loudspeaker locations (the diagonal line), whereas random error is the standard deviation of responses at each loudspeaker location averaged across all loudspeakers (the average size of error bars in Figure 4.10).

Figure 4.12 shows that both random and constant errors, but particularly constant error, increase with high-pass stimuli more than for the other stimuli. As noted earlier in Figure 4.10, the size of the error bars (i.e. variation in responses) was greater for high-pass stimuli and the mean responses with such stimuli diverge from the diagonal line for the lateral loudspeakers. Figure 4.12 also shows that both the constant and random error contributed differently to the overall $\bar{D}$ error for each stimulus. For broadband noise stimulus, it seems that the random error contributed more than the constant error. The opposite error pattern was seen for high-pass stimuli, where the constant error contributed more than the random error. The overall $\bar{D}$ error for speech and low-pass noise, on the other hand, seemed to result from equal contributions from constant error and random error. Nevertheless, all stimuli were associated with relatively small constant error and random error scores, confirming that the responses given by the subjects reflect actual localisation ability rather than biased guessing.

Statistical analysis was conducted to examine the above observations. The results of the normality test indicated that that the distributions of $\bar{C}$ and $\bar{s}$ scores of all stimuli were at least approximately normally distributed (Shapiro-Wilk normality test: P > 0.05). A repeated measures ANOVA was conducted on $\bar{C}$ and $\bar{s}$ scores with the within-subjects factor of stimulus. The effect of stimulus was statistically significant for both $\bar{C}$ (F (4) = 25.0, P < 0.001) and $\bar{s}$ (F (4) = 18.7, P < 0.001). To investigate the stimulus effect further, ten *post hoc* pairwise comparisons were conducted on $\bar{C}$ and $\bar{s}$ scores with Bonferroni corrections. High-pass stimuli were found to be associated with significantly larger bias ($\bar{C}$) and variability in responses ($\bar{s}$) than the other stimuli. High-pass noise burst stimulus was also associated with significantly larger scores for both constant and random errors than high-pass noise stimulus (P =0.002). Low-pass noise was found to be associated with marginally significant greater constant error than the broadband stimulus (P=0.005), but not for random error. There was no significant difference between any of the other stimuli (P > 0.1).

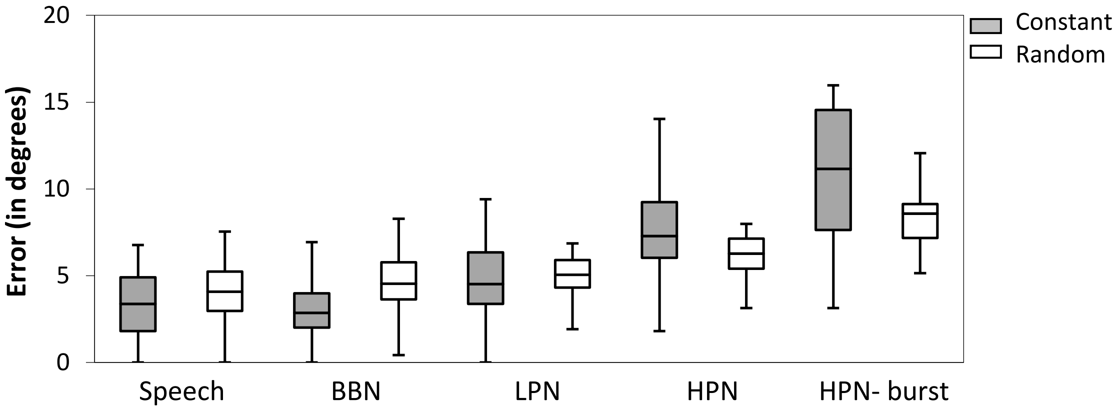


Figure 4.12: Constant error $\bar{C}$ (grey boxes) and random errors $\bar{s}$ (white boxes), in degrees, that contributed to the overall $\bar{D}$ error for each stimulus. The characteristics of the box plots were described above in Figure 4.11.

In summary, the results of the current study indicate that localisation performance of normal-hearing subjects depends on stimulus type. Although normal-hearing subjects showed an ability to localise all the types of stimuli at better than chance range of biased and unbiased guessing, it seems that high-frequency sounds are harder to localise than broadband stimuli and low-pass noise stimulus. The greater overall localisation error with high-frequency sounds was found to result from the increased amount of bias and variability in responses.

4.4 Discussion

The results of the current study show that normal-hearing subjects can localise different types of stimuli at better than chance range of both unbiased and biased guessing. The results of the current also show that high-pass stimuli seem to be localised with less accuracy than the other stimuli containing low frequencies. These findings are discussed in Sections 4.4.1 and 4.4.2.

The current study has also presented the results of a computer simulation which have highlighted some uncertainties regarding the current interpretation of localisation performance by most studies. The results showed that a better than chance level of unbiased guessing reported by the majority of studies may not necessary reflect actual localisation ability. A better than chance level of unbiased guessing can still be achieved by a subject who is biased randomly across all loudspeakers (i.e. unbiased guessing) or consistently towards frontal loudspeakers (i.e. biased guessing). The results from this simulation demonstrate the importance of considering a chance range which depends on the pattern of guessing behaviour for accurate interpretation of localisation performance (Section 4.4.3).

4.4.1 Comparison with previous studies on normal-hearing listeners

The results from the current study replicate those of previous studies that have demonstrated that normal-hearing listeners are able to localise accurately different types of sounds with small overall error scores. Such a finding was expected, given that normal-hearing listeners can take advantages of binaural cues that are known to underlie humans' ability to localise sounds in the horizontal plane. The overall error in the present study averaged across subjects and different stimulus types was 3.7° for MAE and 8.0° for $\overline{D}$ error. Previous studies reported an overall $\overline{D}$ error of about 6° to 10°, depending on different characteristics of the testing environment, set-up and stimulus used (Bogaert et al., 2006; Grantham et al., 2007; Lorenzi et al., 1999).

Figure 4.13 plots the overall error with broadband sounds in the present study with those from previous studies that investigated localisation performance of normal-hearing listeners with broadband sounds for a loudspeaker span of 180°. The overall error in the present study, averaged across subjects and broadband stimuli was about 1.7° for MAE (open square) and 5.2° for $\overline{D}$ error (filled square). It is apparent from the figure that localisation performance of normal-hearing subjects from the current study is comparable to that reported from previous studies.

The current study found an overall $\overline{D}$ error of about 5.2°, similar to the scores of 6.4° and 6.8° from previous studies (Bogaert et al., 2006; Grantham et al., 2007). These two studies used different loudspeaker arrangements than that used in the current study. While the current study used 11 loudspeakers with 18° angular separation, 13 loudspeakers with angular separation of 15° were used by Bogaert et al. (2006) and 9 loudspeakers with 20° angular separation by Grantham et al. (2007). One might, therefore, expect that the different set-up used by the studies may complicate the comparison between studies. However, given that the theroretical advantage of $\overline{D}$ error, in that it is insensitive to the number of loudspeakers, it may be possible to compare across different loudspeaker arrangements. Hartmann et al. (1998) reported that $\overline{D}$ error reached a plateau when there are at least six loudspeakers and the angular separation is greater than 5% of the span (as with the above studies).

With regard to MAE, the current study found MAE of 1.7°, similar to that reported by Lutman and Payne (2002). This finding is promising, given that the characteristics of broadband stimuli and the set-up used in their study were similar to those used in the current study. It should be noticed from the figure that the MAE score which represents mean absolute error is smaller than the $\overline{D}$ error (i.e. RMS error). The latter error measure is more sensitive to large errors than the former one, and thus would be expected to be larger. Taken together, the findings of the current study were similar to those reported by previous studies that investigated localisation ability of normal-hearing listeners, which gives an indication of the suitability of the localisation methodology used in this research.

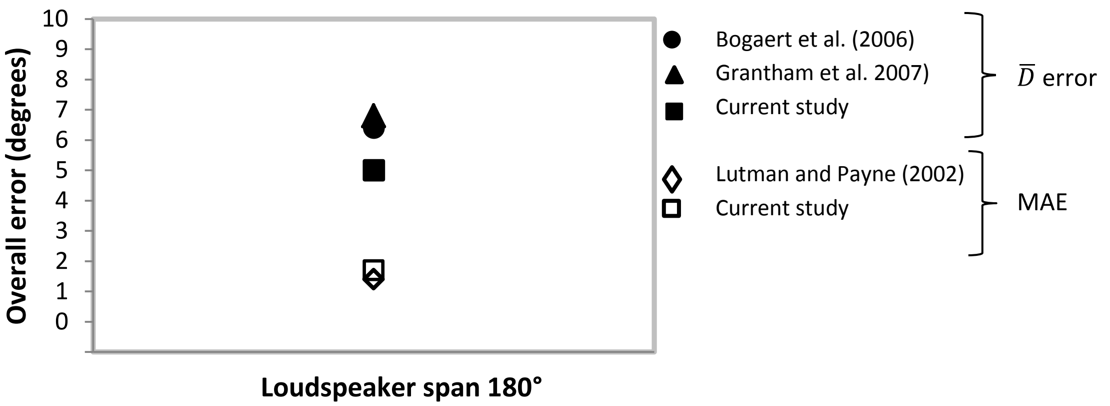


Figure 4.13: Overall error score reported by previous studies on localisation ability of normal-hearing adults with broadband sounds. Filled symbols are for studies which reported for $\overline{D}$ error, whereas open symbols are for studies which reported MAE scores.

4.4.2 Effect of stimulus

The findings of the current study show that localisation performance for low-pass noise (fine structure ITD dominant) was better than performance for high-pass noise (ILD dominant) and high-pass noise burst (envelope ITD dominant). The increase in overall error with high-pass stimuli might be related to the ILDs, where the monotic increase of ILD with azimuths was less apparent for azimuths beyond about 66°. Calculation of the ILDs from the head-related transfer functions (HRTFs) presented in Figure 3.5 above shows a strong monotic increase of the ILD with azimuths between 0° and 66°, but beyond that the rate of increase in ILD with azimuth becomes smaller. In support of this is the finding reported in this chapter that the mean responses given by the subjects for sound sources beyond +/-72° azimuths tend to compress towards the neighbouring loudspeakers (Figure 4.10). The scores for constant and random errors also show that the normal-hearing subjects exhibited greater bias and variability in responses with high-pass stimuli than the other stimuli.

The results of the current study also showed that localisation performance for high-pass noise burst was worse than that for high-pass noise stimulus. The greater increase in localisation error with high-pass noise burst than with high-pass noises suggests that envelope ITD seems not to contribute to localisation of normal-hearing subjects. This finding is consistent with the findings from previous studies, in that the envelope ITDs appear to contribute little or not at all to localisation performance by normal-hearing listeners (Bernstein and Trahiotis, 2002; Macpherson and Middlebrooks, 2002; Smith et al., 2002; Wightman and Kistler, 1992). It is well-documented that localisation performance by normal-hearing listeners is based on the use of ITD in the fine structure of the sound containing low frequencies (Bernstein and Trahiotis, 2002; Smith et al., 2002; Wightman and Kistler, 1992). For sounds containing high frequencies, localisation by normal-hearing listeners is strongly dominated by ILDs with little contribution from envelope ITDs (Macpherson and Middlebrooks, 2000).

Interestingly, the findings of the current study show that localisation performance by normal-hearing-listeners with broadband noise was similar to that with low-pass noise, but significantly worse than that with high-pass stimuli. Such findings indicate that removing the low-frequency component (i.e. ITDs) of a signal significantly increases overall localisation error. However, removing the high-frequency component (i.e. ILDs), did not significantly affect localisation performance. This may suggest that ITD in the fine structure dominates localisation performance of broadband stimuli. This finding is consistent with previous studies, which have demonstrated that localisation performance of normal-hearing listeners is dominated by the ITD in the fine structure of the sounds (Blauert, 1982; Trahiotis and Bernstein, 1986; Wightman and Kistler, 1992). For example, Wightman and Kistler (1992) investigated the relative contribution of ITD and ILDs to localisation of broadband noise, using virtual auditory space. Stimuli were synthesised such that ITD and ILD provided conflicting directions. They found that the perceived source location was mainly determined by the ITD cue, suggesting that the ITD cue is the dominant cue for localisation of broadband signals.

The above finding that the ITD dominates localisation performance of normal-hearing listeners, however, contrasts with the finding of other studies. For example, Carlile et al. (1999) reported similar localisation performance for broadband noise and high-pass noise. However, they reported better localisation performance with broadband noise than with low-pass noise. Carlile et al. (1999) suggest that the auditory system of normal-hearing listeners might be able to compensate for the loss of low frequency information when high frequency information (ILD and spectral cues) are available. Although the reasons behind the conflicting findings between Carlile et al. (1999) and the current study are not clear, it might be possible that normal-hearing listeners have the redundancy to rely on either ITD or ILD for localising sounds in different listening situations.

Due to the limited availability of binaural cues in narrowband signals, one might expect that localisation performance of narrowband noise is less accurate than for broadband signals (Su and Recanzone, 2001; Wightman and Kistler, 1993). The finding of the current study, however, indicates that localisation performance with broadband noise was similar to that with low-pass noise stimuli. However, this does not mean that both stimuli were localised accurately and equally consistently. Scores for constant and random error indicate that low-pass noise was associated with greater bias than the broadband stimuli. This means that even though the consistency of normal-hearing listeners in pointing to the correct sound sources is similar with both broadband stimuli and low-pass noise, their average localisation responses with low-pass noise were less close to the diagonal line (i.e. perfect localisation) than the broadband stimuli. All the narrowband stimuli were found to be associated with greater bias than the broadband stimuli, which may suggest that the limited binaural cues with narrowband stimuli could have biased the subjects' judgment of sound-source locations.

4.4.3 Implications for interpretation of localisation performance

The current study has demonstrated how to distinguish observed localisation ability from guessing in an effective way with regard to chance range assuming different guessing behaviour. The current study raises the possibility that the better than chance level reported from previous studies may not actually reflect localisation ability for two reasons. Firstly, an overall error that is better than chance level does not necessarily exclude the possibility that this error is still based on guessing. Results from the simulation indicate that, by comparing an individual's score to chance level, there is still a likelihood that such a score is based on guessing, and thus a probable range of scores occurring by guessing rather than just single score should be taken into consideration. Secondly, most localisation studies have often assumed unbiased guessing when calculating chance level, so that an individual's score is compared to a value that would be obtained by a listener who responses randomly across all loudspeakers. Results from the present simulation, however, show that a better than unbiased guessing range can still be achieved by biased guessing towards frontal loudspeakers. Therefore, it is crucial to take these issues into account for sound localisation analysis, as failure to consider such issues may lead to misinterpretation of the localisation performance. The implications of these issues for interpretation of localisation performances in previous studies have also been demonstrated (Figures 4.1 and 4.6).

4.5 Conclusions

The conclusions of the present study are as follows:

- The implications of the limited analysis of localisation performance reported by most studies in the literature have been demonstrated, using a computer simulation. Results from the simulation highlight the importance of taking into consideration the chance range rather than chance level expected from the appropriate guessing behaviours when analysing localisation performance of individuals. Results, for example, show that it is possible to outperform unbiased guessing performance through biased guessing.

- Normal-hearing listeners can localise different types of stimuli at better than chance range expected from unbiased and biased guessing. Normal-hearing listeners were found to localise high-frequency sounds with less accuracy than the other stimuli containing low-frequency sounds.

- Similar results were reported by previous studies of localisation ability with normal-hearing listeners, giving an indication of the suitability of the localisation methodology used in this project.

Chapter 5: Reference data on speech perception in noise

5.1 Introduction

The main aim of this project was to assess spatial hearing abilities with synchronised bilateral cochlear implants (CIs). Besides sound-source localisation, the ability of CI users to perceive speech in the presence of background noise was also assessed in this project, as one of the potential measures of binaural hearing benefits. The ability of the listener to segregate concurrent sounds that are spatially separated is at least partly facilitated by the cues of interaural time and level differences (ITD and ILD) (Bronkhorst and Plomp, 1988). Binaural hearing, therefore, leads to various advantages for speech perception in noise over hearing with only one ear.

The spatial advantage for speech perception in noise is typically observed when the interfering sounds are spatially separated from the target sound. An improvement in speech perception ability occurs when the target and interfering sounds are spatially separated, an advantage known as spatial release from masking (SRM). In bilateral CI adults, studies have shown a measured SRM of about 3 dB (Schleich et al., 2004) to 4.5 dB (van Hoesel and Tyler, 2003). Consistently with these results, a SRM of about 3.6 dB was also predicted for bilateral CI users by a model developed by Culling et al. (2012). All the above studies measured SRM by comparing a situation with both target speech and interfering noise in front versus a situation with speech at front and noise at 90° to the right or left of the listener.

The advantage of SRM results from a combination of the monaural head shadow (i.e. better ear listening) and binaural squelch (i.e. binaural unmasking) (Bronkhorst and Plomp, 1988; 1992). When target and interfering sounds are in different locations, one ear will offer a better signal-to-noise ratio (SNR) than the other ear, due to the head shadow effect. The monaural head shadow component assumes that listeners can select the ear offering the better SNR. Binaural squelch, on the other hand, relies on the binaural cues generated by the different locations of the target speech and the interfering sounds. Binaural squelch is processed in the central auditory nervous system, in which the interfering sound with specified ITDs will be cancelled, therefore improving the internal SNR (Equalisation-Cancellation model, see Section 2.4.3 for more details).

Besides SRM and its components, hearing with two ears offers another advantage for speech perception when both the target and interfering sounds are placed at the same location (i.e. binaural summation). Although the target and interfering sounds are presented identically in each ear, binaural hearing leads to a better representation of the target sound than listening with one ear, as the auditory system receives two versions of the target sound and by comparing these versions the internal noise can be minimised (Bronkhorst and Plomp, 1988).

All the above spatial advantages for speech perception in noise have been extensively studied in the literature using different speech materials, such as sentences (Hawley et al., 1999; 2004) or words (Jones and Litovsky, 2011). Given the unsuitability of the most common speech materials for the CI participants, the triplet digit test (TDT) was used as the speech material in the current project. As stated in Section 3.4.2, some adults with synchronised bilateral CIs had scores of less than 70 % for testing in quiet using the Bamford-Kowal-Bench (BKB) test, meaning that they were not able to undertake BKB testing in noise, and the Automated Toy Test (ATT) was also deemed inappropriate, as it is typically used to test children. Another added value of the TDT is that the digits are highly familiar words and they are typically among the first words that are learned in a second language, making the TDT viable for testing non-native speakers of English (Ramkissoon et al., 2002). The digits have generally steep slope of the intelligibility function, due to the lower redundancy of digits and the small measurement error, which suggests accurate measurements can be obtained with the TDT (Hall, 2006). Previous studies on the TDT have also indicated that the test-retest reliability is strong, with no learning effect (Causon, 2012; Hall, 2006; Morgan, 2010). The risk of remembering digits in the TDT was small since it was presented in different triplets.

Unlike sentences and words, the digits may, however, be criticised for lack of representation of daily-life conversational speech (Smits et al., 2013). Although the results of TDT might be less representative of real conversational speech than sentences, TDT seems to be more appropriate than sentences for testing CI users in this project, for the reasons given above. Additionally, evidence shows that the speech perception thresholds (SRTs) with the digits are well-correlated to those with sentences (Smits et al., 2004). This is encouraging, as it suggests that the use of digits might provide similar information to that provided by sentences which have high face validity. Together with that, the TDT is easy and quick test, and thus seems to provide suitable material to test spatial benefits for speech perception in the CI users in this project.

To the best of this researcher's knowledge, the spatial benefits for speech perception in noise have not been determined previously with the TDT. It is necessary, therefore, to obtain normative values for these benefits with the TDT. Thus, the current study was conducted with the aims of obtaining normative values for the spatial benefits with the TDT and ensuring that the methodology used in this project to assess the benefits for speech perception would produce reasonable results and that the method did not need any further refinements. Given that understanding speech in the presence of background noise requires a certain amount of listening effort (Fraser et al., 2010), it is also of interest to determine the listening effort required by normal-hearing listeners to understand speech in noise. As pointed out earlier in Section 3.1, it has been found that the amount of listening effort required to understand speech is much more when the auditory environment is complex (Koelewijn et al., 2015 and 2012; Zekveld et al., 2011). Koelewijn, et al. (2015), for example, found that listening effort increased when a masker was added. The observed effect is in line with previous studies by Koelewijn et al. (2012) and Zekveld et al. (2011), who reported much more listening effort required for perceiving speech in the presence of another talker than in the presence of stationary noise. The concept of informational masking has been invoked to account for the increased listening effort for speech perception in a single-talker masker (Koelewijn et al., 2015; 2012). Given that the amount of informational masking generally tends to be reduced for spatially separated target speech and masker noise (Colburn et al., 2006), the above results may also suggest that the listening effort required to understand speech in noise might be lower for spatially separated speech and noise than for co-located speech and noise. The current study therefore measured listening effort required when speech and noise are spatially separated and co-located, in addition to SRT measurements. The findings of the current study are intended to help in interpreting the results for the CI users.

5.1.1 Summary of objectives

The objectives of this study were to:

1. Evaluate the methodology designed to investigate the spatial benefits for speech perception in noise using the TDT. In other words, to ensure the SRT obtained from the TDT would be similar to what was anticipated from previous studies (Hall, 2006; Dowell, 2010) and that the method does not need any further refinements.

2. Determine normative values of spatial benefits, including SRM, binaural squelch, head shadow and summation effects with the TDT. The normative values were determined by providing the mean and 95% confidence intervals of the mean for each benefit. The hypothesis is that normal-hearing listeners would show all the spatial benefits with a greatest benefit for SRM.

3. Compare the SRM measured with the TDT from the current study to that measured previously by the researcher with other common speech materials that are currently in use. SRM with BKB and ATT was previously measured using similar methods to that used in this project. Given that a similar SRM was reported for sentences (Hawley et al., 2004) and words (Litovsky, 2005),

the hypothesis is that the SRM would be similar across the different speech materials.

4. Determine whether normal-hearing listeners experienced benefit in terms of listening effort required to understand speech in noise when speech and noise were co-located versus when they are spatially separated. Given that the amount of informational masking tends to be reduced for spatially separated speech and noise compared to co-located speech and noise, it was expected that listening effort experienced by the normal-hearing listeners might be lower for spatially separated speech and noise than for co-located speech and noise.

5.2 Additional methods

Testing was approved by the Institute of Sound and Vibration Research Human Experimentation Safety and Ethics Committee (reference number: 1934).

5.2.1 Participants

Sample size calculation was conducted to determine the appropriate sample size required for the current study. The mean difference of the differences in SRTs at two different noise locations was estimated to be 1.1 dB, and the standard deviation of such differences was 1.4 dB, based on the results of Van Deun et al., (2010) who used the Dutch numbers test. The sample size calculation with statistical power of 80% indicated that at least 15 subjects were required to detect a difference in thresholds of about 1 dB between different noise locations (two-tailed tests, δ=1.1 dB and σ=1.4 dB, α=0.05). It should be noted that the above statistical sample size calculation was for detecting the difference between mean SRTs at different noise locations, not for providing a normative value.

Twenty normal-hearing adults were recruited from the student population at the University of Southampton, based on the criteria stated in Section 4.3.1.1. Initial analysis of the data of the 20 adults showed results inconsistent with the study conducted previously in our laboratory by Causon (2011). The mean SRT of the 20 participants was found to be about 5 dB lower (i.e. better) than that reported by Causon's study. Among many attempts made to rule out the possible reasons for that difference between studies (see Section 5.4.1), ten more normal-hearing adults were recruited with the aim of ensuring that their thresholds were comparable to those of the other 20 participants. It should be noted that the ten extra participants were recruited as a practical way of double checking, and no sample size calculation was conducted for that stage. The mean threshold was, indeed, found to be similar across the 20 and the 10 participants. An approval from the Institute of Sound and Vibration Research Human Experimentation Safety and Ethics Committee (reference number: 7846) was obtained for recruiting and testing the 10 extra normal-hearing participants.

In total, 30 normal-hearing participants were recruited, which increased the statistical power to 98%. The experiment was terminated after fully recruiting and testing 30 listeners, in which they all had normal hearing and were aged between 18 and 35 years (mean age: 25 years; 20 females, 10 males). Six who had participated in the localisation task also took part in this study. Participants were paid £10 for their participation. All participants signed informed consent forms after being provided with details about the study.

5.2.2 Procedure

The test procedure was similar to the procedure described in Section 3.4. An overview of the basic points is presented in this section. Participants were seated individually in the centre of a lighted loudspeaker array, facing the frontal loudspeaker at 0° azimuth. The TDT was used, where digits were always presented nominally at 65 dB (A) from the frontal loudspeaker. The noise was presented using the adaptive procedure described in Section 3.4.4, either from the frontal loudspeaker (N0°) or the loudspeaker placed at +90° (N+90°) or -90° (N-90°) to the participant.

Table 5.1 summarises the measurements conducted on each of the normal-hearing participants. Eighteen SRTs were obtained for each participant: 2 listening modes (binaural and monaural listening) x 3 noise locations (N0°, N+90° and N-90°) x 3 repetitions. It is necessary to test normal-hearing listeners listening with one ear, in order to measure some of the spatial benefits for speech perception (Figure 2.6). When switching between binaural and monaural listening modes, participants were engaged in a 5-10 min conversation in order to allow brief acclimatisation to the new listening condition. The order of listening modes was counterbalanced across participants, following a Latin square design, as was the order of noise location within listening modes. However, given that there were only three noise locations and that the completion of the Latin square required a multiple of three participants, the presentation order of noise location was incompletely counterbalanced in the case of the 20 and the extra 10 participants.

Once the binaural SRT was determined for each noise location, the amount of listening effort required to understand speech in noise was estimated using the listening effort scale (Appendix A.1) and response time. Participants were asked to rate their listening effort required to understand speech with noise at N0°, N+90° or N-90° on a scale ranging from 1 (''Extreme effort'') to 7 (''No effort at all''). The total time spent by each participant to determine binaural SRT with N0°, N+90° and N-90° was also determined based on the calculations implemented in MATLAB code. Three listening effort measurements were obtained for each noise location (N0°, N+90° and N-90°) on both the listening effort scale and for response time.

Testing was performed in one session, which took approximately one hour and 45 minutes. Frequent rest intervals were provided during the session. The session started with practice to familiarise the participant with the task.

Table 5.1: Overview of the measurements for speech perception obtained from each of the 30 normal-hearing participants.

Listening mode	N0°	N+90°	N-90°
Binaural listening	3	3	3
Monaural listening (one ear chosen at random was blocked using an earplug and earmuff)	3	3	3

5.3 Results

The results of speech perception in noise obtained from the 30 normal-hearing subjects are presented in this section. The reliability of the adaptive TDT measurements was first determined, as described in Section 5.3.1. The SRTs are then presented in Section 5.3.2. Spatial benefits, including SRM, binaural squelch, head shadow and summation effects as well as listening effort are all described in Section 5.3.3. Section 5.3.3 also presents the SRM with the TDT from this study compared to that with BKB and ATT which was previously obtained in our laboratory by the researcher.

5.3.1 Test-retest reliability

Three SRTs were obtained for each of the 30 subjects and for each listening mode and noise location and so repeatability could be assessed. Table 5.2 shows the mean SRTs (standard deviations) for each of the three repetitions for each listening mode and noise location. It seems that the mean SRT was similar across the three repetitions. The greatest difference in SRTs between the three repetitions was found to be negligible (less than 1 dB) and it was for the monaural listening mode with noise placed at the front. Given that the differences in SRTs between the replications were less than the minimum step size of adaptive procedure used in the current project (i.e. 2 dB), the SRTs for the three replications can be considered equivalent.

Statistical results for reliability involving inter-class correlation (ICC) are also presented in Table 5.2. The ICC among the three SRTs was determined through a two-way mixed effect model (between-subject random factor and within-subject fixed factor of replication), with absolute agreement. Given that the interest here was to assess reliability of the mean, rather than a single replication, the average measure ICC was reported in the table, where a value closer to one indicates higher reliability. Results of ICC indicate a statistically significant and relatively strong relationship between the three SRTs for each listening mode and each noise location (r > 0.60). Generally, the ICC was higher (i.e. better) for the binaural listening mode with a smaller spread of test-retest scores than for the monaural listening. The wider confidence intervals for the test-retest scores for monaural listening might be the result of the unfamiliarity of the normal-hearing listeners with monaural listening. The above results together suggest that the SRTs determined adaptively using the TDT were repeatable without a significant learning effect.

Table 5.2: Mean SRTs (and standard deviation), in dB SNR, for different noise locations and listening modes. Test-retest statistics including two-way mixed intra-class correlation are also listed.

		Mean SRT (SD) for each repetition			ICC	
		rep1	rep2	rep3	***r*** (confidence interval)	***P***
Binaural	N0°	-13.6 (2.1)	-14.0 (1.9)	-13.8 (2.3)	0.65 (0.35-0.82)	<0.001
	N+90°	-20.2 (2.8)	-20.1 (2.7)	-20.4 (2.9)	0.86 (0.74-0.93)	<0.001
	N-90°	-19.4 (2.7)	-19.7 (2.4)	-19.4 (2.9)	0.82 (0.66-0.90)	<0.001
Monaural	N0°	-12.6 (2.2)	-13.2 (2.8)	-13.4 (2.5)	0.60 (0.21-0.78)	0.003
	N-Ipsi	-10.7 (2.9)	-10.0 (3.4)	-10.9 (3.0)	0.61 (0.27-0.79)	0.001
	N-Contra	-17.5 (2.4)	-18.0 (3.1)	-18.3 (2.3)	0.61 (0.33-0.81)	0.001

N-Ipsi= noise on the ipsilateral side of the listening ear; N-Contra=noise on the contralateral side of the listening ear.

5.3.2 SRTs in noise

Figure 5.1 shows the SRTs, averaged across all three repetitions, obtained from normal-hearing subjects when listening binaurally (left panel) and monaurally (right panel) for different noise locations. Lower SRTs reflect an ability to tolerate more adverse SNR (i.e. better performance).

For the binaural listening, the SRTs improved when the noise was separated from the speech for noise at +90° or -90° of the subject. For the monaural listening, the SRTs decreased (i.e. better) by about 5 dB when the noise was moved to the contralateral side of the listening ear, and increased by about 2.5 dB for noise on the ipsilateral side of the listening ear. The higher SRT for noise placed at the ipsilateral side to the listening ear is expected since the noise is on the same side of the listening ear and therefore SNR is not favourable.

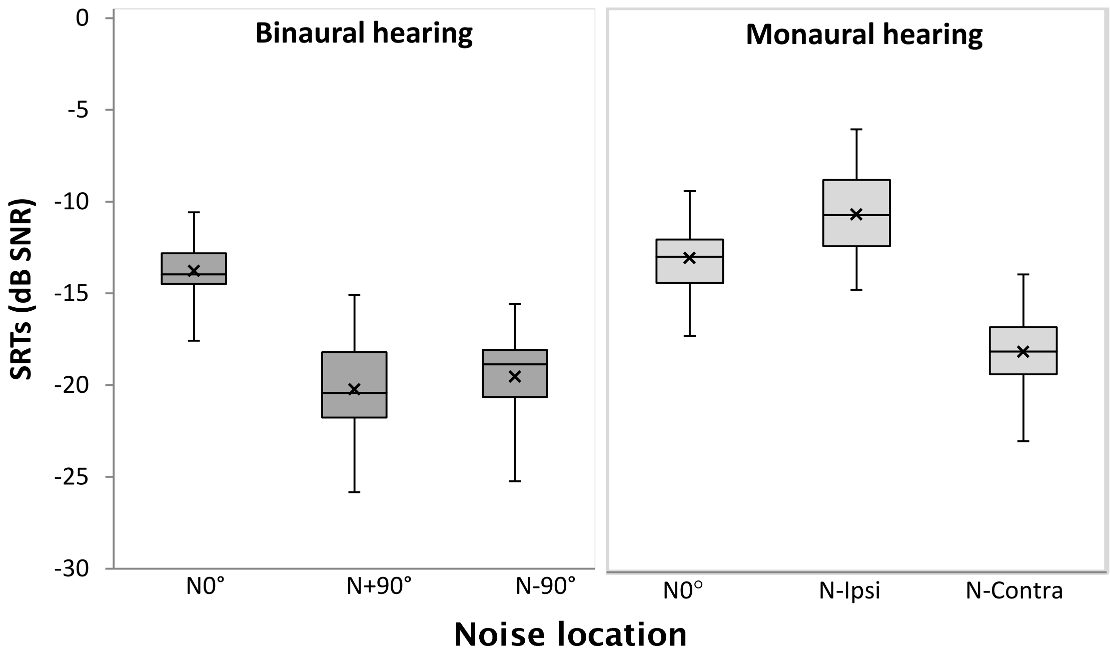


Figure 5.1: Speech reception thresholds (SRTs), in dB SNR. The left panel shows SRTs for the different noise locations (N0°: noise at 0° azimuth; N+90°: noise at 90° to the right; N-90°: noise at 90° to the left) while listening binaurally. The right panel shows SRTs for the different noise locations (N0°: noise at 0° azimuth; N-Ipsi: noise on the ipsilateral side of the listening ear; N-Contra: noise on the contralateral side of the listening ear) while listening monaurally. Each box represents the two middle quartiles (end of boxes), separated by the median (horizontal line), maximum and minimum values (horizontal lines at the end of whiskers), and mean value (cross inside the box).

5.3.3 Spatial benefits

Figure 5.2 shows scores obtained from 30 normal-hearing subjects for SRM, binaural squelch, summation and head shadow, averaged across right and left ears. The normative values of the benefits were determined by showing the mean and the 95% confidence intervals, providing an estimate of population mean (Figure 5.3). The description of the measures of these benefits was presented earlier, in Section 2.3.2. The values of these benefits are derived from Figure 5.1 by comparing SRTs for different noise locations and listening modes, as illustrated in Figure 2.6. The following sections present the spatial benefits for speech perception in noise.

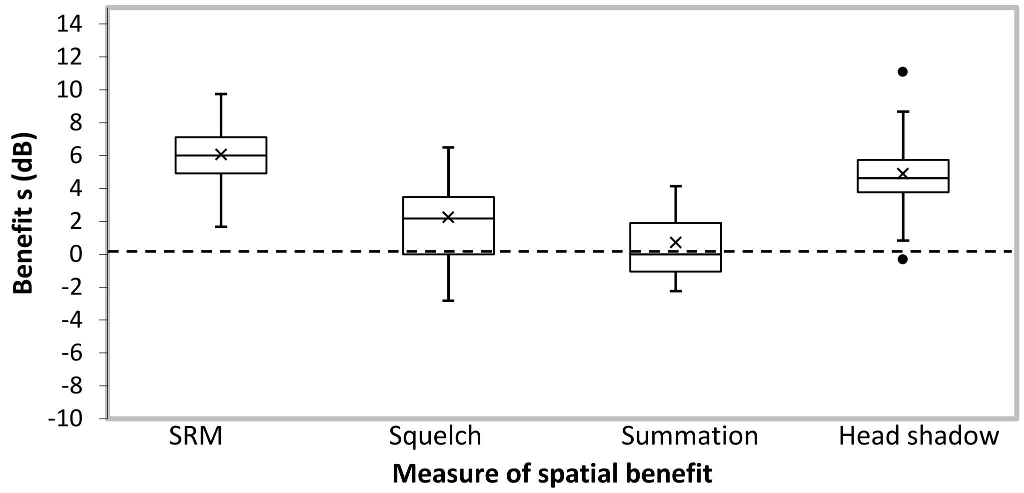


Figure 5.2: Spatial benefits for speech perception in noise, in dB, for the normal-hearing participants, averaged across both ears: SRM, binaural squelch, summation and head shadow effects. The characteristics of the box plots are as described in Figure 5.1. The circles represent outliers, which are values that lie between 1.5 and three times the interquartile range below the lower quartile or above the upper quartile. The horizontal dashed line indicates no benefit.

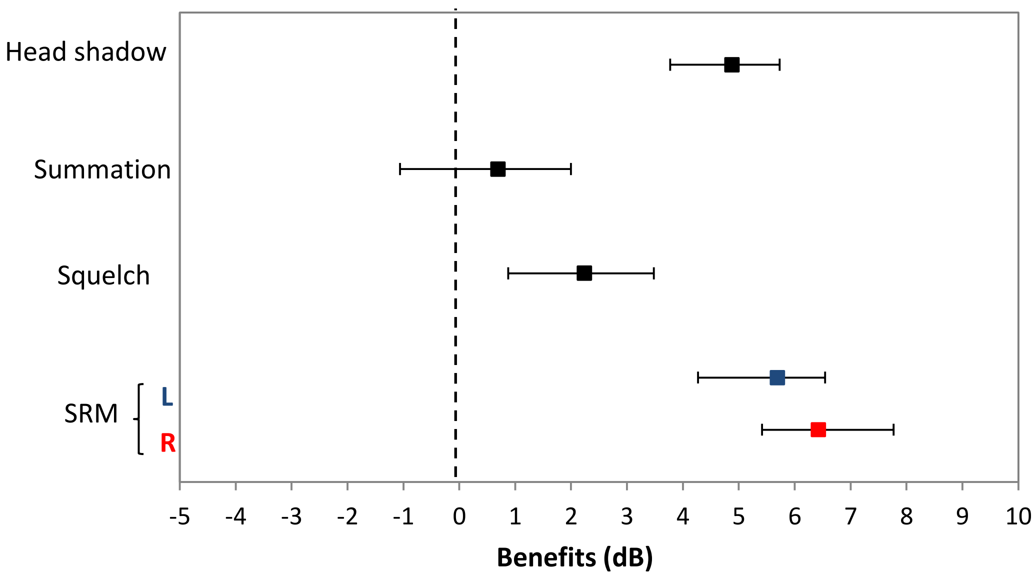


Figure 5.3: Mean spatial benefit, in dB, for normal-hearing subjects. Error bars represent 95% confidence intervals. SRM for each ear (R: right ear; **L**: left ear) is also shown. The vertical dashed line indicates no benefit.

5.3.3.1 Binaural benefit: SRM

The mean SRM benefit was 6.05 dB, meaning that the normal-hearing subjects had lower SRTs for the noise presented from the side than the noise presented at the front, by about 6.05 dB. The smallest SRM experienced by the normal-hearing subjects was 1.6 dB. The mean SRM seems to be similar for the right ear (6.4 dB) and left ear (5.7 dB). The 95% confidence interval for the mean SRM indicates significant SRM (Figure 5.3).

Figure 5.4 compares SRM with the TDT from the current study to the SRM obtained previously with the BKB and ATT. An experiment had been conducted earlier in our laboratory by the researcher to determine SRMs with BKB and ATT (See Appendix B.1 for more details). SRTs of 30 normal-hearing subjects, none of whom participated in the current study with the TDT, had been determined with BKB and ATT for noise at the front and at the side (N+/-90°). The figure shows similar mean amounts of SRM to those obtained with the TDT, BKB and ATT. Statistical analysis was conducted on the SRM values to indicate that the SRM of the TDT was not significantly different from SRM of the BKB (independent *t*-test: $t\,(58)=0.29$, $P > 0.1$) and the ATT (independent *t*-test: $t\,(58)=1.43$, $P > 0.1$).

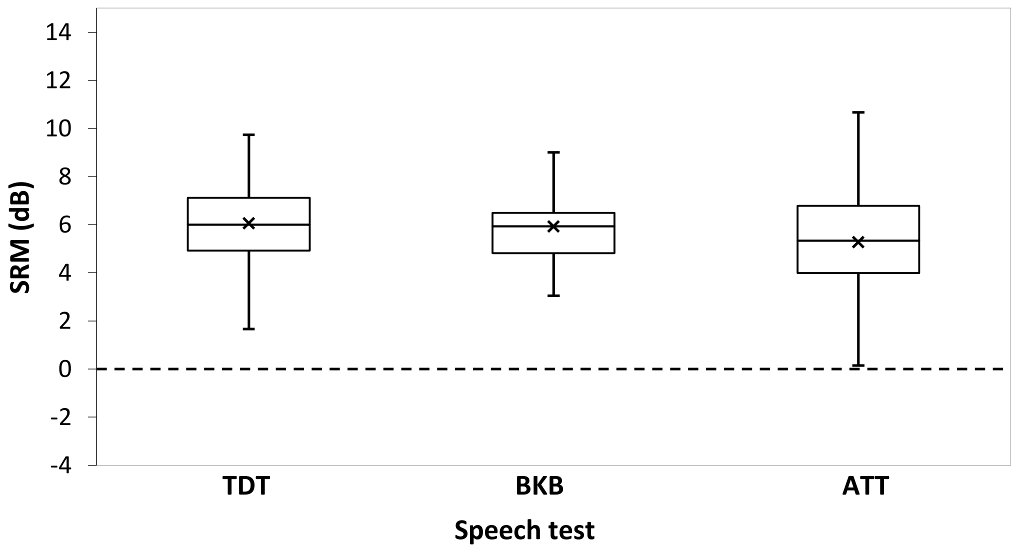


Figure 5.4: SRM (in dB) for different speech tests: TDT, BKB and ATT. The characteristics of the box plots are described in Figure 5.1. The horizontal dashed line indicates no benefit.

5.3.3.2 Binaural benefit: Squelch effect

The squelch effect was calculated as the difference in SRTs between monaural listening with N-Contra noise location and binaural listening. The mean binaural squelch was 2.23 dB (95% confidence intervals 0.87 to 3.47 dB), indicating that normal-hearing subjects significantly benefited from adding the ear with the poorer SNR.

5.3.3.3 Monaural benefit: head shadow effect

Effect of head shadow was calculated as the difference in monaural SRT between N0° and N-Contra noise locations shown in the right panel of Figure 5.1. The mean head shadow effect was 4.8 dB. The 95% confidence intervals for the mean head shadow ranged between 3.77 and 5.73 dB, suggesting significant benefit. The significant head shadow effect was significantly lower than the SRM (*t* (29) =2.3, *P*=0.02).

5.3.3.4 Binaural benefit: Summation effect

The mean summation effect, or the benefit from adding an ear with equal SNR, was less than 1 dB. The SRTs for speech and noise at the front were higher by 0.67 dB for binaural listening than for monaural listening. Given that the 95% confidence intervals for the mean summation effect include zero and negative values, this indicates no significant summation effect by the normal-hearing subjects.

5.3.3.5 Other benefits: Listening effort

Although normal-hearing subjects showed an improvement in SRTs when speech and noise were spatially separated (i.e. positive SRM), it is of interest to determine whether they experienced any benefit in terms of their listening effort (i.e. less listening effort to understand speech for noise at side than at front). Table 5.3 shows the mean and the 95% confidence intervals of the self-rated score of listening effort and the response time spent when the noise was spatially separated from speech (N+/-90°) versus when both speech and noise were co-located (N0°). The self-rated score and the response time were similar for different noise locations, indicating that there was no statistically significant benefit in terms of listening effort experienced by the normal-hearing subjects when speech and noise were spatially separated versus co-located.

Table 5.3: Mean (95 % confidence intervals) of self-rated score on the listening effort scale and response time for noise at the front (N0°) and at the side (N+/-90°).

	N0°	**N+90°**	**N-90°**
Self-rated scale (points)	3.8 (3.33-4.33)	3.8 (3.08-4.66)	3.8 (3.00-4.66)
Response time (seconds)	2.8 (2.5-3.32)	2.7 (2.40-3.16)	2.8 (2.41-3.23)

In summary, the results from the current study showed that normal-hearing subjects experienced significant spatial advantages for speech perception in noise, including SRM, binaural squelch and head shadow effects. Summation benefit was, however, not significant. Normal-hearing subjects appear to spend similar listening effort for both spatially separated and co-located speech and noise.

5.4 Discussion

The purpose of the current study was to provide normative values by determining the mean with 95% confidence intervals for different spatial speech benefits measured with the TDT. The results obtained for the SRTs in the current study agreed with those reported by previous studies which used digit triplets. The results also showed that normal-hearing subjects benefited from listening with two ears in different spatial configurations, as indicated by the statistically significant SRM (mean= 6.05 dB, 95% at 4.91 to 7.11 dB), head shadow (mean= 4.88 dB, 95% at 3.77 to 5.73 dB) and binaural squelch (mean= 2.23 dB, 95% at 0.87 to 3.47 dB). No statistically significant summation effect was, however, established (mean= 0.69 dB, 95% at -1.06 to 2.00 dB). Normal-hearing subjects showed no overall benefits in terms of listening effort in different spatial configurations. In the following sections, the SRTs from the current study are compared to previous studies using the TDT (Section 5.4.1). The spatial speech benefits are then discussed in detail.

5.4.1 SRTs in noise: comparison with previous studies

The results obtained for the SRTs in the current study compare favourably to previous studies that used digit triplets (Table 5.4). All the studies listed in the table presented the triple digits monaurally via headphones, and their SRTs were compared to the monaural SRTs obtained with noise at the front. It should be noted that the studies on the TDT were all conducted in our laboratory.

The mean SRT obtained in the current study is similar to that reported for the Dutch digit triplets and the TDT in previous studies. The similarity in the SRTs between the TDT and the Dutch National Hearing Test is encouraging, given that the two tests used similar parameters and had similar performance functions. Among all the studies listed in the table, only one study reported a higher (i.e. worse) SRT. A mean SRT of about -8 dB SNR was reported by Causon (2012), and the possible factors that might contribute to such differences between their study and the current study were still not clear. Some attempts were made to rule out the possible factors for such differences including checking the internal calibration, the RMS difference between the digits and noise and the code written through MATLAB, and all worked appropriately. A further attempt was made after checking the code and 10 more subjects were tested; all gave similar thresholds.

One possible methodological difference between the current and Causon's study is that the study of Causon was undertaken in a quiet room in our laboratory using the Automatic Sentence Test software. One could argue that the higher thresholds in Causon's study might have resulted from the effect of reverberation, whereas the current study was conducted in an anechoic chamber. The results of Morgan (2010) and Phipps (2007), however, exclude this possibility; they conducted their studies using exactly the same set-up to Causon's study and they still reported similar thresholds to the current study. In fact, the mean SRT reported by Causon was only comparable to the results of Phipps (2007), who reported mean SRT of -7.8 dB SNR from the telephone with limited bandwidth. Smits et al. (2004) also reported a higher threshold from the telephone (-7.1 dB SNR) than from the headphones (-11.2 dB SNR). Taken together, it seems that the SRTs from the current study look reasonable.

Table 5.4: Comparison of mean SRT (95% confidence intervals), in dB SNR, obtained with the TDT from the previous studies. The monaural SRT from Figure 5.1 is reported for the current study, since the SRT reported from the others was obtained monaurally via headphones. All studies presented digits in speech-shaped noise.

	Language	Speaker	Measurement Paradigm	SRT (confidence intervals)
The National Hearing Test (Smits et al., 2004)	Dutch	Trained female	Adaptive Noise fixed at 63 dB (A)	-11.2 (*)
The TDT (Hall, 2006)	English	Trained female	Adaptive Speech fixed at 55 dB (A)	-11.8 (*)
The TDT (Phipps, 2007)	English	Trained female	Fixed SNR Speech fixed at 55 dB (A)	-11.1 (*)
The TDT (Morgan, 2010)	English	Trained female	Fixed Adaptive Speech fixed at 55 dB (A)	-12.1 (*) -12.6 (*)
The TDT (Causon, 2012)	English	Trained female	Adaptive Speech fixed at 62dB (A)	-8.4 (-8.0 to -8.84)
The TDT (current study)	English	Trained female	Adaptive Speech fixed at 65 dB (A)	-13 (-11.8 to -14.2)

*ungiven information

As with the previous studies that determined SRTs adaptively with the TDT, the findings from the current study did not show a short-term learning effect. Only one study showed a significant learning effect in the TDT, which might possibly be due to the use of fixed SNR (Phipps, 2007). It might be possible that varying SNR within the adaptive procedure in the current study and the others makes each presentation different, which may discourage the subject from learning to use any useful cues (e.g. temporal and spectral cues) to recognise the digits. Feedback was not also given, so that the subjects were discouraged from using any cues to recognise the digits.

5.4.2 SRM with the TDT

When both ears were available to the subjects, the spatial separating of the speech and the noise improved understanding of the speech. The present study showed that SRM of about 6.05 dB occurred when the speech and noise were spatially separated (95% at 4.91 to 7.11 dB). The literature reported SRM of at least 3 dB for a single interferer and as high as 12 dB for multiple interferers (Bronkhorst and Plomp, 1988; 1992; Hawley et al., 2004). The larger SRM with multiple interferers can be explained by binaural cue functions, which seem particularly useful in more challenging environments with many interferers and/or that carry linguistic information resembling that in the target speech (Bronkhorst, 2000; Culling et al., 2004).

For a speech-shaped noise interferer, the average amount of SRM reported in this study is consistent with that reported previously of about 6 dB for sentences (Hawley et al., 2004) and 5.2 dB for words (Litovsky, 2005). The amount of SRM reported in the current study was also similar to that predicted by the SRM model (Culling et al., 2012; Lavandier and Culling, 2010), in which an average SRM of about 6 dB was reported for sentences presented in speech-shaped noise.

The above studies also show that the amount of SRM for the sentences and words seems to be similar to that found for the TDT. The finding that the SRM was similar across different speech materials is also consistent with the findings of the current study, showing similar SRM for the TDT, BKB and ATT tests. This finding is encouraging as it indicates that the TDT can be considered an alternative test to the BKB and ATT tests.

5.4.3 Binaural squelch

The SRM benefit had binaural and monaural components. The binaural component is measured by the squelch effect. A squelch effect of about 2.23 dB was reported for the TDT in the current study, which is in the range reported in the literature of 0.5 to 5 dB (Bronkhorst and Plomp, 1988; 1992; Hawley et al., 2004). The average amount of the squelch effect is higher that reported for the Dutch numbers test of about 1 dB (Van Deun et al., 2010). It is, however, lower the squelch effect reported by previous studies such as Hawley et al. (2004) and (Zurek, 1993).

It is not clear whether the squelch effect obtained in the current study was underestimated by the relatively good SRTs obtained in the reference condition when the subjects were listening monaurally. It is possible that the good monaural SRTs in the relatively easy reference condition with the noise contralateral to the listening ear (mean SRT= -18 dB SNR) might have suppressed any additional benefits from hearing binaurally. It might also be possible that the way in which SRTs were measured (i.e. by making the noise louder to achieve more negative SNRs) may have had an influence on the performance of the normal-hearing subjects, although this is probably not a concern for the CI users. The 95% confidence interval for mean squelch effect in this study (0.87 to 3.47 dB), importantly, includes the mean squelch effect in the study of Hawley et al. (2004).

5.4.4 Monaural head shadow

The SRM benefit reported in the current study appears to be largely produced by the monaural head shadow effect. When the noise moved from the front to one side of the subject, one ear will offer a better SNR than the other ear, due to the head shadow effect, so the listener can select the ear with the SNR and ignore the content of the noise in the other ear. The average amount of head shadow benefit was 4.88 dB for the TDT. Other studies have reported head shadow benefit of 4 dB (Hawley et al., 2004) and 3.8 dB (Van Deun et al., 2010).

Although previous studies have shown head shadow effect of up to 13 dB for normal-hearing listeners (Bronkhorst and Plomp 1988; 1992), the magnitude of head shadow is mainly dependent on the location of noise. As with Hawley et al. (2004) and Van Deun et al. (2010), the current study determined the head shadow by comparing monaural SRTs when the noise was at the front versus when on the non-listening side. Other studies calculated head shadow slightly differently from the current study and a larger benefit was reported. Indeed, when the head shadow effect was determined as the difference in monaural SRT when the noise was in the listening ear versus the non-listening ear (see the right panel in Figure 5.1), a head shadow effect of 7 dB was found. The latter finding may have implications for unilaterally deaf listeners and unilateral hearing aid or CI users. When the noise is placed on the ipsilateral side of the listening ear, the listener has to turn her/his head, such that speech is on the side of the listening ear, although this situation will make lip reading impossible.

Overall, the findings of this study showed that both monaural head shadow and binaural squelch effects contributed to the SRM benefit. The head shadow effect seemed to play a major role in understanding speech in a situation where one interfering sound was presented. This may suggest that in such a listening situation monaural listening seems to be sufficient to produce SRM. The findings of a greater contribution of head shadow to SRM are similar to the findings of Hawley et al. (2004) and to those predicted by the SRM model (Lavandier and Culling, 2010).

5.4.5 Binaural summation

Summation benefit with the TDT was found to be not significant for normal-hearing subjects. This finding is not surprising, given that previous studies showed similar thresholds for speech and noise placed in front of the listener when presented monotically (i.e. the signal is presented to a single ear) and diotically (i.e. identical signals presented to both ears) (Hawley et al., 2004). Additionally, studies have reported similar detection thresholds for a tone in noise presented monotically or diotically (Sever and Small, 1979). The current study supports the evidence that both the monotic and diotic masking involve equivalent processing. When speech and noise are placed directly from the front, both have the same interaural cues and therefore, the cues available in the monotic condition seem to be the same as in the diotic condition.

There were, however, some studies that showed a difference between monotic and diotic conditions for tone detection (Davis et al., 1990; Langhans and Kohlrausch, 1992; McFadden, 1972) and speech perception (Bronkhorst and Plomp, 1988). It was suggested that the interactions between the right and left hearing pathways could be responsible for minimising internal noise, leading to better thresholds for diotic over monotic conditions (Langhans and Kohlrausch, 1992). Despite the methodological differences, it might be possible that the better diotic thresholds in the above studies resulted from the use of spectrally non-overlapping signal and noise. Kidd et al. (2005) reported that better thresholds could be obtained in the diotic condition than in the monotic condition when the overlap of spectral information between the signal and noise was limited.

5.4.6 Listening effort

The results from the current study indicated that the amount of listening effort did not change for spatially separated versus co-located speech and noise. To the best of this researcher's knowledge, no previous study has reported the possible listening effort benefits for spatially separated speech and noise for speech perception. One possible reason for the lack of listening effort benefit for spatially separated speech and noise reported on the current study is that the speech perception with the TDT was relatively not difficult enough to require more listening effort, even in more adverse listening situations. It might be possible that listening effort benefit had been suppressed by the lower listening effort reported for the reference condition, where the speech and noise were co-located. Another possible reason is that the subjects themselves may have overestimated their capabilities, and then have reported similar listening effort on the listening effort scale for different noise locations. Previous studies have shown that people are not accurate in judging how much effort they spent to do a task (Downs and Crum, 1978). This possibility was probably excluded, as the subjects also showed no listening effort benefit with regard to the response time measure.

It might also be possible that the lack of statistical evidence for listening effort benefit reflects the insufficiency of the sample size to detect the difference in listening effort for spatially separated versus co-located speech and noise. There is also a possibility that the listening effort measures used in the current project were not sensitive enough to detect any differences in listening effort for spatially separated and co-located speech and noise. It should be noted that the current study was only aimed to get an overall indication of listening effort benefit and it is beyond the scope of the current project to provide an accurate and sensitive measurement for listening effort. The current study used the self-report measure that is usually used in audiological practice (such as the University of Southampton Auditory Implant Services, USAIS) to assess listening effort. However, such a measure may not give an accurate measurements and this limitation is acknowledged. An objective measure that is more sensitive to listening effort for speech perception could therefore be considered as a measure for listening effort benefits, such as dual-task paradigms and pupillometric measures. In the dual-task paradigm, speech perception is the primary task and the secondary task could involve memory or probe reaction time tasks. Any increase in the listening effort to perform the speech perception task is observed when the performance on the secondary tasks decreases. Pupillometric, on the other hand, measures pupil dilation, which increases when greater effort is exerted.

5.5 Conclusions

Spatial benefits for speech perception with the TDT were determined in normal-hearing listeners. Based on the sample of 30 normal-hearing subjects tested, the conclusions of the current study are as follows:

- Normal-hearing subjects experienced statistically significant SRM benefit of about 6.05 dB (95% at 4.91 to 7.11 dB). The mean SRM benefit was similar for the TDT, BKB and ATT tests.

- The SRM benefit occurred from the statistically significant contribution of both monaural head shadow (mean = 4.88 dB, 95% at 3.77 to 5.73 dB) and binaural squelch (mean = 2.23 dB, 95% at 0.87 to 3.47 dB). No statistically significant summation benefit was established in the normal-hearing subjects (mean = 0.69 dB, 95% at -1.06 to 2.00 dB).

- Normal-hearing subjects did not experience statistically significant listening effort benefit for spatially separated speech and noise.

The current study may also indicate that:

- It seems to be impossible to determine the squelch effect and perhaps summation effects in CI users. The difference in squelch effect between CI users and normal-hearing listeners would also be impossible to detect.

- It might also be difficult to determine the difference in SRM and head shadow effect between CI users and normal-hearing listeners.

Chapter 6: Sound-source localisation by adults fitted with a single cochlear implant

6.1 Introduction

One of the main aims of this project was to measure localisation ability with synchronised bilateral cochlear implants (CIs), in order to determine whether adults implanted with such devices can take advantage of binaural cues that are not available when a single CI is used. In the two studies that have assessed localisation ability with synchronised bilateral CIs (Bonnard et al., 2013; Verhaert et al., 2012), one study (Verhaert et al., 2012) assessed localisation performance when the synchronised bilateral CI users were listening with both implants versus when they were listening with only one implant. They reported a significant improvement in localisation performance when their subjects listened bilaterally with both implants activated ($\overline{D}$ error = 35.0°) compared to when they listened unilaterally with one of their implants deactivated ($\overline{D}$ error =77.5°). Such findings led the authors to suggest that the synchronised bilateral CI subjects were able to make use of binaural cues that are not available when either implant is deactivated.

The study of Verhaert et al., (2012) may, however, be at risk of bias caused by the unfamiliarity of the bilateral CI users with listening unilaterally with one implant. It is possible that the deterioration in localisation performance by these subjects when listening with only one implant was attributable to the fact that they were not accustomed to listening in everyday life with a single implant. This means that the performance of the synchronised bilateral CI subjects listening with one implant might be underestimated and the true difference in localisation performance between listening bilaterally with two implants activated and unilaterally with one implant deactivated might be smaller than the reported difference. A fairer assessment would be then to compare localisation performance of bilateral CI subjects listening bilaterally to another group of unilateral CI users who had been implanted on only one side and who had become acclimatised to listening with one implant in everyday life.

A search in the literature revealed three studies that assessed localisation abilities of CI adults who are implanted with single CIs (Table 6.1). Although Buhagiar et al. (2004) concluded that unilateral CI subjects cannot localise sounds at better than chance level of unbiased guessing, the other two studies arrived at different conclusions. Nava et al. (2009) reported that some of the prelingually deafened unilateral CI subjects and all the postlingually deafened unilateral CI subjects showed localisation abilities at better than chance level of unbiased guessing. They suggest that the better than chance level of their unilateral CI subjects is more likely to reflect their ability to make use of monaural level cues that were not eliminated by the small range of roving in their study (±3 dB). A similar conclusion was also reached by Grantham et al. (2008) who reported that that half of their unilateral CI subjects could localise at better than chance range of unbiased guessing. Grantham et al. (2008), however, suggest that the localisation ability of two of the three subjects could reflect their ability to make use of monaural spectral cues determined by the head shadow effect. It is worth remembering that monaural spectral cues depend on how the sounds coming from different directions are spectrally shaped as a function of the pinnae and/or head shadow effects, whereas monaural level cues depend on how the sounds coming from different directions are attenuated as a function of the head shadow effect (Section 2.3.1).

While the studies of Grantham et al. (2008) and Nava et al. (2009) showed that some unilaterally implanted subjects who are accustomed to listening with one implant can show overall localisation error scores at better than unbiased guessing, it is of interest to consider whether these subjects can identify the locations of sound sources. That is, does their better than unbiased guessing performance reflect some ability rather than different guessing behaviour (Section 6.1.1). If so, the possible cues the unilateral CI users might be using to identify the locations of sound sources at better than unbiased guessing were explored in Section 6.1.2.

6.1.1 Do unilateral CI subjects localise at better than chance range expected from unbiased guessing?

Grantham et al. (2008) and Nava et al. (2009) both reported that some of their unilateral CI subjects could localise sounds at better than unbiased guessing performance. However, while the study of Grantham et al. (2008) considered the chance range expected from unbiased guessing when analysing the localisation ability of their subjects, Nava et al. (2009) did not. As pointed out in Section 4.2.2, a probable range of errors occurring by guessing, rather than just a single value, should be considered in order to be more certain that chance is not the basis of observed localisation ability. Thus, the results of Nava et al. (2009) should be treated with caution, since they did not consider the chance range when analysing their data. It is possible that the better than chance level of unbiased guessing shown by some of their subjects was still based on unbiased guessing.

Table 6.1: Details of localisation studies on unilateral CI adults.

Study	Subjects	Set-up	Data analysis	Conclusions
Buhagiar et al. (2004)	***n***=18, all postlingual deaf.	**Set-up:** 11 loudspeakers between +/-90° at 18° intervals. **Stimuli:** speech, pink noise, tone at 1 kHz and transient. **Level roving:** the nominal stimulus level of 60 dB SPL was roved by ±5 dB. **Spectral roving:** the spectral content was roved randomly using 10 modifications of the master stimulus[5].	Scores of mean absolute error (MAE) were compared to chance level expected from unbiased guessing of 65.5°.	*''localisation performance was found to be close to chance for all stimuli''*
Grantham et al. (2008)	***n***= 6, all postlingual deaf.	**Set-up:** 9 loudspeakers between +/-90° at 20° intervals. **Stimuli:** speech and pink noise. **Level roving:** the nominal stimulus level of 70 dB SPL was roved by ±5 dB. **Spectral content** was fixed.	Scores of root mean square error ($\overline{D}$) were compared to chance range expected from unbiased guessing (between 68.8° and 74.6°). Scores of constant and random errors were also reported.	*''Some unilaterally implanted subjects can localise sounds at a better than chance level''*
Nava et al. (2009)	***n***= 14, 10 prelingual deaf and 4 postlingual deaf.	**Set-up:** 8 loudspeakers at +/-30°, +/-60°, +/-120° and +/-150°. **Stimuli:** noise burst. **Level roving:** the nominal stimulus level of 70 dB SPL was roved by ±3 dB. **Spectral content** was fixed.	Scores of MAE were compared to chance level expected from unbiased guessing of 90°.	*''some prelingually deafened adults implanted with a single CI can learn to localise sound at a better than chance level…''*

[5] When the researcher was tempted to use exactly the same spectral roving as Buhagiar et al. (2004), it was found that the spectral content of the stimulus was not roved in the way it was supposed to be carried out. The spectral content of the stimulus was roved using 5 spectral modifications with +3 dB (0-150 Hz, 150-200 Hz, 200-300 Hz, 300-400 Hz and 400-600 Hz) and 5 other modifications with -3 dB (75-150 Hz, 150-200 Hz, 200-300 Hz, 300-400 Hz, 400-600 Hz. The authors of the article were contacted and they acknowledged that the way they roved the spectral content of stimulus seems inappropriate due to something going wrong with the filter generation, although this was not noticed until too late.

Although Buhagiar et al. (2004) reported that unilateral CI subjects cannot localise at better than chance level, scanning the overall localisation error scores of their subjects showed that a few subjects might have been able to localise sounds at better than unbiased guessing range. Given that Buhagiar et al. (2004) used a similar localisation set-up to that used in the current research project, their data were re-examined with reference to the chance range expected from unbiased guessing. Figure 6.1 shows overall localisation error scores of their 18 unilateral CI subjects for speech and broadband noise. The chance range expected from unbiased guessing estimated by the simulation presented in Section 4.2.2 was also shown in the figure (the grey area surrounding the chance level in Figure 6.1). The figure shows that six of Buhagiar et al.'s subjects could localise at better than the chance range expected from unbiased guessing for either speech or broadband noise, and four of them achieved better than chance range for both stimuli. Taken together, it seems that some of the unilateral CI subjects in the study of Buhagiar et al. (2004), as well as that of Grantham et al. (2008), could show overall localisation error scores at better than chance range of unbiased guessing, while they may not have in Nava et al.'s study.

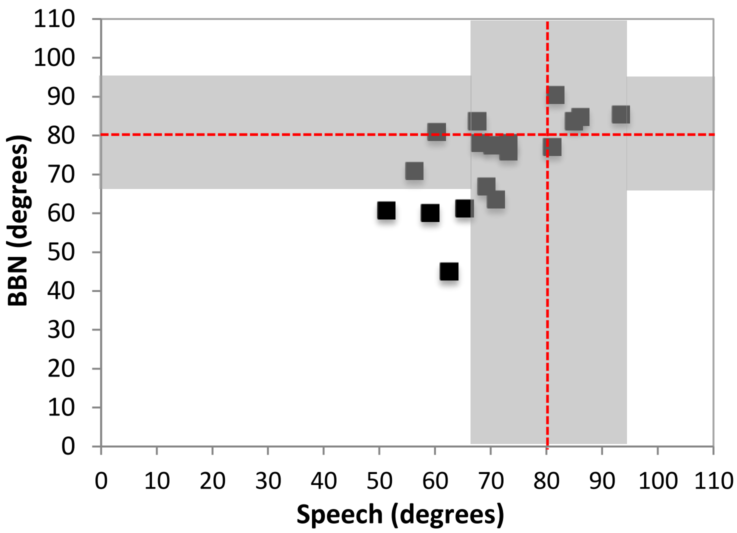


Figure 6.1: Overall localisation error ($\overline{D}$ error) scores of 18 unilaterally implanted subjects from a previous study conducted in our laboratory by Buhagiar et al. (2004) for speech and broadband noise stimuli. The red lines show the chance level expected from unbiased guessing, with the grey area indicating the chance range of unbiased guessing that was estimated by the simulation presented in Section 4.2.2. It should be noted that the MAE scores reported by Buhagiar et al. were converted to $\overline{D}$ error, which is generally preferable, since it is more sensitive to large errors.

6.1.2 How can unilateral CI subjects localise sounds at a better than chance range of unbiased guessing?

Given that some unilateral CI subjects can show overall localisation error scores at better than the chance range expected from unbiased guessing, the natural next question is: how can they localise sounds at better than unbiased guessing? The first possibility is that the better overall error score than expected from unbiased guessing might be achieved because the unilateral CI subjects were following biased guessing, where their responses were biased towards the frontal loudspeakers. As demonstrated in Section 4.2.2, a better than unbiased guessing performance does not necessarily reflect localisation ability, because such performance can also be achieved by a subject who is simply biased towards frontal loudspeakers. The results from the simulation, for example, showed that an overall $\overline{D}$ error score of about 54° can be obtained for biased guessing towards frontal loudspeakers.

With regard to Buhagiar et al.'s data displayed in Figure 6.1, it seems that the better than chance range of unbiased guessing shown by the six unilateral CI subjects fell within the chance range of biased guessing ($\overline{D}$ error of 54° to 66°) for all cases, except for one subject, with broadband noise. Given that Buhagiar et al. only reported the overall error scores of their subjects, it is impossible to determine whether better than unbiased guessing performance resulted from biased guessing or not. The authors of the article were contacted in an attempt to examine the pattern of responses shown by those subjects and to provide the whole picture of localisation performance, including constant error (i.e. bias) and random error (i.e. variability in responses). The authors, however, seem to have lost their data. Grantham et al. (2008) also did not investigate the possibility of biased guessing that might be followed by some of their subjects to perform at better than chance range of unbiased guessing. Scanning the scores of constant and random errors of their subjects, however, showed that the better than unbiased guessing performance by their subjects is unlikely to reflect biased guessing. Figure 6 in their article shows that the unilateral CI subjects who performed at better than chance range of unbiased guessing exhibited a relatively smaller constant error than random error. As shown in Section 4.2.2, one of the characteristics of biased guessing is that it is usually associated with a greater amount of constant error and much smaller random error.

Given that some unilateral CI users can localise sounds at better than chance range of unbiased guessing and that their performance is more unlikely to reflect biased guessing, they must then depend, in principle, on the use of monaural spectral and/or level cues. Grantham et al. (2008) suggest that the localisation abilities of some of their subjects were based on the use of monaural spectral shape cues, based on head shadow effect. Their suggestion was based on the fact that changing the spectral characteristics of the stimulus in Buhagiar et al.'s study results in chance localisation performance. Grantham et al. (2008) noted that the one main difference between the design of their study and that of Buhagiar et al. (2004) was that the spectrum of the signal was held constant during the former study, and thus the subjects were given the opportunity to make use of spectral cues. Such a suggestion, however, can be doubted for two reasons. Firstly, as demonstrated in Figure 6.1, six of Buhagiar et al.'s subjects can show overall error scores at better than chance range of unbiased guessing. Secondly, the validity of spectral roving used in Buhagiar et al.'s (2004) study is questionable, given that the way they roved the spectral content of the stimulus seems not to be roved in the way it was supposed to be carried out (See Footnote 5).

Although the subjects of Grantham et al. (2008) might have been able to make some limited use of spectral cues determined by head shadow effect, it is not clear whether such cues on their own could provide sufficient and reliable information for unilateral CI subjects to localise sounds. Although Grantham et al. (2008) attempted to exclude the contribution of monaural level cues in the localisation performance of their subjects, because the level of stimulus was roved by ±5 dB in their study, it might be possible that their subjects could still make use of this small range of level roving, through their acclimatisation to their implants. As documented by Agterberg et al. (2012), monaural level cues based on head shadow effect can be ± 15 dB, for high frequencies. A search in the literature did not reveal any studies that assessed localisation performance of unilateral CI subjects with larger than ±5 dB level roving, leaving it unclear to what extent the better than guessing performance exhibited by unilaterally implanted subjects could still be maintained with a relatively larger range of level roving.

Given the limitation in analysis reported by Buhagiar et al. and the conclusions of the above studies, the current study aims to determine whether localisation with a single implant is possible using the same procedures to those used with the synchronised bilateral CIs. In order to draw a solid conclusion on whether the synchronised bilateral CIs can actually provide any binaural advantage for localisation over signal CIs, the "better" performance that would be expected from adults implanted with single CIs was first established. The results of the current study are intended to help determine whether the bilateral CI subjects can make use of binaural cues for localisation. Two experiments are described in this chapter. The main experiment assessed localisation performance of unilaterally implanted adults who might be more likely to have some localisation ability. Individuals who showed better than guessing performance (biased and unbiased guessing) in the main experiment were tested in a follow-up experiment with different ranges of level roving, with the aim to determine whether the better than guessing performance could be maintained with a greater roving level.

6.1.3 Summary of objectives

The objectives of the current study were as follows:

1. Measure horizontal sound-source localisation performance in adults with single CIs, who might be more likely to have some localisation ability, using an identical set-up and procedure to those used with the synchronised bilateral CIs (Chapter 7) and normal-hearing subjects (Chapter 4). Given the findings of Buhagiar et al. (2004) and Grantham et al. (2008), it was expected that some unilateral CI subjects might be able to perform at better than the chance range expected from unbiased guessing, which is unlikely to reflect biased guessing.

2. Determine whether the better than guessing performance (unbiased and biased) shown by any unilateral CI subject could be maintained with greater roving level and whether it means they could actually localise. Although it was not known whether the better than guessing performance of unilateral CI subjects could be maintained with increased roving, it was expected that the localisation performance of unilateral CI subjects would deteriorate as the range of roving increased.

6.2 Additional Methods

Approvals were obtained from the National Research Ethics Committee Service (REC reference: 12/SC/0421, Appendix C.1), as well as the University of Southampton Research Governance Office and the Institute of Sound and Vibration Research Human Experimentation Safety and Ethics Committee (reference number: 2915), before commencing these experiments.

6.2.1 Participants

The present study aimed to establish the “upper limit” localisation performance that would be expected from adults with single CIs, with the main aim to compare their performance to that of the synchronised bilateral CI adults (Chapter 7). To help recruit unilaterally implanted subjects who might be more likely to be able to localise, the subjects were required to meet the following criteria:

- Unilateral CI user aged between 18 and 55 years, in order to minimise the ageing-related auditory and cognitive processing factors that might affect listening ability, including localisation. Emerging evidence suggests that such age-related factors generally begin to occur in 60-year-olds (Gates, 2012).

- Have at least one year of full use of implant, to ensure they had sufficient experience with their implant.

- Have a speech reception threshold (SRT) of no higher (i.e. worse) than +5 dB signal to noise ratio (SNR), determined adaptively using Bamford-Kowal Bench (BKB) sentences in speech-shaped noise. This cut-off point was selected based on the recommendation of the head of the University of Southampton Auditory Implant Services (USAIS), Dr Carl Verschuur, who suggested that this cut-off point would be reasonable given the performance of the unilateral CI users at the USAIS centre.

- Have profound hearing loss in the non-implanted ear, and have not worn a hearing aid in the non-implanted ear since they were implanted. This would help to eliminate any possible availability of binaural cues because of residual hearing in the non-implanted ear.

Thirty unilaterally implanted adults at the USAIS qualified to be invited to participate, based on the above criteria. Out of the 30 CI users contacted, only three subjects were willing to take part in the study. In order to get more subjects, the research team decided to slightly extend the above criteria to include those aged up to 65 years with a speech score in noise of maximum +8 dB SNR. A total of 16 additional unilateral CI adults met the extended criteria; however, only five of them responded to say they were willing to participate. Approval from the National Research Ethics Committee Service (REC reference: 12/SC/0421, Appendix C.2), as well as the University of Southampton Research Governance Office and the Institute of Sound and Vibration Research Human Experimentation Safety and Ethics Committee (reference number: 5358) was obtained for changing the inclusion criteria of the unilateral CI subjects.

The subjects who completed the experiment were 8 severely-to-profoundly postlingually bilaterally deafened adults from the USAIS. They consisted of four females and four males (median age of 45 years). They were implanted with a single CI which had one speech processor worn in the standard position, in which the microphone is located over the top front portion of the pinna, similar to the microphone position used in behind-the-ear hearing aids. Subjects were fitted using a clinical procedure standard at the USIAS, and their implants were programmed with the different speech processing strategies. They had their implants activated 1 to 21 years prior to being tested (median CI experience of 9.5 years). Subject information, including subject characteristics, duration of deafness prior to implantation, ear receiving the CI, and speech scores in noise post-implantation, is listed for all subjects in Table 6.2. Pure tone thresholds of the non-implanted ear for each subject were tested and are shown in Figure 6.2.

Before the start of testing, new batteries were provided. Subjects were instructed to select the volume settings on their clinically fitted processors that they were most accustomed to use. Neurelec paid for the subjects' transportation to the University of Southampton and for their lunch during their visit. Subjects were also paid £15 at the end of the testing day, after completion of both localisation and speech perception experiments. Subjects are identified by numbers assigned according to their performance.

Table 6. 2: Characteristics for unilateral CI subjects

Subject	Gender	Age	Aetiology	Duration of deafness	Ear implanted (type, strategy)	Years since activation	SRT (dB SNR)
S1	M	63	Unknown	2	L (Nucleus, ACE)	7	2.5
S2	F	48	Unknown	10	L (Med-EL, ACE)	1	4.7
S3	F	64	Family history	10	R (Nucleus, ACE)	6	6.7
S4	M	38	Head injury	1	R (AB, HiRes 90K)	6	5.2
S5	F	22	Unknown	10	R (Nucleus, ACE)	13	7.2
S6	M	54	Unknown	5	L (Nucleus, ACE)	16	4.0
S7	F	42	Meningitis	4	L (Nucleus, MP3000)	12	4.5
S8	M	24	Meningitis	2	R (Nucleus, SPEAK)	21	1.7

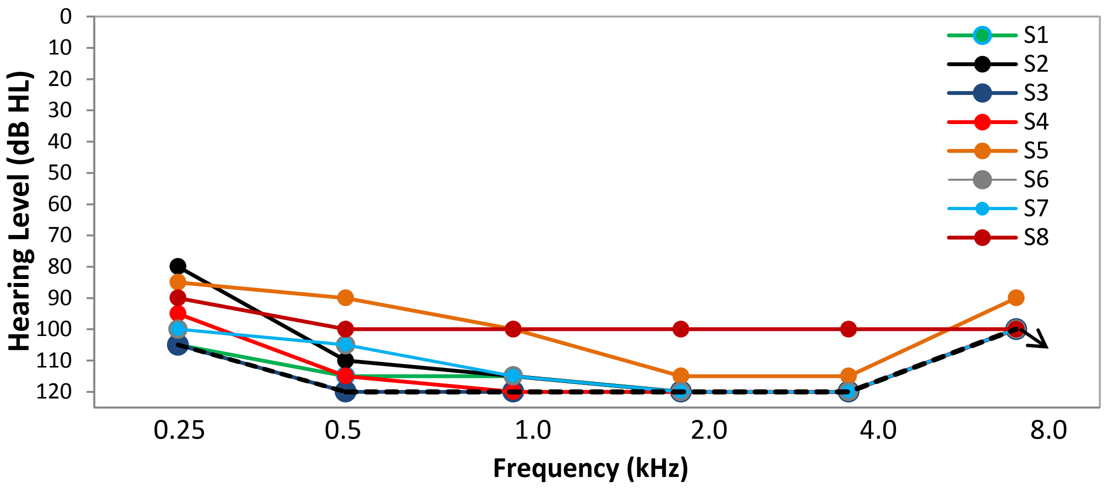


Figure 6.2: Pure tone thresholds for the eight unilateral cochlear implant subjects in their non-implanted ear. The dashed black line represents the limits of the audiometer for each frequency.

6.2.2 Procedure

Subjects each took part in two sessions on a single day, separated by a lunch break. Sound localisation and speech perception in noise were each tested in one session, selected at random. Subjects were fully informed and provided written consent before the first session.

For the localisation portion of testing, subjects each took part in one session lasting 2.5 to 3 hours, including frequent rest intervals. Testing set-up, stimuli and procedure details were identical to those described in Section 3.3. Subjects were seated in the centre of a lighted anechoic chamber. Eleven loudspeakers were positioned in a horizontal arc extending from -90° to +90° (Figure 6.3). After each stimulus presentation, the subject was asked to identify the loudspeaker from which the stimulus was presented by using a touch screen with an image of the loudspeaker array and clicking on the letter corresponding to the loudspeaker. Subjects were also instructed to keep their head directed towards the mirror placed above the central loudspeaker at 0° azimuth while the stimulus was presented, to minimise head movement. Each of the five stimuli listed in Table 3.1, including speech, broadband noise (BBN), low-pass noise (LPN), high-pass noise (HPN) and high-pass noise burst (HPN-burst) was presented 66 times (3 times from each of the 11 loudspeakers x 2 replications). The nominal stimulus level was 65 dB SPL (A-weighted) and it was randomly roved by ±4 dB from trial to trial during testing, whereas the frequency content of the stimulus was kept constant. The test session began with practice trials, which typically included presenting speech stimulus three times from each of the 11 loudspeakers.

Figure 6.3: Localisation set-up.

6.3 Results

Localisation performance of the eight unilaterally implanted subjects is described in this section. This includes the overall localisation error that is usually used to quantify localisation performance (Section 6.3.1) and random and constant errors (Section 6.3.2).

6.3.1 Overall localisation error

Overall localisation error, represented by $\overline{D}$ error, is shown in Figure 6.4 (MAE scores are presented in Appendix C.3). In Figure 6.4, the scores of $\overline{D}$ error of each of the eight unilaterally implanted subjects are displayed for different types of stimuli, where the grey area surrounding the chance level indicates the 99% chance range expected from unbiased guessing. Overall localisation error, presented in Figure 6.4, was averaged across the two replications, since neither consistent nor large differences in overall error were found between the two replications (see Appendix C.4).

Examination of Figure 6.4 reveals that three major 'categories' of subjects were observed among the unilateral CI subjects. Category A (subjects S1 and S2) showed a pattern of overall error scores that were consistently worse than unbiased guessing for all stimuli. Category B (subjects S3 and S4) showed a pattern of overall error scores that were consistently indistinguishable from unbiased guessing for all stimuli. Category C (S5, S6, S7 and S8) showed a pattern of overall error scores that were better than chance range of unbiased guessing in the stimuli usually associated with best error scores (i.e. broadband stimuli and/or high-pass noise).

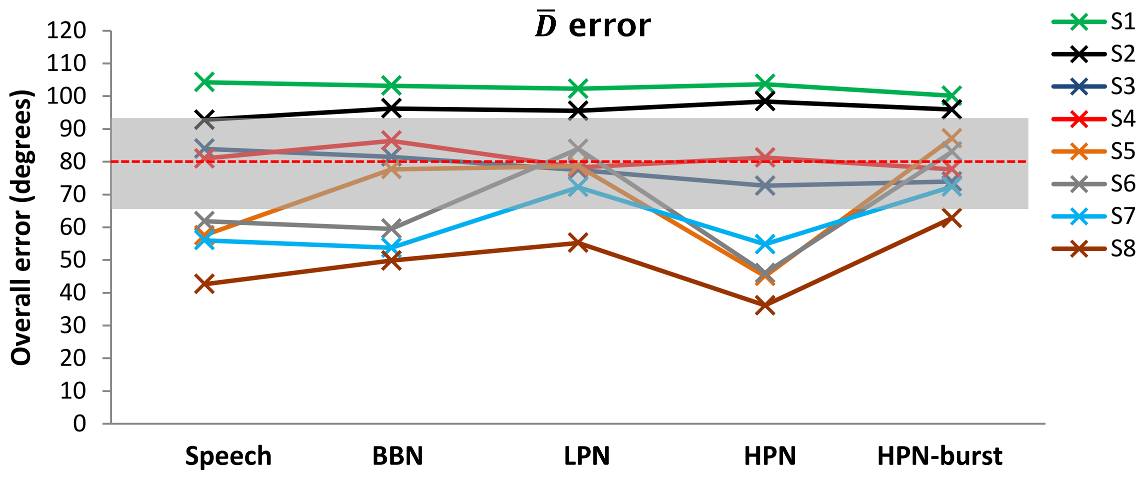


Figure 6.4: Individual overall localisation error (overall root mean square error, $\overline{D}$ error), in degrees, of the eight unilaterally implanted subjects and for each stimulus, averaged across the two repetitions: speech, broadband noise (BBN), low-pass noise (LPN), high-pass noise (HPN) and high-pass noise burst (HPN-burst). Each line represents a separate, numbered listener. The horizontal red line shows the chance level expected from unbiased guessing with the grey area indicating the chance range of unbiased guessing (see Section 4.2.2).

The three major categories of subjects noted in Figure 6.4 were found to reflect different response patterns. Localisation data of the unilaterally implanted subjects are displayed in Figure 6.5 for category A and B subjects and in Figure 6.6 for category C subjects. In these two figures, the mean response location (data point) is plotted as a function of actual loudspeaker location, whereas the standard deviation in responses for each loudspeaker location is represented by the size of the error bar. Data points falling on the diagonal line represent correct responses (i.e. perfect localisation performance), points falling below the diagonal line represent responses to the left of the actual loudspeaker location and points falling above the diagonal line represent responses to the right of the actual loudspeaker location. Only the localisation data of speech, broadband noise and high-pass noise are displayed, as they are usually associated with better overall error scores. Localisation data for low-pass noise and high-pass noise burst stimuli can be found in Appendix C.5.

Figure 6.5 shows the response patterns exhibited by category A and B subjects. Category A subjects, whose overall error scores were above the chance range expected from unbiased guessing, showed a pattern of guessing where responses were biased towards the end-most loudspeakers on their implant side. Subjects S1 and S2 were consistently pointing to loudspeakers at -72° and/or -90°, regardless of the actual loudspeaker locations. With regard to category B subjects, whose overall error scores were within the chance range expected from unbiased guessing, one might expect that their scores were achieved by responding randomly across all loudspeakers. This was, however, true for one subject, but not for the other. Subject S3 showed a pattern of unbiased guessing, where the mean responses were near to 0° and standard deviations were relatively large. However, subject S4 showed biased guessing towards the middle loudspeakers on the implanted side, between 36° and 72°. Although subject S4 showed biased guessing, like the category A subjects, this subject achieved a lower overall error score than those shown by category A subjects. The explanation of such a result can be postulated on the basis of the location of the loudspeaker towards which they were biased. The difference between response to loudspeaker location and actual loudspeaker location was smaller for those biased towards the middle loudspeakers than the end-most loudspeakers. Assuming the actual loudspeaker location is 90 °, for example, a greater error would be obtained for those biased to -90° (error=180°) than for those biased towards -54° (error =144°).

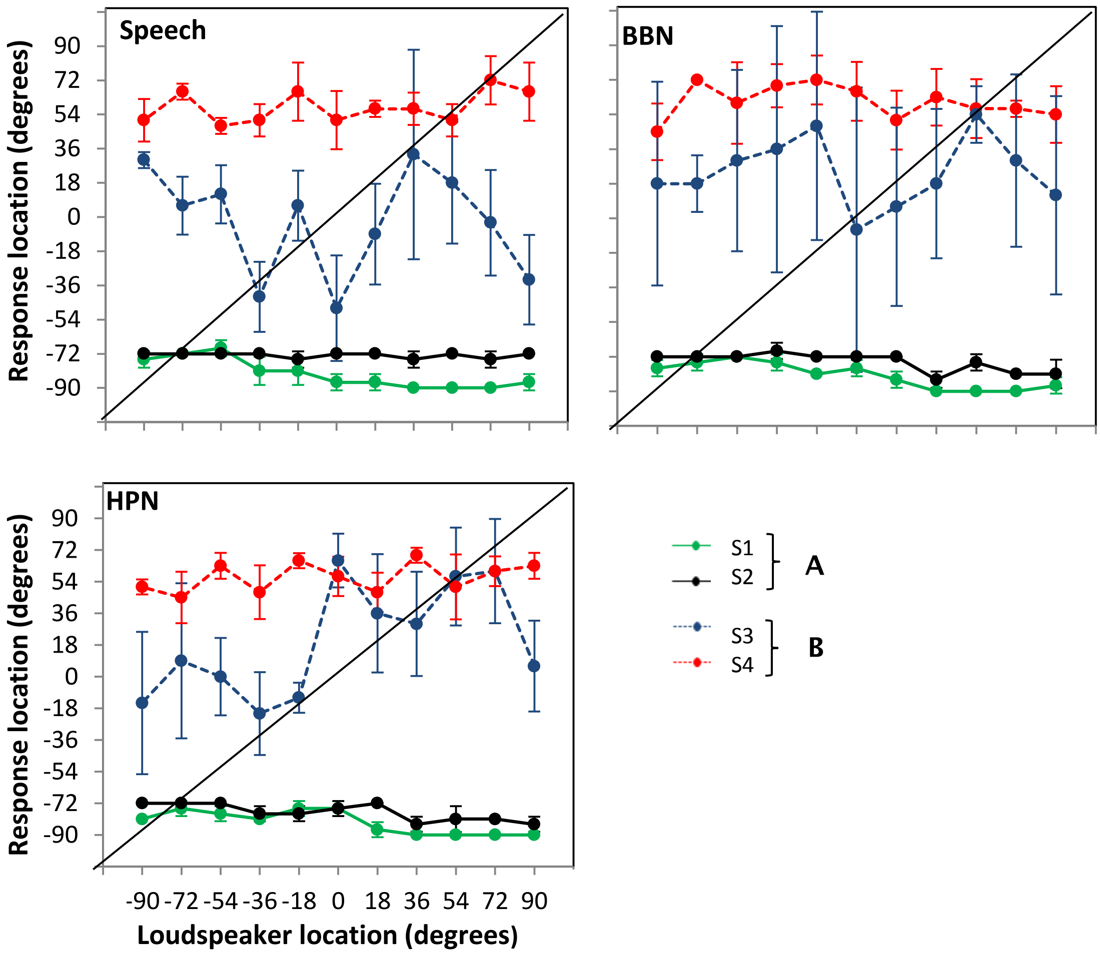


Figure 6.5: Sound localisation performance for unilateral CI subjects of category A and B while listening to different stimuli. Each data point represents the mean response given by a subject for each loudspeaker location. The error bar indicates the standard deviation across the 6 responses obtained at each loudspeaker location. The diagonal line represents the perfect localisation performance.

Figure 6.6 shows response patterns exhibited by category C subjects, whose overall errors were better than chance range expected from unbiased guessing. A better than chance range performance was shown by three subjects (S6, S7 and S8) for speech, broadband noise and high-pass noise stimuli and another subject (S5) for speech and high-pass noise stimuli. The responses of these subjects more or less showed a relationship between response locations and loudspeaker locations, with the data points lying relatively close to the diagonal line, particularly for azimuths between ±54°. Such a finding is of great importance, as it indicates that the better than unbiased guessing performance seems unlikely to reflect biased guessing. Assuming biased guessing towards frontal loudspeakers, an overall $\overline{D}$ error of about 54° to 66° can be obtained (see Section 4.2.2 for more details). While the overall error score of subject S8 was far below this range expected from biased guessing, the other three subjects had overall error scores that fall within the biased guessing performance. The next section examines in more detail the possibility of whether the better than unbiased guessing performance shown by category C subjects reflects biased guessing or not.

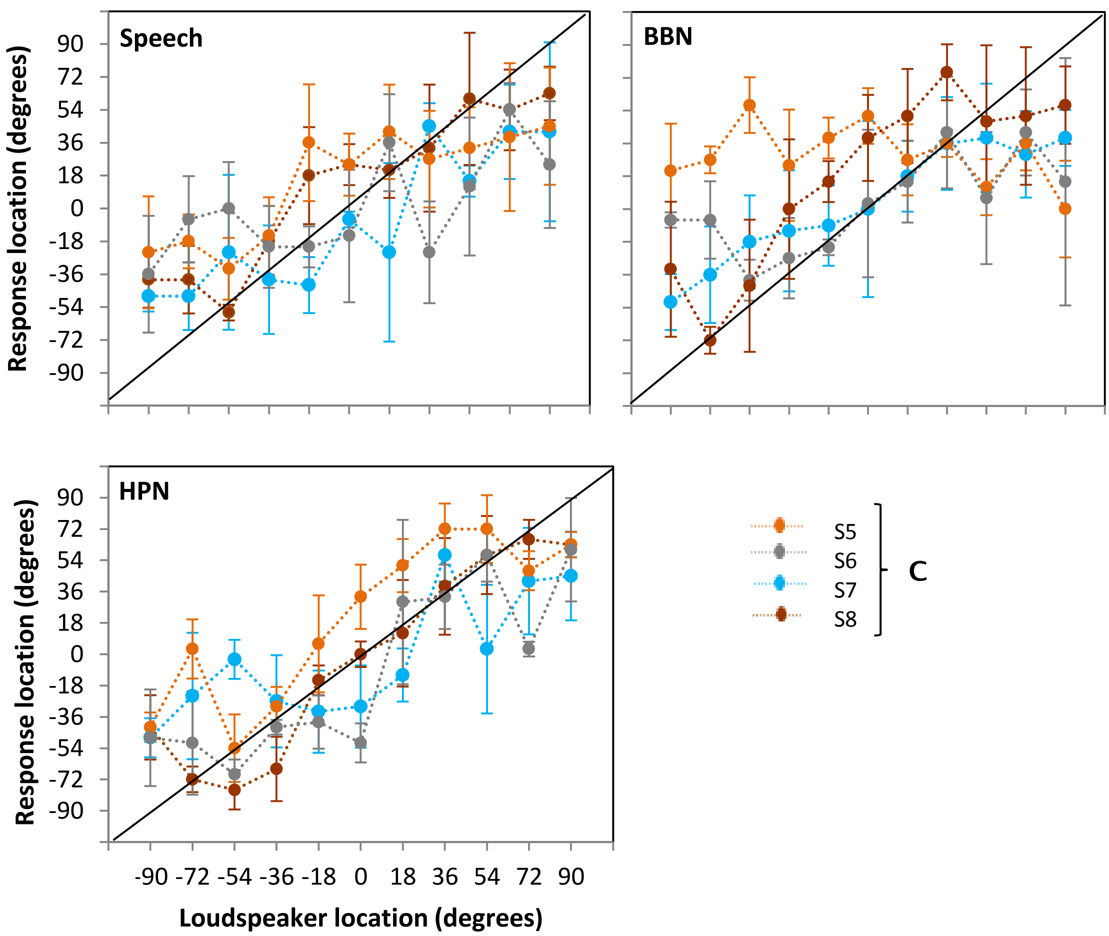


Figure 6.6: Sound localisation performance for unilateral CI subjects of category C while listening to different stimuli.

6.3.2 Random and constant errors

The overall error presented in Figure 6.4 only reflects the overall localisation error and does not provide on its own the main reason underlying the overall error. Overall $\overline{D}$ error is actually composed of both constant error (i.e. bias) and random error (i.e. variability in responses). It is worth remembering that the constant error refers to the deviation of the mean responses (the data points in Figures 6.5 and 6.6) from the loudspeaker locations (the diagonal line), whereas the random error is the standard deviation of responses at each loudspeaker location averaged across all loudspeakers (the average size of the error bars in Figures 6.5 and 6.6). In this section, the scores of constant error and random error are calculated and presented in Figure 6.7, with the aim to understand the main reason underlying the overall error shown by each category of subjects. The scores of constant and random errors can help to rule out whether the better than unbiased guessing performance shown by category C subjects is based on biased guessing or not.

Starting with category A subjects, Figure 6.7 shows that subjects S1 and S2 exhibited a massive amount of constant error and much smaller random error scores. Such scores are expected, given the responses of those subjects were consistently biased towards end-most loudspeakers on the side of their implants (Figure 6.5). The results from the simulation presented in Section 4.2.2 also showed that biased guessing is usually characterised by a considerably larger amount of constant error than random error. Category B subjects, on the other hand, showed considerable difference in the scores of both constant and random errors. As noted in the previous section, one subject (S3) showed unbiased guessing, whereas the other one (S4) showed biased guessing towards the middle loudspeakers on the implanted side. The unbiased guessing shown by subject S3 is characterised by relatively large scores for both constant error and random error. However, the biased guessing shown by subject S4 is associated with a greater amount of constant error and smaller random error. The amount of constant error was, however, smaller than that shown by category A subjects. Results from the simulation showed that the amount of constant error decreased as the loudspeaker towards which the subject was biased moved from the side towards the front. Figure 6.8 also shows that that category A subjects exhibited a greater response bias to the side of their implant than subject S4, where a signed constant error ($\overline{E}$) of about 80° off midline was reported for subjects of category A, compared to 54° for subject S4 of category B.

With reference to category C subjects, Figure 6.7 shows that the subjects exhibited lower scores on both constant error and random error than those in the other categories. Most importantly, the figure shows that scores of both constant and random error were far below those expected from biased guessing towards frontal loudspeakers (represented by the dashed area in the figure). This finding confirms that that the overall error scores of such subjects are unlikely to reflect biased guessing towards frontal loudspeakers. The figure also shows that category C subjects exhibited larger random error than constant error, indicating that their ''good'' ability to identify the correct loudspeakers was not necessary consistent. High-pass noise stimulus seems to be associated with smaller constant and/or random error than the other stimuli.

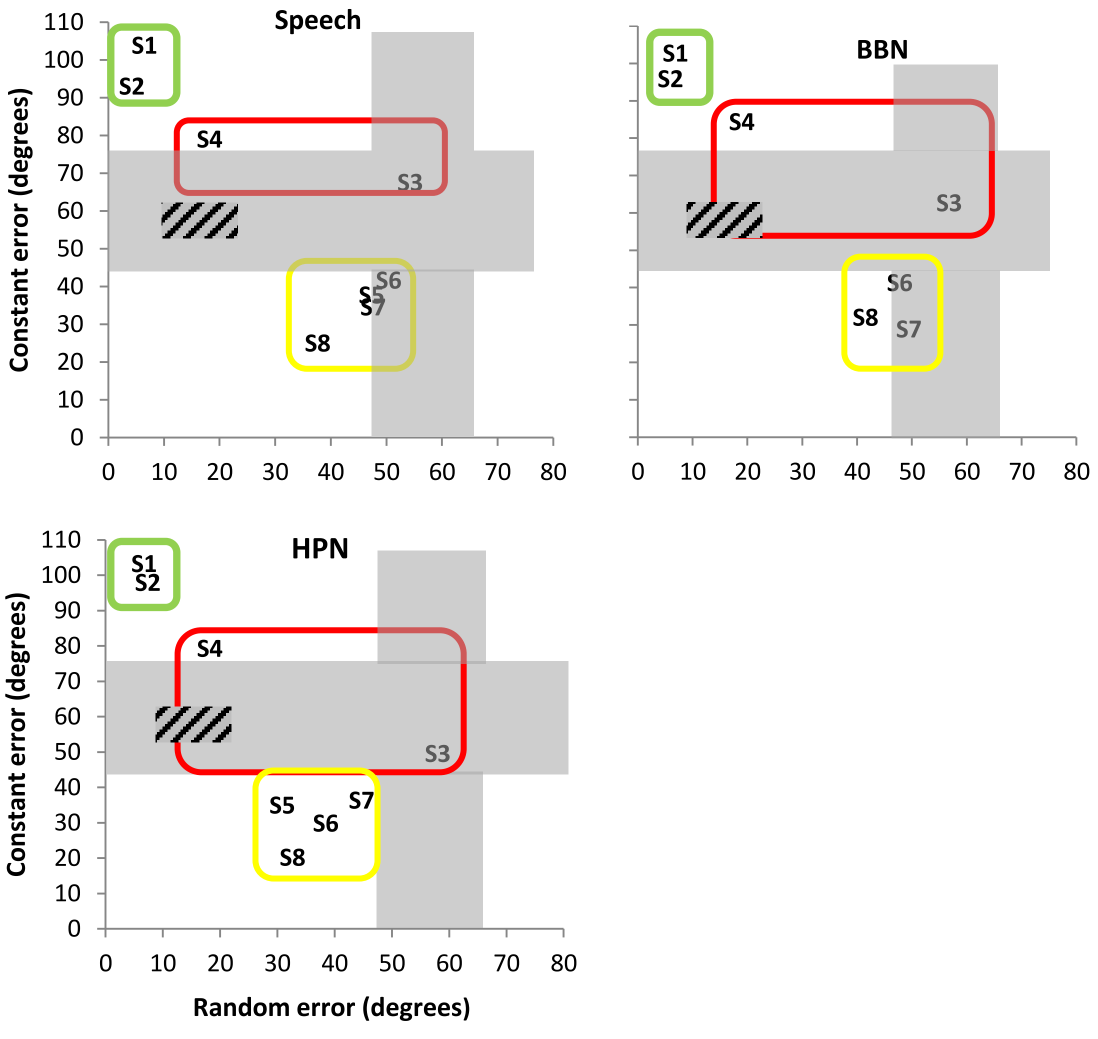


Figure 6.7: Random error (i.e. variability in responses) versus constant error (i.e. bias) for the eight subjects for different stimuli. Subjects were grouped according to their categories: category A (green box), category B (red box) and category C (yellow box). The grey area indicates the 99% chance range expected from unbiased guessing, whereas the dashed area indicates 99% chance range expected from biased guessing towards frontal loudspeakers (Section 4.2.2).

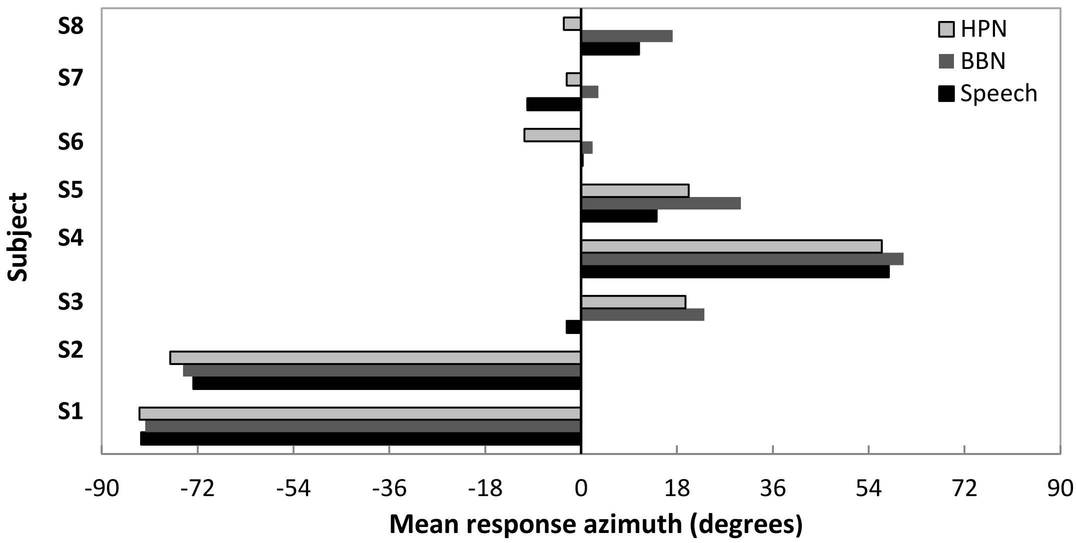


Figure 6.8: Signed constant error ($\bar{E}$) for each stimulus and each subject.

In summary, the results of the current study showed that some unilateral CI subjects could identify the locations of sound sources at better than chance range of unbiased guessing. The results also showed that the better than unbiased guessing performance was not the result of biased guessing. Given that the level of the stimulus presentation was roved by ±4 dB in the current study with the intention to discourage the use of monaural level cues, it is not entirely clear what cues they were using to identify sound sources. Although the role of monaural spectral cues cannot be excluded, there is a possibility that unilateral CI subjects, through their acclimatisation to their implants, can learn to use subtle monaural level cues to identify sounds, particularly with such a small range of roving. It is noteworthy that these subjects had at least 12 years' experience with their implant, which is much longer than that of other subjects (Table 6.2).

Given that the monaural level cues are more effective for high-frequency sounds, the finding of the current study that most of the unilateral CI subjects who showed better than guessing performance seemed to localise high-pass noise stimulus with better accuracy than the other stimuli may support the role of monaural level cues. In order to investigate this possibility, the localisation abilities of subjects who showed better than guessing performance in the current study (Category C subjects) were re-tested with a relatively large roving range, with the aim of determining whether their better than guessing performance could be maintained with a larger range of roving (see next section).

6.4 Follow-up study: cues used by unilaterally implanted subjects

This section presents a follow-up study where the subjects who showed overall localisation error scores at better than chance range of unbiased guessing from the previous experiment returned for another visit to our laboratory. The aim was to determine whether the better than unbiased guessing performance with ±4 dB roving in the previous experiment could still be maintained with a relatively larger range of roving and whether it meant that they can actually perceive the correct locations. Although it was expected that localisation performance of unilateral CI subjects would deteriorate as the range of roving increases, it is unknown whether those subjects can still localise at better than guessing with a larger range of roving.

6.4.1 Additional Methods

Approval from University of Southampton Research Governance Office and the Institute of Sound and Vibration Research Human Experimentation Safety and Ethics Committee (reference number: 6494) was obtained before commencing this experiment. Unilaterally implanted subjects who performed at better than chance range of unbiased guessing in the previous experiment (Category C subjects: S5, S6, S7 and S8) were invited for a second visit, lasting approximately 2 hours, with frequent break intervals. Out of the four subjects invited, only two subjects (S5 and S8) responded and they were tested in this subsequent experiment.

Testing set-up and procedure details were identical to those used in the previous experiment. Since monaural level cues are not effective for low-frequency sounds, and to minimise measurement time, the research team decided to only include speech, broadband noise and high-pass noise stimuli. Each of the three stimuli was presented with a nominal level of 65 dB SPL with two levels of roving: ±4 dB (61-69 dB SPL, as in the previous experiment) and ±8 dB (57-73 dB SPL). In order to make sure subjects could actually hear the minimum level of the ±8 dB roving range (i.e. 57 dB SPL), each stimulus was also presented nominally at 60 dB SPL with ±4 dB roving (56-64 dB SPL). Any deterioration in performance when the level presented was 60 dB SPL (±4 dB), compared to when the level presented was 65 dB SPL (±4 dB), would, therefore, indicate that subjects could not hear a sound level as soft as 56 dB SPL. The order of presentation levels as well as stimulus type was counterbalanced using the Latin square design.

Following the formal localisation testing, subjects were presented with each of the three stimuli at 65 dB SPL (± 4dB) and were instructed to say where they actually heard the sound coming from rather than identifying which loudspeaker, from a surrounding arc of loudspeakers, the sound came from. It should be noted that this additional instruction was only applied to a single condition (65 dB SPL with ± 4 dB level roving) and not to all conditions. The difference between the two instructions was supposed to measure different abilities. A previous study by Shub et al. (2008) suggests that when the subjects were instructed to identify the location of the sound source, they were asked to use all available information to get the correct locations, whereas asking them to report the perceived location of the source would probably have measured localisation ability in more realistic situations.

The order of stimuli was counterbalanced using the Latin square design. The experimenter was in the test room with the subject to record responses manually. Each response was scored on a scale from A to B, with A indicating correct response and B indicating incorrect response. The percentage of correct responses was calculated across all the loudspeakers for each stimulus and for each subject. Table 6.3 summarises the measurements conducted on subjects S5 and S8 in this follow-up experiment.

Table 6.3: Overview of the measurements for sound localisation conducted in the follow-up experiment obtained for two unilateral CI subjects (S5 and S8).

Condition	Speech	BBN	HPN
65 dB SPL (±4 dB), as in the previous experiment	2	2	2
60 dB SPL (±4 dB)	2	2	2
65 dB SPL (±8 dB)	2	2	2
65 dB SPL (±4 dB), with different instruction (subjects were instructed to report where they heard the sound coming from)	2	2	2

6.4.2 Results

Figure 6.9 plots overall $\overline{D}$ error scores at 60 dB SPL (±4 dB) and 65 dB SPL (±4 dB) from the previous and the current experiments and 65 dB SPL (±8 dB) for each stimulus type, for subjects S5 and S8. Four main observations are apparent in the figure. Firstly, $\overline{D}$ error scores with 65 dB SPL (± 4 dB) obtained from this experiment were similar to those obtained from the main experiment reported in Section 6.3.1 for all stimuli and for both subjects, with the exception of the score of S5 with broadband noise. The overall $\overline{D}$ error score for subject S5 was lower by 12° in this experiment, compared to the score reported in Figure 6.4, although both were still within the chance range of unbiased guessing.

Secondly, it is observed that the $\overline{D}$ error scores obtained from both subjects were better than chance range of unbiased guessing, for most cases. The overall error scores of subject S8 were all better than chance range of unbiased guessing, whereas subject

S5 exhibited better than unbiased guessing performance for all cases except for broadband noise with ±4 or ±8 dB roving. Results from the current experiment showed that the overall $\overline{D}$ error score of subject S5 for broadband noise with a ±4 or ±8 dB roving range approached unbiased guessing performance. With the exception of subject S5 with broadband noise, these results indicate that both subjects could identify the locations of sound sources at better than chance range of unbiased guessing, even with ±8 dB roving. The overall $\overline{D}$ error score with a ±8 dB roving range was far below the unbiased guessing performance for subject S5 with high-pass noise and for subject S8 with speech and high-pass noise. Figure 6.10 reveals that the lower overall error with high-pass noise for subject S5 resulted from the decrease in the magnitude of both constant error and random error. For subject S8, the lower overall error with speech and high-pass noise mainly resulted from the decrease in the magnitude of constant error, compared to that of broadband noise. Generally, it seems that the overall error scores with ±8 dB roving were below the chance range of unbiased guessing for high-pass noise. Scores of constant and random errors indicate that the better than unbiased guessing performance with ±8 dB roving was unlikely to be the result of biased guessing.

Thirdly, the $\overline{D}$ error scores with 65 dB SPL (±4 dB) were similar to those with 60 dB SPL (±4 dB), for most cases. The results of subject S5 showed similar scores with 65 dB SPL (±4 dB) and 60 dB SPL (±4 dB) for speech only. Subject S5 showed a higher score with 65 dB SPL than with 60 dB SPL with broadband noise and high-pass noise. Subject S8 also showed similar overall error scores with 65 dB SPL (±4 dB) and 60 dB SPL (±4 dB), indicating that this subject can hear sounds as soft as 56 dB SPL (the minimum range of roving with 60 dB SPL). Given that the performance of both subjects did not deteriorate with 60 dB SPL (±4 dB) compared to 65 dB SPL (±4 dB), it seems that both subjects were probably able to hear such soft sounds. Thus, any difference in scores when the stimulus was presented at 65 dB SPL with ±4 dB and ±8 dB would have resulted from the effect of level roving, and would not be because the sound level was not heard.

Fourthly, Figure 6.9 shows that the scores of $\overline{D}$ error when the level was roved by ±8 dB and ±4 dB were comparable for subject S5, but not for subject S8. Subject S8 exhibited higher $\overline{D}$ error scores when the sound level was roved by ± 8 dB compared with ± 4 dB roving, for all stimuli. The main reason for the higher overall error with ± 8 dB roving for subject S8 was the constant error, where a higher magnitude of constant error was exhibited by the subject in localising stimuli with ± 8 dB compared to ± 4 dB (Figure 6.10). Subject S5, on the other hand, seems to show similar scores for all stimuli, with ±4 dB and ±8 dB level roving.

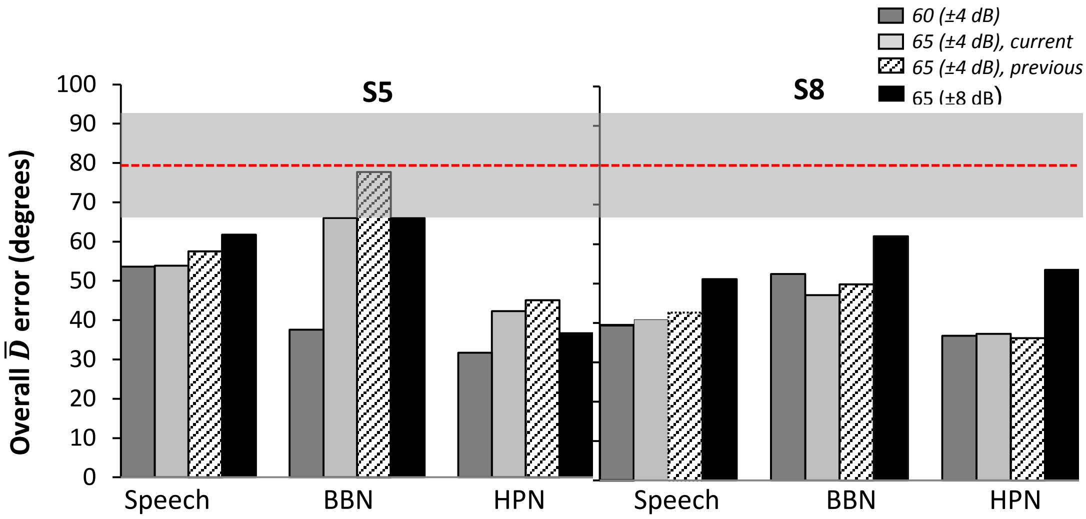


Figure 6.9: Overall $\overline{D}$ error scores for unilaterally implanted subjects (left panel for S5 and right panel for S8) for different stimuli with different level presentations. The horizontal red line shows the chance level expected from unbiased guessing, with the grey area indicating the chance range of unbiased guessing.

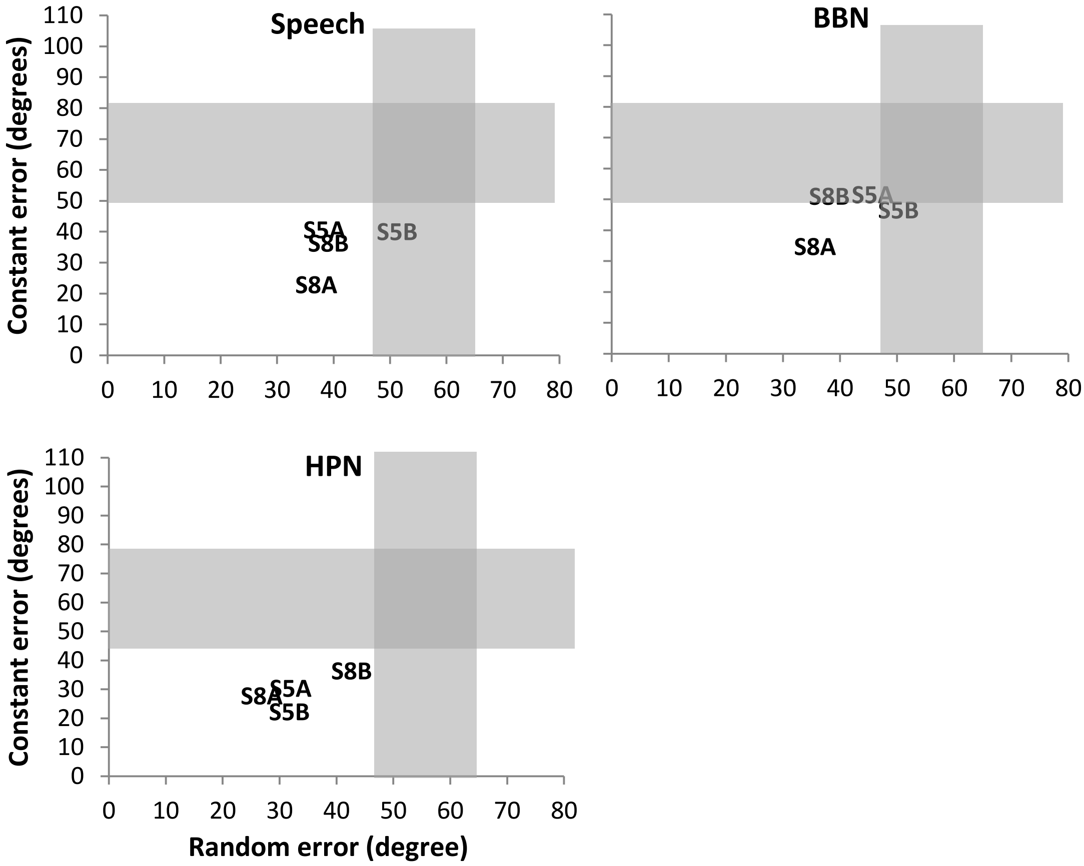


Figure 6. 10: constant and random errors for subjects S5 and S8 for stimuli presented at 65 dB SPL with ±4 dB (indicated by letter A) and ±8 dB level roving (indicated by letter B). The grey area indicates the chance range expected from unbiased guessing.

Although the above results generally showed that the unilateral CI subjects can show overall error scores on a simple localisation/identification task that are better than chance range of unbiased guessing with stimulus presentation levels roving between ±4 dB and ±8 dB and no spectral-shape roving, this does not necessarily mean that their perceived locations are appropriate. When the subjects were instructed to say where they actually perceived the stimuli originated, they seemed to perceive locations were scattered in all directions in the test room. The percentage of correct responses did not exceed 15% (Table 6.4).

Table 6.4: The percentage of correct responses for the two unilaterally implanted subjects when they were instructed to report the perceived location of sound source.

	Speech	**BBN**	**HPN**
Subject S5	10.6 %	4.5 %	4.5 %
Subject S8	7.6 %	7.6 %	15.2 %

6.5 Discussion

The present study assessed localisation abilities in CI users who were fitted with a single CI and might be more likely to have some localisation ability. Given that the unilateral CI subjects tested in the current study had relatively very good speech scores in noise, it may be speculated that they might also be more likely to have some localisation ability. The results of the current study on localisation ability of unilateral CI subjects revealed four main issues, which are discussed in detail in the following sections. First, some unilaterally implanted subjects can show overall localisation error scores of better than chance range expected from unbiased guessing, at least for some stimuli, which was unlikely to be achieved by biased guessing (Section 6.5.1). Secondly, these findings agreed with previously published results, in that some unilateral CI subjects can localise at better than chance range of unbiased guessing (Section 6.5.2). Thirdly, it was speculated that the better than unbiased guessing performance shown by some unilaterally implanted subjects is more likely to be mediated by monaural level cues than spectral cues (Section 6.5.3). Fourthly, the ‘’good’’ ability of unilateral CI subjects to identify the location of a sound source was found to be not related to their actual perceived location of the sound source (Section 6.5.4).

6.5.1 Comparison with guessing performance

The findings of the current study show that some unilaterally implanted subjects, who have been acclimatised to using a single implant in their everyday life, can show overall localisation error scores on a simple sound-source identification task at better than chance range of unbiased guessing, at least for some stimuli. With the exception of low-pass noise and high-pass noise burst stimuli, half of the unilateral CI subjects showed better than chance range expected from unbiased guessing with the level of stimulus roved by ±4 dB and no spectral-shape roving. Another key finding of the current study emerged when assessing localisation performance with stimulus presentation level roves of ±8 dB and no spectral-shape roving. The results indicate that, with the exception of one case, the two unilaterally implanted subjects tested in the follow-up experiment could still identify the location of a sound source at better than unbiased guessing performance, even with a greater level of roving, particularly for high-pass noise. This indicates that the level rove of ±4-5 dB used in this project as well as in previous studies investigating localisation performance of CI users may not be sufficiently large to cause listeners using monaural cues into chance performance. Although such results indicate that the better than unbiased guessing performance by some unilaterally implanted subjects can still be maintained with ±8 dB roving, the limit of their ability to identify sound at better than unbiased guessing performances is still unknown.

The findings of the current study also show that the better than unbiased guessing performance shown by unilateral CI subjects in this study seems unlikely to be the result of biased guessing. As noted earlier, in Section 6.1.2, an overall localisation error score that is better than unbiased guessing range can still be achieved by a subject who is simply biased towards the frontal loudspeakers. Whereas the overall $\overline{D}$ error scores expected from unbiased guessing ranged from 66° to 94° for the test-setup used in this project, smaller $\overline{D}$ error scores of about 54° to 66° can be achieved by biased guessing towards frontal loudspeakers (see Section 4.2.2 for more details). Therefore, it is of importance to consider the possibility of biased guessing in the interpretation of better than unbiased guessing performance. Given that the ‘‘good’’ unilateral CI performers in the current study exhibited lower scores on both constant error and random error than those expected from biased guessing and that their localisation data shows a slight relationship between loudspeaker locations and their response locations, it seems more likely that the better than unbiased guessing performance by those subjects in the current study reflects some ability to identify the locations of sound sources rather than biased guessing. It should be noted that those subjects who can show some ability to identify the locations of sound sources seem to be the ones who had longer experience with their implants. This suggests that there may be a relationship between years of experience with the implants and the development of abilities to identify the sound-source locations in unilateral CI subjects. Further research is needed to determine the possible predictors for the ability of unilateral CI users to identify the locations of sound sources.

6.5.2 Comparison with previous studies on unilateral CIs

To the best of this researcher's knowledge, no study has assessed the localisation ability of unilateral CI subjects with levels of roving greater than ±5 dB; thus, in the rest of this section only the finding with ±4 dB level roving is compared to the previous studies that have used such a range of level roving.

The findings of the current study replicate previously published results, in that some unilaterally implanted subjects can show overall error scores that are better than chance range of unbiased guessing. In the study of Grantham et al. (2008), three of six unilateral CI subjects performed at better than chance range expected from unbiased guessing, although one had access to binaural cues through the residual hearing in the non-implanted ear. The results of Nava et al. (2009) also showed a better than chance level expected from unbiased guessing for five of their 10 prelingual unilateral CI subjects and all the four postlingual subjects tested in their study. However, their results should be treated with caution, given that they did not consider the chance range when analysing their data. As mentioned in Section 4.2.2, failure to consider the chance range means one might conclude that an individual is performing better than chance level, when it is actually not the case. Thus it is possible that the better than chance level of unbiased guessing shown by some of Nava et al.'s subjects was still based on unbiased guessing.

Although the above finding of the current study contradicts the conclusion published by Buhagiar et al. (2004), the finding of the current study seems similar to their finding in that some unilateral CI subjects can show overall error scores at a better than chance range of unbiased guessing. Although Buhagiar et al. concluded that ''localisation performance was found to be close to chance for all stimuli'', scanning the overall localisation error scores of their subjects showed that six of their 18 subjects did perform at better than the chance range expected from unbiased guessing (see Figure 6.1). Apparently, the overall localisation error scores showed by those six unilateral CI subjects seems comparable to the scores showed by the ''good'' unilateral CI performers in the current study. However, it must be emphasised that it is still not clear whether the better than unbiased guessing performance achieved by these six subjects in Buhagiar et al.'s study reflects some ability or just biased guessing. Although the findings of the current study showed that the better than unbiased guessing performance by some of the unilateral CI subjects was unlikely to have been achieved by biased guessing (as discussed in the previous section), this may not be the case for Buhagiar et al.'s subjects. There is a possibility that the better than unbiased guessing performance achieved by six of Buhagiar et al.'s subjects was simply based on biased guessing. As pointed out previously, the authors of Buhagiar et al. (2004) were contacted with the aim to investigate this possibility; however, they seem to have lost their data.

The current study seems the first that directly considers the possibility of biased guessing when analysing localisation data and its findings indicate that the better than unbiased guessing range shown by some unilateral CI subjects was not likely to be achieved by biased guessing. Although Grantham et al. (2008) did not rule out this possibility with their subjects, scanning the scores of constant and random errors of their subjects showed that the better than chance range of unbiased guessing shown by their subjects is not likely to reflect biased guessing (Figure 6 in their article). It was found that the unilateral CI subjects in their study who performed at better than unbiased guessing range exhibited a relatively smaller amount of constant error (i.e. bias) than random error (i.e. variability in responses). As shown in Section 4.2.2, biased guessing is usually characterised by a greater amount of constant error and much smaller random error.

Taken together, it seems that some unilaterally implanted subjects can show overall error scores on a simple localisation/identification tasks at better than chance range of unbiased guessing, as shown in the current study and the studies of Buhagiar et al. (2004) and Grantham et al. (2008). Although it is impossible to establish whether better than unbiased guessing performance by some of Buhagiar et al.'s subjects was achieved by biased guessing or not, the current study shows that the better than unbiased guessing range reported for some unilaterally implanted subjects in both the current study and Grantham et al.'s study are very unlikely to reflect biased guessing.

6.5.3 Cues used by unilaterally implanted subjects

The fact that some unilaterally implanted subjects can show overall error scores on a simple identification task at better than chance range of unbiased guessing that are unlikely to reflect biased guessing leads to the question of what cues they were using to do this. Given the fact that the unilaterally implanted subjects who showed overall error scores at better than chance range of unbiased guessing in the current study all had pure tone thresholds of more than 90 dB hearing level (dB HL) in their non-implanted ears (Figure 6.2), it is very unlikely for those subjects to have had any useful binaural inputs. The existence of the better than guessing performance by unilateral CI subjects would, therefore, depend in principle on two types of monaural cues.

The first is the group of monaural spectral cues, which is largely result from the direction-dependent filtering by the head and pinnae. Although the spectral cues are mainly useful for localisation in the vertical plane, they can also contribute to some extent to localisation in the frontal horizontal plane (Langendijk and Bronkhorst, 2002).

It has been demonstrated that spectral cues, particularly those created by the pinnae, can provide reliable cues for localisation of sound frequencies exceeding about 3-4 kHz on the frontal horizontal plane (Lopez-Poveda and Meddis, 1996). Previous studies by Shub et al. (2008) and Van Wanrooij and Van Opstal (2004) have shown that monaural spectral pinna cues can provide useful information for frontal horizontal localisation for unilaterally deaf listeners, by relying on the spectral cues of their normal ears. However, given that the unilaterally implanted subjects had their CI microphone over the top front portion of the pinna, instead of in the ear canal, it is very unlikely that they would have use of the pinnae cues which would be normally available to unilaterally deaf listeners.

Another source of spectral cues could arise from the loudspeakers/audio equipment, which could also differently affect the spectral characteristics of the signal arriving at the CI microphones. However, it seems very difficult, if not impossible, that the good unilateral CI performers have learnt to make use of these spectral cues provided by loudspeakers, given that that the spectral cues provided by the loudspeakers are unlikely to vary systematically with azimuths. Thus, the spectral cues provided from the loudspeakers are unlikely to provide reliable cues for unilateral CI subjects to localise sounds, particularly in view of the fact that they were not receiving feedback about their performance. In support of this speculation, the findings of the current study indicate that the good unilateral CI performers did not show a lower overall error for speech than for broadband noise. As documented by Van Wanrooij and Van Opstal (2004), spectral cues can be more easily learned with familiar than unfamiliar sounds. As this is the case, one might expect speech to be localised with better accuracy than the noise stimulus. Results of the current study, however, show generally comparable performance for speech and broadband noise stimuli by most of the good unilateral CI performers. Moreover, given that the spectral cues are more effective with broadband stimulus than narrowband stimulus (Shub et al., 2008), one might also expect the overall error scores with broadband noise to be lower than high-pass noise stimulus. However, this was not the case, either, as most of the good unilateral CI performers showed relatively lower scores for high-pass noise than for broadband noise stimulus.

Nevertheless, it might be possible that the unilateral CI subjects were able to make use of changes in spectral shapes arising from head shadowing effects, which could differently affect the spectral characteristics of signals arriving at their CI microphones from different locations on the horizontal plane. The ability of listeners to detect small changes in the spectral shapes of a broadband/complex sound is considered in a profile analysis study, of which an overview is given by Green (1988). An important cue to detect changes in spectral shapes is the comparison of levels in different parts of the sound spectrum (i.e. across-channel comparison). Previous studies show that normal-hearing listeners can utilise across-channel comparison to perform profile analysis experiments (Green, 1988; Moore et al., 1989). It might be possible that, as with normal-hearing listeners, the good unilateral CI performers were able to make use of across-channel comparison for localisation. One of the most common methods of showing whether a listener is using an across-channel comparison is to include overall level roving, because the profile analysis is highly robust to level roving (Green, 1988; Spiegel and Green, 1982). A key finding that might support the role of across-channel comparison in the current study is that increasing the range of level roving of the sound to ±8 dB does not result in higher overall error scores, although this was observed for one subject, but not the other. The overall error scores by subject S5 were similar for presentation level roves of ±4 dB and ±8 dB, which may support the suggestion that this subject was using an across-channel comparison for localisation. However, given that across-channel comparison requires analysis of the level spectrum across a broader range of frequencies, one might expect across-channel comparison to be more effective for broadband stimulus than narrowband stimulus. Thus, the effect of level roving should have less effect for broadband stimulus than narrowband stimulus. However, this was not the case for subject S5, as similar overall error scores for level roving of ±4 dB and ±8 dB were exhibited by that subject for both broadband noise and high-pass noise stimuli. It seems, therefore, more unlikely that subject S5 was using across-channel comparison for localisation. Further support for this speculation comes from the studies by Goupell et al. (2008), Henry et al. (2005) and Henry and Turner (2003) in which all reported that CI users do not seem to utilise across-channel comparison, leaving it unclear whether and to what extent across-channel comparison can be determined with CIs.

Although the role of spectral shape cues cannot be entirely excluded, it might be possible that the unilateral CI subjects relied, at least to some extent, on the second group of monaural level cues. Under familiar acoustic environments, changes in sound level, as a result of head shadow effect, could provide a reliable cue for horizontal localisation, because the learned sound would appear louder on the side of implanted ear than the unimplanted one. Given that monaural level cues can be easily learned and applied to different stimuli (Van Wanrooij and Van Opstal, 2004), it might be possible that the good unilateral CI performers in the current study have gained some familiarity with the stimuli and thus have learned to make use of monaural level cues to identify the location of the sound source. Apparently, many of the good unilateral CI performers in the current study described how they attended to the ‘’loudness’’ of sounds for identifying the sound source locations. They reported that the stimuli presented from the side of their non-implanted ear sounded quieter than stimuli presented from the side of their implanted ear. One key finding of the current study that may point to the role of monaural level cues is that most of the good unilateral CI performers showed relatively lower overall error scores for high-pass noise than for the other stimuli for both presentation roves of ±4 and ±8 dB. It is well documented that the contribution of monaural level cues is largest with high frequency sounds, for which the attenuation by the head can be ±15 dB for high frequencies (Agterberg et al., 2012). That is, the monaural level cues are greater for within-channel level (as with high-pass noise) than for the overall level across the entire range of frequencies (as with broadband noise). Another finding that may support the role of monaural level cues is that increasing the range of level roving of the sound to ±8 dB results in a higher overall error scores, although this was observed for one subject, but not the other.

Although one might argue that the overall level cues would not have provided a reliable cue to location because the level of the of the stimulus was roved in the current study, it might be possible that the good unilateral CI subjects, through their acclimatisation with unilateral listening, can still make use of overall level cues for localisation. This may also suggest that the ranges of level roving that have been usually used to test the localisation ability of unilateral CI subjects may not sufficient to eliminate overall level cues. It might also possible that the good unilateral CI subjects were using within channel level cues for location. As noted previously, the current study used an 8 dB roving range, which is much smaller than the range necessary to eliminate within channel cues (30 dB roving range for high frequencies). It might also the case that the good unilateral CI subjects could only tell whether sounds were on their left or right side (i.e. lateralisation), rather than being able to actually determine the sound's location accurately, even though their performance was not biased guessing. It seems that further research is necessary to address the role of monaural level cues, including overall and within-channel level cues, in CI users. For example, it may be necessary to determine the extent to which the monaural level cues may have played a role in localisation with unilateral CI users. Further research that compares localisation ability of unilateral CI users with different ranges of level roving might also be required in order to draw a solid conclusion.

Taken together, the ability of unilateral CI subjects to identify the locations of sound sources seems more likely to be mediated by the use of monaural cues determined by the head shadow effect. The findings of the current study seem more likely to point to the role of monaural level cues in localisation ability of unilateral CI users than spectral-shape cues, even though the latter cues were made available to subjects (i.e. no spectral-shape roving). However, if this was not the case, one might speculate that monaural level cues would still not able to provide reliable cues for localisation, even if the spectral cues are not made available, suggesting that subjects must rely on something else to identify the sound source locations. The fact that none of the unilateral CI subjects could localise high-pass noise burst at better than unbiased guessing may, however, support the role of monaural cues. It has been suggested that monaural localisation deteriorates as the duration of stimulus decreases, due to the inability to accurately extract spectral or level information with short stimulus duration (Vliegen and Van Opstal, 2004).

Much more work is necessary to address the question of which cues the unilateral CI users are using to identify location of sound sources at better than unbiased guessing. For example, the role of spectral cues could be investigated by assessing localisation ability of unilateral CI users with random-spectrum stimuli or under reverberant situations. As documented by Giguère and Abel (1993), spectral cues are more likely to be disrupted by reverberation. The current study showed that better than unbiased guessing range can still be achieved with ±8 dB roving, as a first attempt to determine to what extent the better than unbiased guessing performance of unilaterally implanted subjects could be maintained. Further study might be required to determine the extent to which monaural level cues may have played a role in localisation by unilateral CI users, although it might be practically very difficult, due to the effect of compression activation.

6.5.4 Real-world implications of the good localisation ability with unilateral CIs

The findings of the current study indicate that the monaural cues associated with azimuth locations could provide sufficient and reliable cues for some unilateral CI subjects to identify the locations of sound sources at better than guessing performance (i.e. chance range). This ability was, however, tested in a controlled laboratory environment, which might not necessarily reflect localisation ability in everyday life. The current study assessed only a limited sample of ability where there are stationary sound sources and a stationary listener. However, this might be different from the real-world situations where multiple sounds are presented at once. It might be possible that the monaural cues that might have been used by the unilateral CI subjects to do the task can no longer provide reliable cues with multiple sound sources, which may lead to considerable difficulty in localising in real-world situations. In support of this is the finding that the localisation performance shown by the unilateral CI subjects was not correlated with their ratings of residual ability in everyday life (which will be presented in Chapter 9). In particular, their ratings of residual ability to localise sounds in everyday life were found not to correlate to their localisation performance.

Further support of this comes from the finding of the current study that the unilateral CI subjects could not tell where the sound was actually perceived. The findings of the current study show that neither of the two unilateral CI subjects who showed some ability to identify the locations of sound sources (i.e. ability to relate precepts to external locations) at better than guessing performance could tell where the source is actually perceived. Both subjects seemed to perceive the locations of the sound source as coming from different directions. Shub et al. (2008) suggests that asking the subjects to identify the locations of sound sources would encourage the subjects to use any information to identify the correct locations, and therefore a better than chance performance might be achieved. On the other hand, asking the subjects to report the perceived location of the source would probably have measured spatial ability in more realistic situations. The finding of the current study, therefore, might have an important implication, as it suggests that the ‘‘good’’ ability of unilateral CI users to use monaural cues to identify the location of sounds was not related to their actual perceived locations of the sound sources. Thus, considerable care is required in interpreting the localisation ability of CI users

The findings of the current study may also have implications for interpretation of the localisation ability of CI users. In previous localisation studies, for example, a better than unbiased guessing performance by bilateral CI users is interpreted as evidence of a bilateral advantage. The findings of the current study, however, indicate that monaural cues are sufficient for unilateral CI subjects to identify the locations of sound sources at better than chance range of unbiased guessing. Thus, the benefit of bilateral implantation might only be considered as a bilateral advantage if the overall error score of a bilateral CI user is lower than the range of error scores achieved by good unilateral CI performers who rely on monaural cues. As will be shown in Chapter 7, a few of the synchronised bilateral CI subjects who localised at better than unbiased guessing range did show similar performance to the good unilateral CI performers. This finding may suggest that the localisation performance of such bilateral CI subjects is based on the use of monaural cues, and thus, the bilateral implantation may not provide any bilateral advantage for them. A larger study might be required to determine the range of overall error scores that could be obtained by unilateral CI users who only relied on monaural cues to identify the locations of sound sources.

6.6 Conclusions

Given the limited sample of unilateral CI subjects tested in the current study, the conclusions of the present study are as follows:

- Some unilateral CI subjects can show overall localisation error scores on a simple identification task at better than chance range of unbiased guessing, consistent with the findings of previous studies. The better than unbiased guessing performance shown by the unilaterally implanted subjects in the current study seems to reflect some ability rather than one form of biased guessing.

- The better than chance range of unbiased guessing is still achievable with stimulus presentation level roves of ±4 dB and ±8 dB and no spectral-shape roving.

- The ability of some unilateral CI subjects to identify the locations of a sound source seems more likely to be mediated by the use of monaural level cues than spectral-shape cues, though the role of latter cues cannot be excluded.

- The finding of a better than chance range of unbiased guessing on a simple identification task does not necessarily mean that the listener's perceived locations are appropriate.

Chapter 7: Sound-source localisation by adults fitted with synchronised bilateral cochlear implants

7.1 Introduction

Most bilateral cochlear implant (CI) users have sound-source localisation that is better than that of unilateral CI users and worse than that of normal-hearing listeners. The discrepancy between bilateral CI users and normal-hearing listeners can be explained, in part, by the technical limitations of the current speech processors and implants, which hinder the perception of interaural time and level differences (ITD and ILD cues). One such limitation is the independent operation of both speech processors which might introduce differences in processing between the two sides and then distorts ITD and ILD cues. Previous studies with direct stimulation and with control of interaural parameters have shown that sensitivity to ITD and ILD can be accessed through electrical stimulation (Section 2.6.4). It has been shown by Long et al. (2006), for example, that adults with bilateral CIs can benefit from a phase delay in envelope ITD of a stimulus to detect a signal in noise. Such a finding is encouraging, as it indicates that the spatial hearing with bilateral CIs could be enhanced if the processing between the two implants is synchronised.

A synchronised bilateral CI system, the Digisonic® SP Binaural (DSPB) implant, has been developed with the aim of improving binaural cues and thus hearing through synchronised processing of the acoustical input, using a single speech processor and two microphones (Figure 2.12). Prior to starting this project and to this researcher's knowledge, no study on the spatial hearing benefits with this system of CIs has been conducted. However, two studies have been published over the time span of this project. These two studies have shown that sound localisation with DSPB implants is possible, with mean overall localisation error ($\overline{D}$ error) of about 35.0° (Verhaert et al., 2012) and 49.9° (Bonnard et al., 2013). Verhaert et al. (2012) reported that the overall localisation error of the DSPB implant subjects was significantly lower (i.e. better) when listening bilaterally than unilaterally. The study of Bonnard et al. (2013) showed that the overall error with the DSPB implants did not significantly differ from that with the conventional bilateral CIs where two speech processors are used ($\overline{D}$ error =38.2°). Although these two studies concluded that adults with DSPB implants could localise sounds in the horizontal plane similarly to users of conventional bilateral CIs, there are some important issues that need further consideration.

First, it is of interest to consider the limitations in the data analysis of the above studies. Although both studies reported overall $\overline{D}$ error (i.e. root mean square error), neither study took into account the chance range expected from guessing. Bonnard et al. (2013) reported individual overall error scores of their seven subjects which ranged between 25.9° to 89.2°, whereas Verhaert et al. (2012) did not. It seems that both studies quantify spatial hearing benefits with the DSPB implants by comparing the $\overline{D}$ error of the DSPB implant subjects listening bilaterally to when they are listening unilaterally (Verhaert et al., 2012) or to another group of subjects fitted with conventional bilateral CIs (Bonnard et al., 2013). Both studies reported that localisation performance of the DSPB implant subjects listening bilaterally is better than when listening unilaterally (Verhaert et al., 2012) and that localisation performance of the DSPB implant is similar to what has been shown by the conventional bilateral CI subjects (Bonnard et al., 2013). Neither study, however, investigated whether DSPB implant subjects can localise sounds at better than chance range expected from guessing (unbiased and biased guessing). Although Verhaert et al. (2012) reported the system of errors introduced by Nopp et al. (2004), the exact contributions of constant error (i.e. bias) and random error (i.e. variability in responses) for the overall error score shown by each subject were not possible to estimate, as the authors have not defined their subjects. Bonnard et al. (2013), on the other hand, only report individual $\overline{D}$ error scores. It is therefore difficult to determine whether the localisation ability showed by the DSPB implant subjects in both studies reflects some ability or is simply due to guessing.

Another issue worth considering is which cues the DSPB implant subjects were using to do the localisation task. Given the findings of the study presented in Chapter 6, which show that some unilateral CI subjects can show overall error scores at better than chance range of unbiased guessing and that such scores seem unlikely to be achieved by biased guessing, it is not clear whether the localisation ability of DSPB subjects reported in the previous studies was based on binaural or monaural cues. Although Verhaert et al. (2012) suggest that the DSPB subjects were able to make use of binaural cues that are not available when either implant is deactivated, the design of their study might be at risk of bias caused by the unfamiliarity of bilateral CI users with listening unilaterally with one implant. Thus, it is not clear whether the localisation performance of the DSPB implant subjects in Verhaert et al. (2012) and Bonnard et al. (2013) was based on monaural or binaural cues, particularly considering the fact that both the spectral content and level of the stimulus were kept constant in their studies. Further research is therefore required to determine whether the DSPB implants could actually provide any binaural advantage for localisation over single CIs.

Closely related to that, a further area of interest concerns the effects of stimulus type on localisation performance of DSPB implant subjects. That is, there is a need to evaluate the relative contribution of ITD and ILD cues in horizontal plane localisation with the DSPB implants. Previous studies have provided evidence that localisation by users with conventional bilateral implants is more likely to be dominated by ILD cues, with little or no contribution of envelope ITD cues (Grantham et al., 2007; Seeber and Fastl, 2008; Verschuur et al., 2005). The ITDs on the fine structure were eliminated, since the fine structure information is usually discarded in the current signal processing strategy in CIs. To the best of this researcher's knowledge, no study has addressed the relative contribution of these cues in localisation by DSPB implant users, and thus it is not known whether localisation ability by such users, if present, is dominated by ILD cues.

This chapter describes an experiment conducted on the DSPB implant users with the aims of assessing their localisation ability and determining whether stimulus type affects the localisation ability. The localisation ability of the DSPB implant users was also compared to the ability of other groups of subjects from the previous experiments described in Chapter 4, on normal-hearing listeners, and in Chapter 6, on unilateral CI users, and from a previous published study in our laboratory on conventional bilateral CI users (Verschuur et al., 2005). This comparison will provide clear evidence of localisation ability with DSPB implants. For example, comparing overall error scores of the DSPB implant users to those achieved by ''good'' unilateral CI performers, as reported in Chapter 6, is intended to help determine whether the DSPB implant subjects can make use of binaural cues for localisation. The benefit of DSPB implants would only be considered as a bilateral advantage when the overall error score of a DSPB implant subject is lower than the range of overall error scores reported by good unilateral CI performers.

7.1.1 Summary of objectives

The objectives of this study were as follows:

1. Measure horizontal sound-source localisation performance in adults with DSPB implants. The hypothesis is that adults with DSPB implants can show overall error scores on a simple localisation task at significantly better than the chance range of unbiased guessing, and that such scores are unlikely to result from biased guessing.

2. Determine whether stimulus type affects sound localisation performance of DSPB implant adults, specifically, to assess the relative roles of envelope ITD and ILD cues in horizontal plane localisation. The hypothesis is that, based on previous studies on bilateral CI adults, the localisation performance of DSPB implant adults is likely to be dominated primarily by the ILD cues.

3. Compare the performance of sound-source localisation in the horizontal plane by DSPB implant adults to data collected from other groups in the previous experiments. The hypothesis is that adults with DSPB implants can localise sounds significantly better than those with unilateral CIs, and that they might be able make use of binaural cues for localisation. Given that the factors limiting the spatial hearing abilities of CI users are also apparent for the DSPB implant users (Section 2.6.4), it was expected that the DSPB implant adults would still perform significantly worse than normal-hearing adults.

4. Compare the performance of sound-source localisation in the horizontal plane by DSPB implant adults with that reported by adults fitted with conventional bilateral CIs in a previous study conducted in our laboratory (Verschuur et al., 2005). Given the way that the processing between the two ears is synchronised in the DSPB implants, in which the sounds arriving at the two CI microphones are still processed independently in two signal processing lines (Section 2.6.6), it is unlikely that DSPB implants would provide benefits for bilateral CI users above those of the conventional bilateral CIs. It was expected that that the DSPB implants would offer roughly similar advantages for localisation to conventional bilateral CIs.

7.2 Additional methods

Three centres were invited to take part in the study: the University of Southampton Auditory Implant Service (USAIS, Southampton), the Hearing and Balance Assessment, Rehabilitation and Research Centre (HARC, Birmingham) and the Royal National Throat, Nose and Ear Hospital (RNTNE, London). The RNTNE centre, however, did not agree to take part, as their patients were already involved in two other studies. Approvals from the National Research Ethics Service (REC reference: 12/SC/0421, Appendix D.1), as well as the University of Southampton Research Governance Office and the University Hospitals Birmingham Clinical Research Office (reference: PRK4537, Appendix D.2), were all obtained prior to the start of testing. Approval from the Institute of Sound and Vibration Research Human Experimentation Safety and Ethics Committee (reference: 2915), where all the experiments were conducted, was also obtained before commencing the experiments.

7.2.1 Participants

The study was mainly designed to assess horizontal sound-source localisation performance by DSPB implant adults. A sample size calculation was conducted with a statistical power of 80% and a probability of 0.05 with a two-tailed *t*-test. The mean difference in overall localisation error between stimuli for bilateral CI subjects was estimated to be 4° and the standard deviation of this difference to be 5°, based on the results of Verschuur et al. (2005). Accordingly, the sample size calculation indicated that at least 14 DSPB implant subjects were required to detect the differences in overall error scores of about 4° between stimuli (two-tailed tests, δ=4°, σ=5° and α=0.05).

All DSPB implant adults at the USAIS (*n*= 16) and HARC (*n*=2) were qualified to be invited, based on the inclusion criteria, which were adults aged 18- 95 years fitted with a DSPB implant, full time implant users and having at least 3 months experience with their implants. Subjects with cognitive or learning difficulties which might affect the results were excluded. It should be noted that, unlike the unilateral CI subjects in the previous chapter, who were chosen based on specific criteria to reflect the upper limit of performance that could be expected from unilateral CI users, the DSPB subjects in the current study were chosen based on more relaxed criteria, in order to include more subjects. For example, the unilateral CI subjects were required to have at least one year experience with their implant, whereas the DSPB implant subjects were only required to have at least 3 months of experience. Out of the 18 DSPB implant users contacted, ten subjects responded, all from the USAIS: eight subjects were willing to participate, whereas the other two subjects were not able to take part for transport reasons. It should be noted that the current study was not able to recruit any further subjects since the USAIS and institutions elsewhere in the UK stopped implanting people with the DSPB Implants, due to technical issues, as of March 2013.

The subjects who completed the experiment were 8 severely-to-profoundly deafened adults implanted with DSPB implants from the USAIS. They consisted of four females (mean age: 61.7 years) and four males (mean age: 67.2 years), and all except one were postlingually deafened. They had their devices activated 4 to 18 months prior to being tested. Their implants had one speech processor worn in the standard position, in which the microphone is located over the top front portion of the pinna, similar to the microphone position used in behind-the-ear hearing aids. The subjects were fitted using the clinical procedure standard at the USAIS, which includes comfortable loudness levels matching across the 12 electrodes. Subject information for all subjects, including subject characteristics, duration of deafness prior to implantation, ear receiving the speech processor, and speech scores in noise prior to and post implantation, is listed in Table 7.1.

During testing, a spare processor was used rather than the clinical speech processor that the subject had been using in everyday life. As a part of speech perception testing, subjects were tested bilaterally and unilaterally, and therefore, a change in the mapping software was needed to enable switching off the side receiving the speech processor (i.e. ipsilateral side). The research team decided to make the change in the mapping software on a spare processor that was programmed for each subject prior to testing. Three different maps had been downloaded into the spare processor: bilateral implants, right implant only and left implant only. The right ear map, for example, was used when the subject was supposed to listen with the right ear only. This was carried out by turning the most comfortable levels (i.e. M levels) of all electrodes on the left ear to the minimum, so that nothing could be heard from the left side. Although this change was only needed for speech perception testing, since subjects were only tested with bilateral implants for localisation, the spare processor was also used for localisation testing, to eliminate any difference in speech processing that may occur when using different speech processors for localisation and speech perception.

Before the day of testing, each subject was asked to inform the researcher which program they use in everyday listening, so that the subject could be provided with a spare speech processor with the most accustomed program to use. Before the start of testing, new batteries were provided. Subjects were also instructed to select the volume settings on the spare processor that they were most accustomed to use. Neurelec paid for subjects' transportation to the University of Southampton and for their lunch during their visit, and it also provided two spare speech processors to use during testing. Subjects were also paid £15 at the end of the testing day, after completion of both localisation and speech perception experiments. Subjects are identified by numbers assigned in the order in which they were tested.

Table 7.1: Characteristics for DSPB implant subjects

Subject	Gender	Age	Etiology	Duration of Deafness (years)	Months Since Activation	BKB score in quiet	
						Pre	Post
D1	M	74	Noise	1	18	0%	98%
D2	F	74	Unknown (progressive)	26	8	41%	100%
D3	F	66	Unknown (progressive)	13	12	0%	57%
D4	M	53	Cochlear otosclerosis	20	10	0%	47%
D5	M	75	Noise	20	4	25%	52%
D6	F	64	Unknown (progressive)	33	10	0%	74%
D7	M	45	Maternal rubella (Congenital)	10	12	15%	94%
D8	F	65	Unknown (progressive)	3	6	0%	88%

7.2.2 Procedure

Subjects each took part in two sessions on a single day, separated by a lunch break. Sound localisation and speech perception in noise were each tested in one session, selected at random. Subjects were fully informed and provided written consent before the first session.

For the localisation portion of testing, subjects each took part in one session lasting 2.5 to 3 hours. They were only tested when listening bilaterally with both implants. Frequent rest intervals were provided during the session. Testing set-up, stimuli and procedure details were identical to those described in Section 3.3. A subject, who was seated in the centre of an array of 11 loudspeakers in a lighted anechoic chamber, was asked to identify where the sound was coming from by using a touch screen with an image of the loudspeaker array and clicking on the letter corresponding to the loudspeaker. Subjects were also instructed to keep their head directed towards the mirror placed above the central loudspeaker at 0° azimuth while the stimulus was presented, to minimise head movement. Each of the five stimuli listed in Table 3.1, including speech, broadband noise (BBN), low-pass noise (LPN), high-pass noise (HPN) and high-pass noise burst (HPN-burst) was presented 66 times (3 times from each of the 11 loudspeakers x 2 replications). The nominal stimulus level was 65 dB SPL (A-weighted) and it was randomly roved by ±4 dB from trial to trial during testing, whereas the frequency content of the stimuli was kept constant. Although the results previously reported in Chapter 6 indicated that ±8 dB level roving seems insufficiently large to disrupt use of monaural level cues, the DSPB implant subjects in the current study were still tested with ±4 dB level roving, and this was because the current study with the DSPB implant subjects was conducted before testing the localisation ability of unilateral CI subjects (Chapter 6). The test session began with practice trials, which typically included presenting speech stimulus three times from each of the 11 loudspeakers.

7.3 Results

Localisation performance of the eight DSPB implant subjects for different stimuli is described in this section. This includes an overview of localisation performance (Section 7.3.1), overall localisation error (Section 7.3.2), and random and constant error (Section 7.3.3). Localisation performance of those subjects is also compared to that of subjects with conventional bilateral CIs, unilateral CIs and normal-hearing and the results presented in Section 7.3.4.

7.3.1 Exploration of localisation performance

Sound-source localisation of each stimulus by each of the DSPB implant subjects is shown in Figure 7.1, where mean response location (data point) is plotted as a function of actual loudspeaker location. Data points falling on the diagonal line represents correct responses (i.e. perfect localisation performance), points falling below the diagonal line represent responses to the left of the actual loudspeaker location and points falling above the diagonal line represent responses to the right of the actual loudspeaker location. For the sake of clear presentation, the standard deviation in responses for each loudspeaker was not plotted in Figure 7.1, and it can be found in Appendix D.3.

Figure 7.1 shows that, despite the considerable variation in localisation performance between subjects, there is a slight relationship between the response locations and the loudspeaker locations for all stimuli, particularly broadband stimuli and high-pass noise. The relationship between response locations and the loudspeaker locations is, however, less apparent for stimulus presenting from the right-side loudspeakers than the left-side loudspeakers. Median localisation performance across all subjects for each stimulus is presented in Figure 7.2, showing that median response location was somewhat close to the diagonal line for all stimuli, although standard deviations are large for stimuli presented on the right-side loudspeakers.

The above observations were statistically examined and results of the Pearson correlation are presented in Table 7.2. Median response locations were found to be at least approximately normally distributed for all stimuli (Shapiro-Wilk normality test: $P > 0.05$), although it is possible that the statistical power of the current study was insufficient to detect deviation from normality. Results indicated that the relationship between median response locations and the loudspeaker locations was statistically significant and robust (as indicated by r^2) for all stimuli, albeit less robustly so for broadband noise stimulus. In the analyses of the responses to loudspeakers on the right- and left-side (Table 7.2), the median responses to stimuli presented from the right-side loudspeakers were found to be not correlated for broadband noise stimulus (r=0.74, P=0.08). Similar results were obtained with non-parametric analyses.

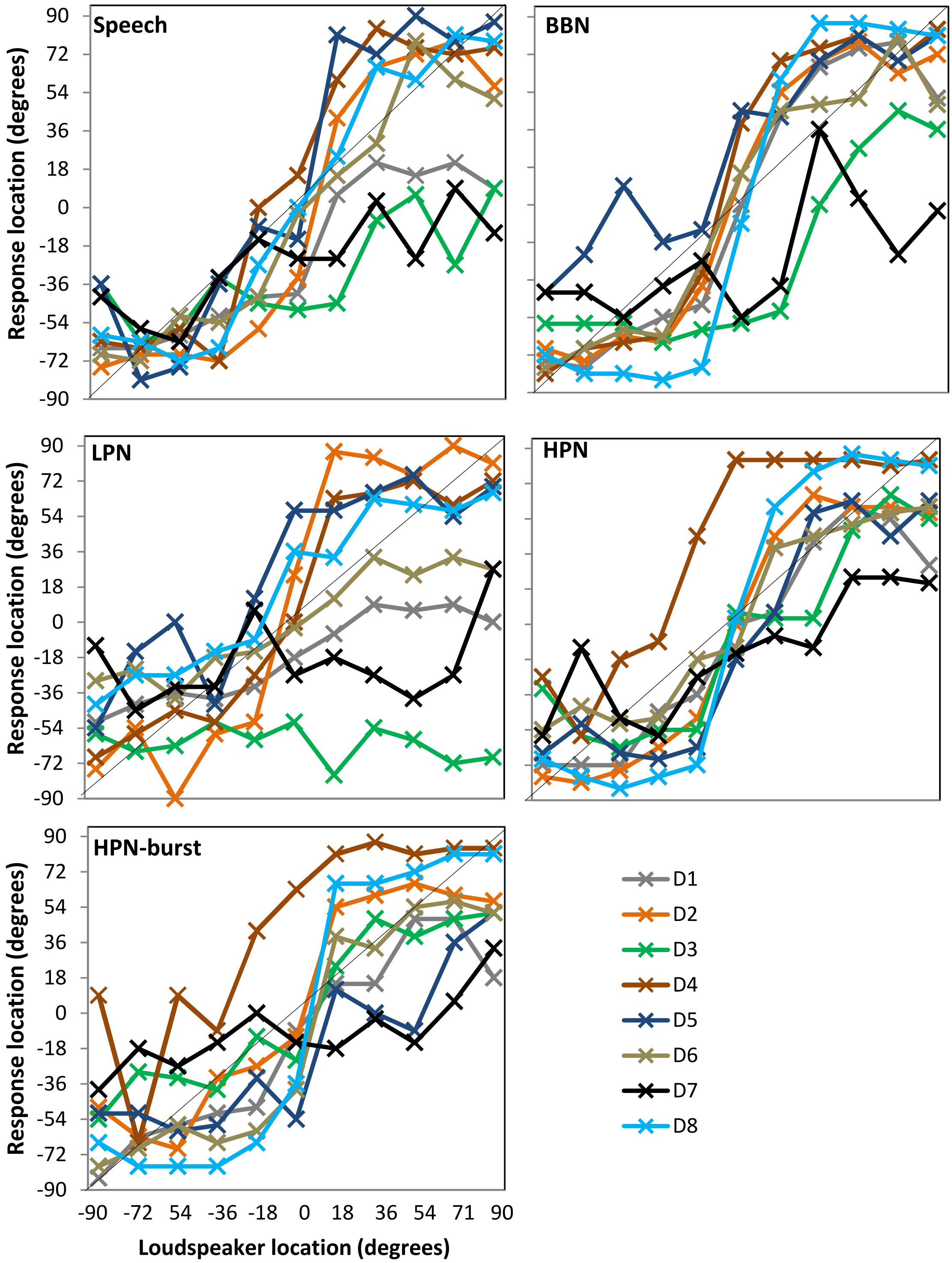


Figure 7.1: Sound localisation performance for each of the eight subjects while listening to different stimuli: speech, broadband noise (BBN), low-pass noise (LPN), high-pass noise (HPN) and high-pass noise burst (HPN-burst).Each coloured data point represents the mean response location given by a subject for each loudspeaker location. The diagonal line represents the correct responses.

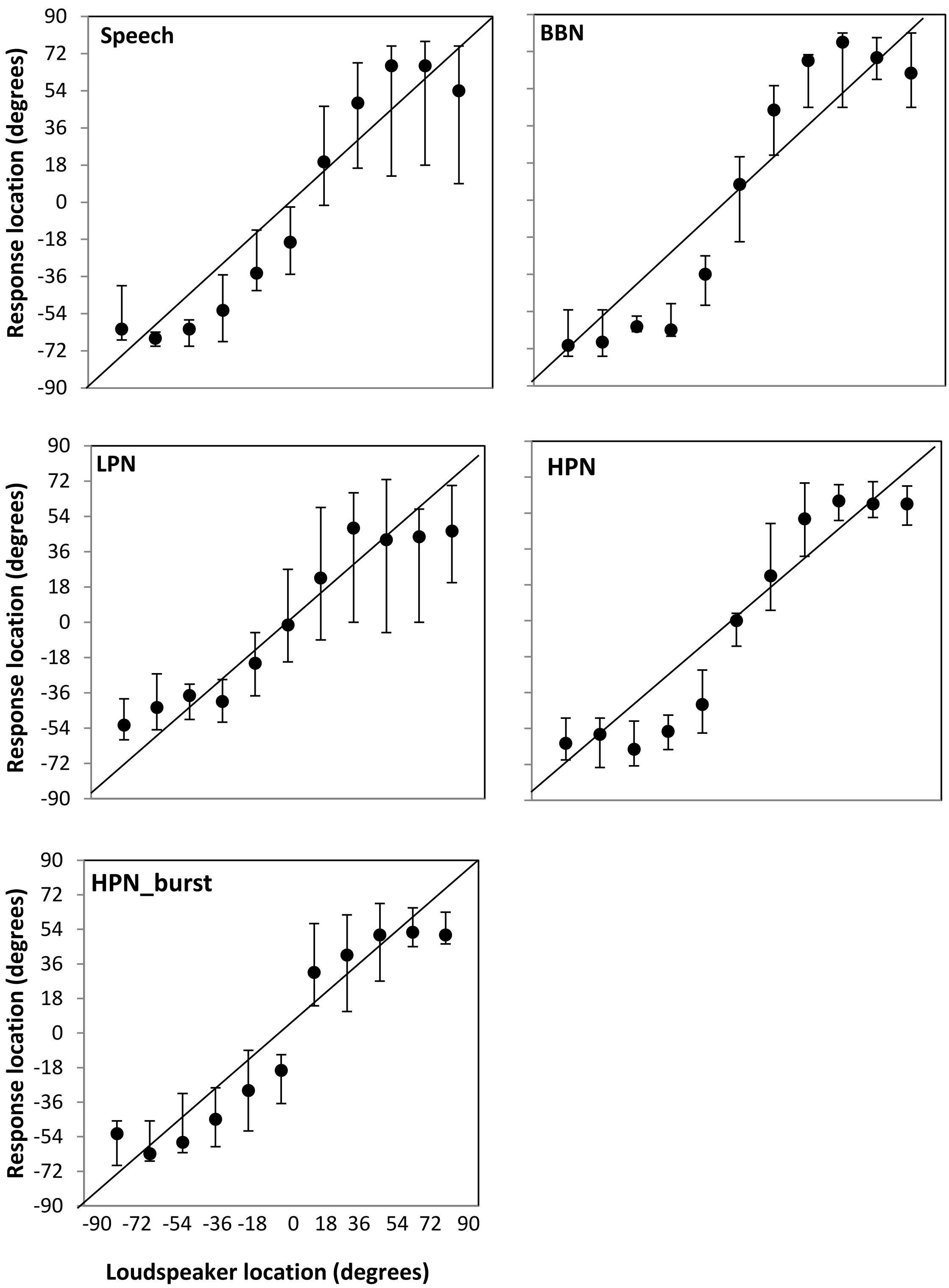


Figure 7.2: Median response locations across all subjects (data points) as a function of loudspeaker location for each stimulus. Error bars represent the upper and lower quartiles. The diagonal line represents the correct responses.

Table 7.2: Results of the Pearson correlation between loudspeaker location and median response location for each stimulus. Results for median responses for stimulus presenting from right-side loudspeakers (0° to +90°) and left-side loudspeakers (0° to -90°) are also presented.

Stimulus	*r*	r^2	*P*
Speech	0.96	0.92	< 0.001
Right-side loudspeakers	0.84	0.70	0.036
Left-side loudspeakers	0.91	0.85	0.012
BBN	0.94	0.88	< 0.001
Right-side loudspeakers	0.74	0.55	0.088
Left-side loudspeakers	0.86	0.74	0.027
LPN	0.95	0.90	< 0.001
Right-side loudspeakers	0.81	0.66	0.048
Left-side loudspeakers	0.92	0.85	0.008
HPN	0.95	0.90	< 0.001
Right-side loudspeakers	0.88	0.77	0.02
Left-side loudspeakers	0.79	0.62	0.04
HPN-burst	0.95	0.90	< 0.001
Right-side loudspeakers	0.82	0.67	0.04
Left-side loudspeakers	0.88	0.77	0.02

7.3.2 Overall localisation errors

Overall localisation error represented by mean absolute error (MAE) and root mean square error ($\overline{D}$ error) is shown in Figure 7.3. The overall error score across all the eight DSPB implant subjects and for each stimulus are displayed in Figure 7.3, where the grey area surrounding the chance level indicates the 99% chance range expected from unbiased guessing. It should be noted that the overall error scores presented in the figure were averaged across the two replications, since neither a consistent nor large difference in overall error was found between the two replications (see Appendix D.4).

Figure 7.3 shows two main trends. First, the overall error scores with all stimuli and for most subjects were below the chance range expected from unbiased guessing (grey area in the figure). Median overall error scores across stimuli ranged between 26° to 37° for MAE and 34° to 47° for $\overline{D}$ error, all of which were far below the chance range of unbiased guessing. Although this suggests that the DSPB implant subjects can generally localise sounds at a better than chance range of unbiased guessing, there were, however, a few overall error scores that approached or were within the range of unbiased guessing performance. Figure 7.4 displays the scores of MAE and $\overline{D}$ error for each subject separately and for each stimulus. The figure shows that the overall error was within the chance range of unbiased guessing for subject D3 for speech and low-pass noise stimuli and subject D7 (who was prelingually deafened) for all stimuli except for high-pass noise stimulus. The other six DSPB implant subjects (D1, D2, D4, D5, D6 and D8), however, showed overall error scores that were better than unbiased guessing range for all stimuli.

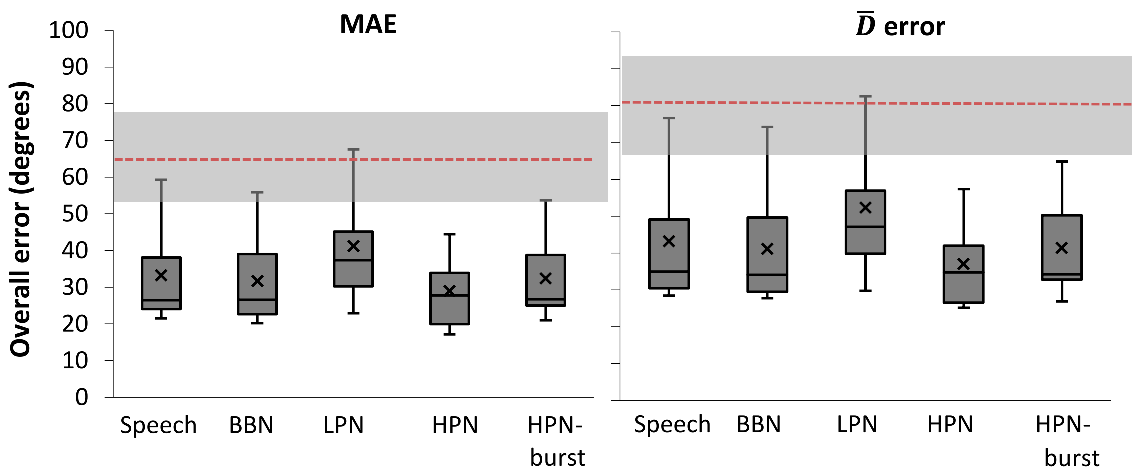


Figure 7.3: Overall localisation error (left panel: MAE; upper panel: $\overline{D}$ error) across all subjects for different stimuli: speech, BBN, LPN, HPN and HPN-burst. Each box represents the two middle quartiles (end of boxes), separated by median (horizontal line), mean (cross inside the box), maximum and minimum values (horizontal lines at the end of whiskers). The horizontal red line shows the chance level expected from unbiased guessing, with the grey area indicating the 99% chance range of unbiased guessing.

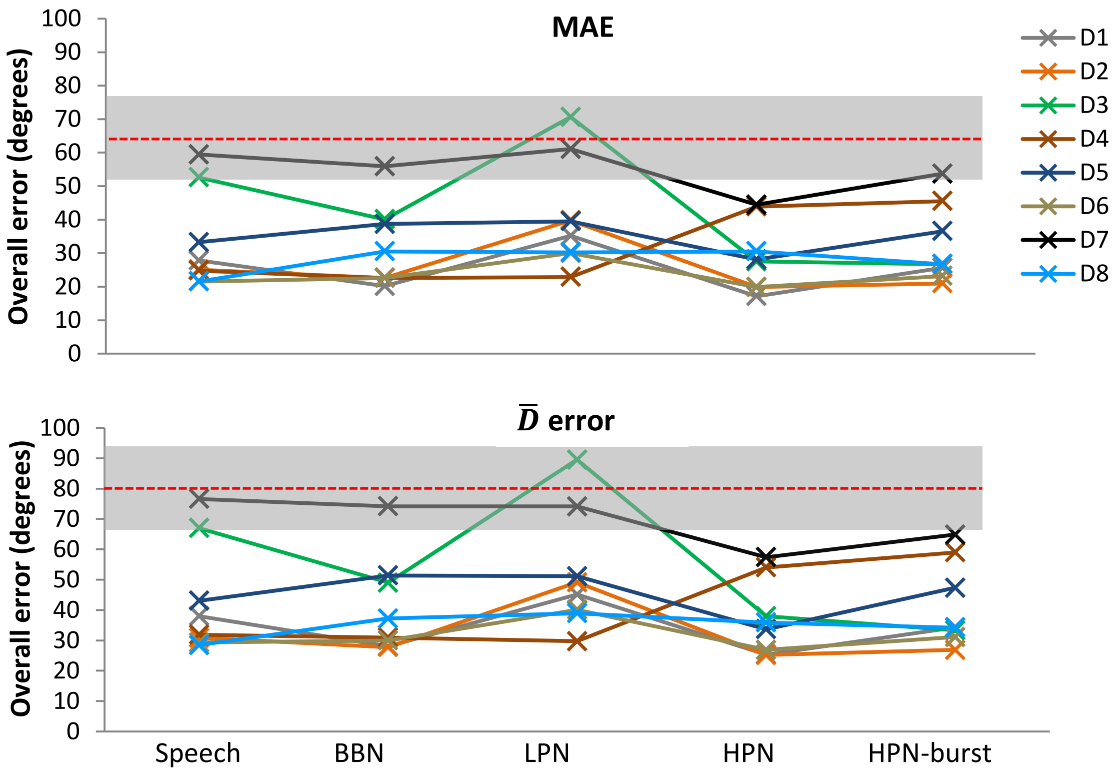


Figure 7.4: Individual overall localisation error (upper panel: MAE; lower panel: $\overline{D}$ error) of the eight DSPB subjects and for each stimulus. Each line represents a separate, numbered listener. The horizontal red line shows the chance level expected from unbiased guessing with the grey area indicating the chance range of unbiased guessing.

Given that an overall error score that is better than chance range of unbiased guessing can also be achieved by biased guessing towards frontal loudspeakers, it is of great importance to rule out whether the overall error scores by subjects D1, D2, D4, D5, D6 and D8 reflect some ability or just biased guessing. As demonstrated in Section 4.2.2, an overall error of about 45° to 51° for MAE and 54° to 66° for $\overline{D}$ error can be obtained by assuming biased guessing towards frontal loudspeakers. While overall error scores of subjects D1, D2, D5, D6 and D8 were far below this range expected from biased guessing, for all stimuli, subject D4 had overall error scores that fall within the biased guessing range for high-pass stimuli. Examination of responses given by subject D4 reveals a relationship between response locations and loudspeaker locations, though this was only true for left-side loudspeakers (Figure 7.1). The responses of subject D4 for sounds coming from the right-side loudspeakers were, however, biased to loudspeakers at 72° and 90°. Given that the left ear of subject D4 is the ear receiving the CI package (i.e. speech processor with ipsilateral electrodes) and that the side receiving the CI package is often chosen to be the better ear before implantation, this finding may indicate that subject D4 might only able to localise sounds on the side of the better ear. Although the pre-implantation performance of left and right ear, respectively, was not reported for subject D4, the subject reported that his hearing is better with the left ear than the right ear. The possibility of that this subject might only able to localise sounds on the side of the better ear may, however, be excluded, given that the subject D4 can show some localisation ability for the other stimuli (speech, BBN and LPN) coming from all loudspeakers. Taken together, the above results indicate that the majority of DSPB implant subjects can show overall error scores at better than chance range of unbiased guessing, and that such scores seem to reflect some ability rather than biased guessing, at least for some stimuli.

The second trend is that median overall error scores appeared to be similar across broadband stimuli and high-pass stimuli. High-pass noise stimulus had the lowest overall error score with the smallest variation between subjects. In contrast, low-pass noise stimulus had the highest overall error scores and the greatest variation between subjects. The median overall error score of low-pass noise was higher by at least 9.5° for MAE and 12° for $\overline{D}$ error than that of the high-pass noise. All subjects but one (Subject D4) had an overall error score that was higher for low-pass noise than the other stimuli (Figure 7.4). With the exception of subject D4, the overall error of high-pass noise was also found to be similar to or lower than other stimuli. Across broadband stimuli, the DSPB implant subjects had lower overall error scores for broadband noise than speech stimulus, except for subjects D5 and D8 who showed a higher error for broadband noise.

7.3.2.1 Statistical analyses

The distributions of overall errors shown in Figure 7.3 indicate that both the MAE and $\overline{D}$ error scores were somewhat skewed towards higher errors (i.e. positively skewed), particularly for broadband stimuli. The results of the normality test indicate that the distributions of MAE and $\overline{D}$ error scores with speech and broadband noise reached statistical significance (Shapiro-Wilk normality test: P = 0.03). A logarithmic transformation on the MAE and $\overline{D}$ error was then applied to indicate that the MAE and $\overline{D}$ error scores of all stimuli were at least approximately normally distributed (Shapiro-Wilk normality test: P > 0.05). Mean, logarithmically transformed MAE and $\overline{D}$ error scores are presented in Table 7.3 for each stimulus.

Table 7.3: Mean (95% confidence interval) logarithmically transformed MAE and $\overline{D}$ error scores, in degrees, for each stimulus.

	Speech	BBN	LPN	HPN	HPN-burst
MAE	1.48 (0.11 -0.09)	1.47 (0.12-0.12)	1.58 (0.10-0.06)	1.44 (0.13-0.08)	1.48 (0.08-0.09)
$\overline{D}$ error	1.60 (0.11-0.09)	1.58 (0.11-0.10)	1.69 (0.09-0.06)	1.55 (0.12-0.07)	1.59 (0.08-0.1)

Initially, two-tailed-one-sample t-tests were conducted on the logarithmically transformed overall error scores (MAE and $\overline{D}$ error) to determine whether the scores of the DSPB implant subjects were significantly different from chance range of unbiased guessing (P < 0.05). The results indicated that the mean MAE and $\overline{D}$ error scores were significantly better than chance range of unbiased guessing, for all stimuli (Table 7.4). One-way ANOVA was also conducted on the logarithmically transformed MAE and $\overline{D}$ error scores with the within-subjects factor of stimulus using an adjusted Bonferroni correction of 0.005 (0.05/10). The effect of stimulus was found to be not significant for MAE (F (4) = 1.01, P = 0.05) and $\overline{D}$ error (F (4) =0.97, P =0.07), indicating that overall error scores were similar across stimuli. While there was some indication that overall error score tended to be higher with low-pass noise than with the other stimuli, the lack of statistical evidence may reflect the insufficiency of the small sample (n=8, as opposed to 14 subjects, as planned in Section 6.2.1) and the great variation between them.

Table 7.4: Results of two-tailed one-sample *t*-tests to determine whether the logarithmically transformed MAE and $\overline{D}$ error scores of the DSPB implant subjects were significantly different from chance range of unbiased guessing (P <0.05).

Stimulus	MAE		$\overline{D}$ error	
	t	P	t	P
Speech	23.8	< 0.001	26.4	< 0.001
BBN	24.9	< 0.001	28.1	< 0.001
LPN	26.6	< 0.001	29.9	< 0.001
HPN	25.5	< 0.001	30.2	< 0.001
HPN-burst	27.9	< 0.001	31.6	< 0.001

7.3.3 Random and constant errors

In order to understand the whole picture of localisation performance and to determine the main reason behind the overall $\overline{D}$ error of the DSPB implant subjects, scores of constant error (i.e. bias) and random error (i.e. variability in responses) that contributed to the overall $\overline{D}$ error score shown by each DSPB implant subject are displayed in Figure 7.5 with the aim of understanding the main reason underlying the overall error shown by the DSPB implant subjects. The scores of constant and random errors can also help to determine whether the better than chance range of unbiased guessing shown by the majority of the DSPB implant subjects is based on some localisation ability or just biased guessing. It is worth remembering that the constant error refers to the deviation of the mean responses (the data points in Figure 7.1) from the loudspeaker locations (the diagonal line), whereas the random error is the standard deviation of responses at each loudspeaker location averaged across all loudspeakers (the average size of the error bars in Appendix D.3).

Starting with the subjects whose overall error scores were within the chance range expected from unbiased guessing, one might expect that their $\overline{D}$ error scores were attributable to relatively large scores for both constant and random errors. This, was true for subject D7, but not for subject D3, however. Subject D3 showed unbiased guessing for speech only, and biased guessing for low-pass noise. It should be remembered that unbiased guessing is usually characterised by relatively large scores on both constant error and random error, whereas biased guessing is associated with a greater amount of constant error and smaller random error. With low-pass noise, subject D3, indeed, showed a greater amount of constant error and smaller random error. The pattern of responses shown by subject D3 with low-pass noise also shows that her responses were biased towards the most-end loudspeakers on the left side (Figure 7.1).

For those subjects who showed overall error scores at better than chance range of unbiased guessing, Figure 7.5 shows that these subjects exhibited smaller scores for both constant error and random error than those who showed scores within unbiased guessing performance. Most importantly, the figure shows that scores of both constant and random error were generally far below those expected from biased guessing towards frontal loudspeakers (represented by the dashed area in the figure), with the exception of subject D4 with high-pass stimuli. Scores on both constant and random errors for subject D4 with high-pass noise stimuli were within the range of errors expected from unbiased guessing (grey area in Figure 7.5) and close to those expected from biased guessing towards frontal loudspeakers (dashed area Figure 7.5). Examination of the responses given by subject D4 reveals a relationship between response locations and loudspeaker locations for left-side loudspeakers, whereas his responses for sounds coming from the right-side loudspeakers were biased to loudspeakers at 72° and 90°. Therefore, the better than chance range expected from unbiased guessing shown by subject D4 with high-pass noise stimuli should be treated with caution, as it is more likely to reflect guessing, rather than ability.

Although it was not significant, the greater overall error scores exhibited for low-pass noise were found to be the result of the increase in the constant error and/or random error. When considering the subjects who showed some ability to localise all types of stimuli (D1, D2, D5, D6 and D8), they seem to have a greater constant error and/or random error for low-pass noise, and a lower constant error and/or random error for high-pass noise stimulus.

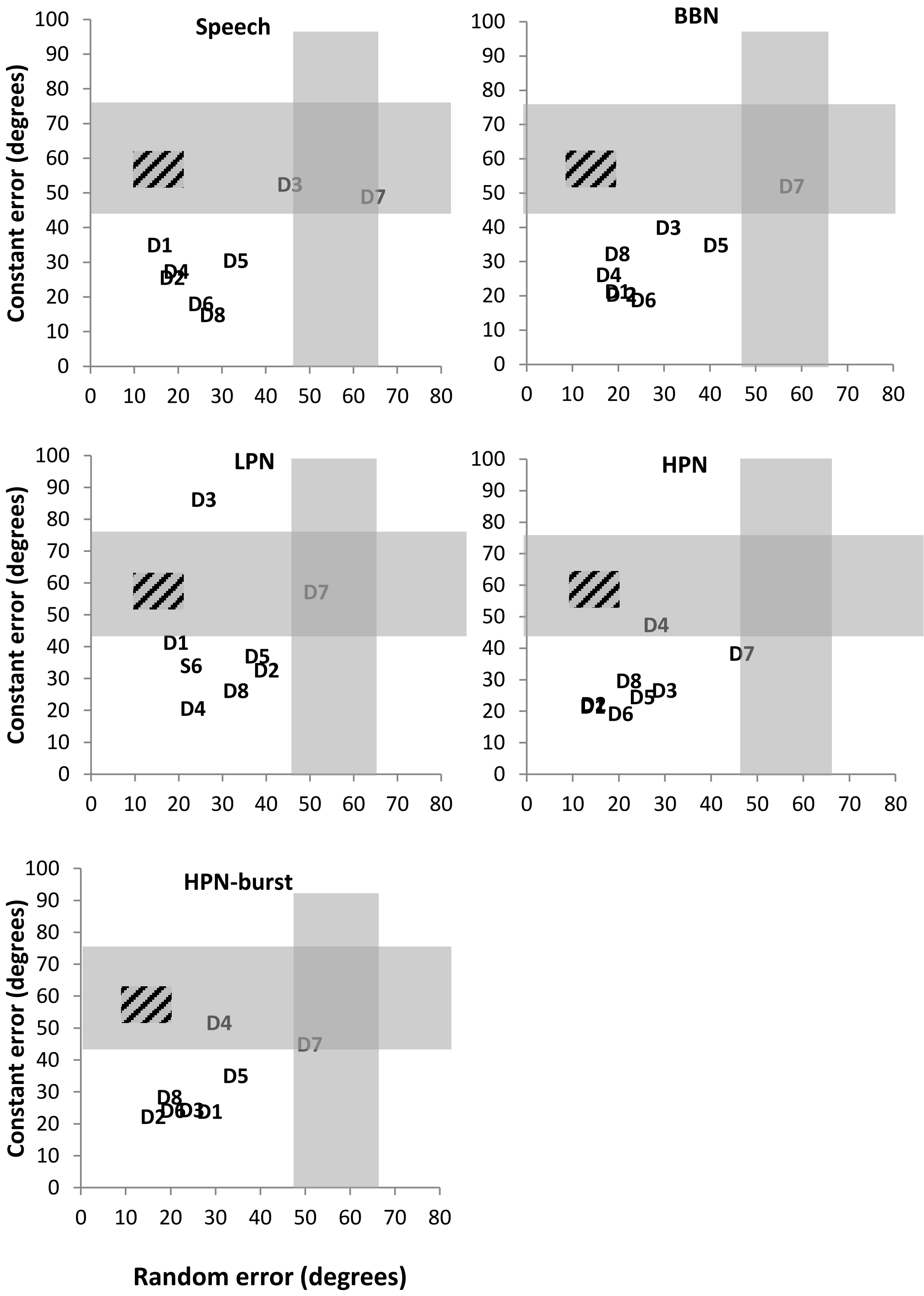


Figure 7.5: Random error (i.e. variability in responses) versus constant error (i.e. bias) for the eight DSPB subjects for different stimuli. The grey area indicates the chance range expected from unbiased guessing, whereas the dashed area indicates chance range expected from biased guessing towards frontal loudspeakers (Section 4.2.2).

7.3.4 Localisation performance across different groups

The above results show that the majority of DSPB implant subjects can show overall error scores at better than chance range of unbiased guessing. The better than unbiased guessing performance by those subjects was found to reflect some ability rather than biased guessing, at least for some stimuli. This section compares localisation performance of DSPB implant subjects with that of unilateral and conventional bilateral CI subjects. The overall $\overline{D}$ error scores of the DSPB implant subjects are plotted in Figure 7.6 with the scores of unilateral CI subjects (Chapter 6) and normal-hearing subjects (Chapter 4). In addition, the overall $\overline{D}$ error scores of conventional bilateral CI subjects from a previous study conducted in our laboratory using similar procedures to those used in this project (Verschuur et al., 2005) are also plotted in the figure, for comparison. Although Verschuur et al. assessed localisation performance with a variety of stimuli, only the data for speech and broadband noise were used, since the characteristics of their other stimuli were not comparable to the stimuli used in the current study. Since Verschuur et al. (2005) only reported MAE scores, a re-analysis of their data was carried out in order to provide the whole picture of localisation performance.

Figure 7.6 displays the overall $\overline{D}$ error scores for speech (on the abscissa) and for broadband noise (on the ordinate), where the grey area indicates the chance range expected from unbiased guessing. Given that some of the unilateral CI subjects tested in the study reported in Chapter 6 can show overall error scores at better than chance range of unbiased guessing solely based on monaural cues, the range of error scores that was achieved by these subjects was also shown (the blue area in the figure). The overall error score of a bilaterally implanted subject should be lower than the range of scores that can be achieved based on monaural cues, to be more certain that the bilateral CIs can actually provide bilateral advantage over single CIs. The overall error score of a bilaterally implanted subject that is better than chance range of unbiased guessing, but still within the range of scores exhibited by good unilateral CI performers will not be interpreted as bilateral advantage, because such scores can also be achieved based solely on monaural cues rather than binaural cues.

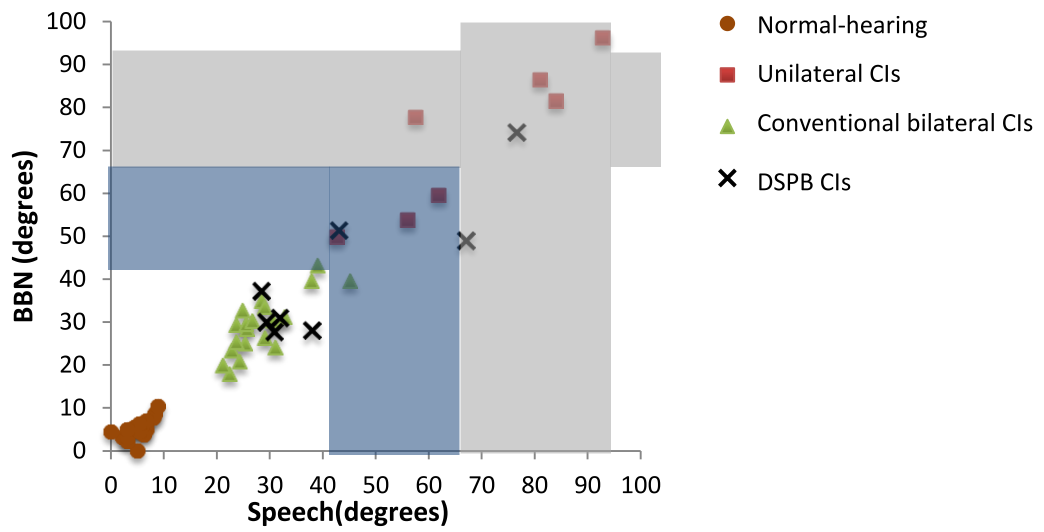


Figure 7.6: Overall $\overline{D}$ error scores for speech and broadband noise for different groups of subjects: subjects tested in the current study with DSPB implant (black x), unilateral CI (red square) and normal-hearing (brown circle) and subjects tested in the study of Verschuur et al. (2005) with conventional bilateral CIs (green triangle). The grey area indicates the chance range expected from unbiased guessing, whereas the blue area indicates the range of scores achieved by good unilateral CI performers relying solely on monaural cues.

The figure shows that the overall error scores of most DSPB implant subjects fall in the range of scores exhibited by conventional bilateral CI subjects, although none of the DSPB implant subjects approached the ‘‘better’’ performance shown by the conventional bilateral CI subjects. Only two DSPB implant subjects had overall error scores that are higher than those of the conventional bilateral CI subjects for speech and/or broadband noise stimuli. It is worth remembering that these two DSPB implant subjects were found to have higher overall error scores than the other DSPB implant subjects: their scores were actually within the chance range expected from unbiased guessing (subject D3 for speech and D7 for speech and broadband noise).

Given that some of the unilateral CI subjects tested in the study reported in Chapter 6 can show overall error scores at better than chance range of unbiased guessing, it is of importance to determine whether the better than unbiased guessing performance shown by the bilateral CI subjects was based on binaural or monaural cues. Figure 7.6 shows that the majority of bilateral CI subjects whose overall error scores were better than chance range of unbiased guessing still exhibited lower scores than those from the ‘‘good’’ unilateral CI performers. The overall error scores of most of the bilateral CI subjects implanted with either the DSPB CIs or conventional CIs were lower than the range of scores that can be achieved solely based on monaural cues (blue area in the figure) for speech and broadband noise. This indicates that bilateral implantation can offer bilateral advantages over unilateral CIs for such subjects. There were, however, a few bilateral CI subjects whose overall error scores fall in the range of scores from the good unilateral CI subjects (blue area in the figure). For example, two DSPB implant subjects (subject D3 for broadband noise and D5 for speech and broadband noise) exhibited overall error scores that were below the chance range of unbiased guessing but still within the range of scores from the good unilateral CI performers. The above result indicates that such bilateral CI subjects might use monaural cues to localise sounds rather than binaural cues, and thus bilateral implantation might not offer advantage for localisation over the single CI for those particular DSPB implant subjects.

The above observations were examined statistically to determine whether the localisation performance differs across different groups. As noted in Section 7.3.2.1, the overall $\overline{D}$ error of the DSPB implant appeared positively skewed, and the positive skew was reduced following a logarithmic transform. However, the overall $\overline{D}$ error scores of normal-hearing subjects, which were at least approximately normally distributed, became negatively skewed following the logarithmic transform. For this reason, the logarithmic transform was not applied and then non-parametric analyses were used. As a compromise, non-parametric tests on the overall error of all groups and parametric tests on the logarithmically transformed error of the DSPB implant, conventional bilateral CI and unilateral CI groups were conducted and the results compared.

Kruskal-Wallis tests were carried out with group as the independent variable. The results showed a significant difference in overall $\overline{D}$ error between groups for speech (χ=45.6, $P < 0.001$) and broadband noise (χ=46.3, $P < 0.001$). *Post hoc* Mann-Whitney tests with a Bonferroni correction were used to assess which groups differed and the results are presented in Table 7.5. The DSPB implant group was found to have significantly higher overall errors than the conventional bilateral CI group when localising speech. The overall error scores of the DSPB implant group for speech were found to be only marginally significantly different from those of the unilateral CI group. With broadband noise, however, the overall error was found to be similar for both the DSPB implant and conventional bilateral CI groups, in which it was significantly higher than in the unilateral CI group. The overall error of the DSPB implant group was still higher than that of the normal-hearing group, for both stimuli. Similar results were also found with the parametric analyses (i.e. one-way ANOVA).

Table 7.5: The results of Mann-Whitney tests to compare the overall $\overline{D}$ error of the DSPB implant subjects with those with conventional bilateral CIs, unilateral CIs and normal hearing.

	Speech	BBN
DSPB implant vs conventional bilateral CI	2.72 (*P*=0.005*)	1.88 (*P* =0.06)
DSPB implant vs unilateral CI	2.41 (*P*=0.016)	2.94 (*P*=0.003*)
DSPB implant vs normal hearing	4.04 (*P*< 0.001*)	4.04 (*P*< 0.001*)

**P with Bonferroni correction* < 0.016

The significantly higher overall error shown by the DSPB implant subjects for speech was found to be the result of the greater variability in responses shown by those subjects compared to the conventional bilateral CI subjects. Figure 7.7 displays both random error and constant error in two-dimensional space for different groups. The figure shows that the magnitude of constant and random errors exhibited by most of the DSPB implant subjects falls in the range of errors shown by the conventional bilateral CI subjects for both speech and broadband noise. It appears that the DSPB implant subjects approached the performance of ʺbetterʺ conventional bilateral CI subjects only on either random error or constant error, but not on both. The unilateral CI subjects were found to have generally higher constant error than the DSPB implant subjects.

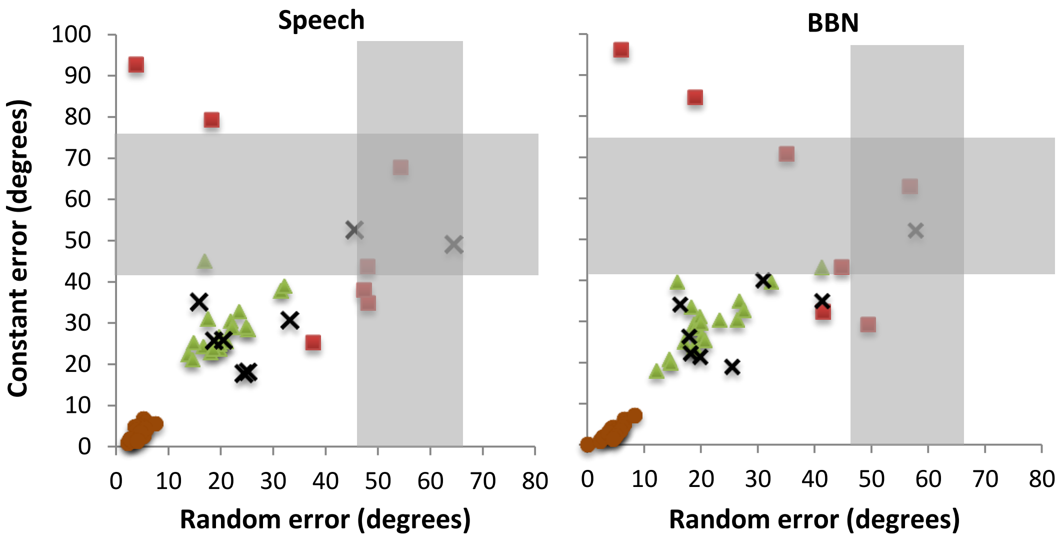


Figure 7.7: Random error versus constant error for speech (left panel) and broadband noise (right panel) for different groups of subjects: subjects tested in the current study with DSPB implant (black x), unilateral cochlear implant (red square) and normal hearing (brown circle) and subjects tested in previous study with bilateral cochlear implants (green triangle; Verschuur et al., 2005).

Results of Mann-Whitney tests on the constant and random error with a Bonferroni correction are presented in Table 7.6. These show that the significantly higher overall error by the DSPB implant group with speech compared with the conventional bilateral CIs mainly resulted from the significantly higher random error exhibited by the DSPB implant subjects than the conventional bilateral CIs. The significantly lower overall error by the DSPB implant group with broadband noise compared with the unilateral CIs mainly resulted from the marginally significant lower constant error exhibited by the DSPB implant subjects than unilateral CI subjects. The DSPB implant group was found to have significantly higher constant and random error than normal-hearing subjects.

Table 7.6: The results of Mann-Whitney tests to compare the constant error ($\bar{C}$) and random error ($\bar{s}$) of the DSPB implant subjects with those with conventional bilateral CIs, unilateral CI and normal-hearing.

	Speech		**BBN**	
	$\bar{C}$	$\bar{s}$	$\bar{C}$	$\bar{s}$
DSPB implant vs conventional bilateral CI	2.44 (*P* >0.1)	1.88 (*P*=0.006*)	2.33 (*P*>0.1)	0.91 (P >0.1)
DSPB implant vs unilateral CI	1.99 (*P*= 0.046)	0.31 (*P* > 0.1)	2.41 (*P*=0.016)	0.52 (P > 0.1)
DSPB implant vs normal hearing	4.03 (*P* < 0.001)	4.03 (*P* <0.001)	4.03 (*P*=0.00)	4.03 (*P*<0.001)

**P with Bonferroni correction* < 0.016

In summary, the above results indicate that localisation performance by the DSPB implant subjects with broadband noise, which was better than that by unilateral CI subjects, was similar to that by the conventional bilateral CI subjects. When localising speech, however, the DSPB implant subjects showed comparable performance to that by the unilateral CI subjects, in which it was significantly better than that shown by the conventional bilateral CI subjects. Given that two DSPB implant subjects performed within the unbiased guessing performance with speech, whereas only one subject did so with broadband noise, it seems more likely that the differences in performance between the DSPB implant and conventional bilateral CI groups resulted from the higher variability in the performance of the DSPB implant subjects with speech than with broadband noise.

7.4 Discussion

The aim of the current study was to explore localisation performance of the DSPB implants for different types of stimuli. The findings of the current study show that five out of the eight DSPB implant subjects can show overall localisation error scores on a simple localisation task at better than chance range of unbiased guessing for all stimuli. This finding is consistent with the findings of the two previous studies in which sound localisation was found to be possible with the DSPB implants (Bonnard et al., 2013; Verhaert et al., 2012). The findings of the current study, however, provide evidence that the localisation performance shown by the DSPB implant subjects is very likely to reflect some ability to identify the apparent locations of sound sources rather than guessing (i.e. unbiased and biased guessing).

With the exception of a few subjects, the current study is the first to provide evidence that the localisation ability shown by the DSPB implant subjects is more likely to result from their ability to make use of binaural cues that are not available with unilateral CIs. A few DSPB implant subjects, however, showed comparable overall error scorers to those achieved by the ‘‘good’’ unilateral CI performers, so that it might be possible that such DSPB implant subjects were using monaural cues to localise sounds. Localisation performance of the DSPB implant subjects seems to be significantly similar to that of conventional bilateral implant subjects (Verschuur et al., 2005), for broadband noise, but not for speech; yet localisation ability of bilateral CI users including both the DSPB implants and conventional bilateral CIs was still much worse than that of normal-hearing listeners. All the above findings of the current study are discussed in the following sections.

It should be stressed that the above findings are limited to the sample of subjects tested in the current study. The current study tested only eight DSPB implant subjects, in which a considerable variation in their characteristics was apparent between subjects. For example, one of the eight subjects was prelingually deaf. Although the current study was intended to test 14 DSPB subjects, it was not possible to achieve the intended sample size, as the CI centres involved in the current study abruptly ceased providing DSPB implants during the time span of this project. A larger study with many more DSPB implant subjects might able to detect a significant difference in performance between stimuli and/or groups.

7.4.1 Comparison with guessing performance

The findings of the current study show that the majority of the DSPB implant subjects can show overall error scores on a simple localisation task at better than the chance range expected from unbiased guessing. Scores on constant and random errors confirmed that the better than unbiased performance shown by the DSPB implant subjects is more likely to reflect some ability, rather than biased guessing, except for one subject with some stimuli.

Across all stimuli, the findings of the current study show that all the DSPB implant subjects but one had overall localisation error scores that fell below the chance range of unbiased guessing. Interestingly, the DSPB implant subject who performed within the unbiased guessing range was the one who was prelingually deaf and used hearing aids at 5 years old. This might be due to a relationship between early deafness and the development of sensitivity to binaural cues. A previous study with direct electrical stimulation to a single pair of electrodes showed better binaural cue sensitivity when bilateral CI adults had had access to acoustic cues early in life (Litovsky et al., 2010).

Another finding of the current study emerged from the effect of stimuli on localisation performance of the DSPB implant subjects. Although it was not statistically significant, low-pass noise was tended to be associated with higher overall error scores than the other stimuli. All the DSPB implant subjects but one showed higher overall error scores with low-pass noise than high-pass noise stimuli. Such a finding is not surprising, given that the signal processing strategy used in the DSPB implants does not preserve the fine structure ITD in the stimulus. The absence of ITD cues in the low-pass noise seems to bias subjects' responses and/or increase the variability in response and thus increase overall localisation error. High-frequency stimuli, on the other hand, were found to localise at better than chance range of unbiased guessing by all the DSPB implant subjects, although the result of one subject needs to be treated with caution, as it is more likely to reflect biased guessing for sounds coming from the right-side loudspeakers. The relatively better localisation ability with high-frequency stimuli is also not surprising, given that the signal processing strategy used by the processors in the DSPB implant subjects does represent ILDs.

Given that the strategy used by the processors in the DSPB implant does not represent ITDs in the fine structure of a stimulus, one might also expect that the DSPB implant subjects should not able to localise low-pass noise stimulus at better than chance range of unbiased guessing. However, the findings of the current study show that six out of eight subjects showed overall error scores with low-pass noise stimulus at better than chance range expected from unbiased guessing. The ability of DSPB implant subjects to localise low-pass noise is more likely to rely on the use of ILD cues. As demonstrated in Figure 3.5, small ILDs (< 5 dB) can be observed for frequencies lower than 1 kHz. Although such small ILDs are unlikely to serve as a good localisation cue, they might provide some information for azimuths between 0° and 55°, where a monotonic increase with azimuths can be observed. It is likely that the small ILDs may be sufficient to allow some subjects to localise a low-pass noise stimulus. Examination of responses by the DSPB subjects for low-pass noise, in which responses were rarely given for azimuths beyond +/-54° (Figure 7.2) may support the dominance of ILDs for localising low-pass noise. It is well established that for conventional bilateral CIs, the ILD's ambiguity increases with increasing azimuths beyond 60°, due to the effects of compression settings in the CI processors (Seeber and Fastl, 2008). Such ambiguity seems to be also apparent with the DSPB implants.

Taken together, the above findings may suggest that the better than unbiased guessing by the DSPB implant subjects is more likely to be mediated by ILDs, although this was only true for some of the DSPB implant subjects. Few DSPB implant subjects showed overall error scores that fell within the range of scores achieved by the ''good'' unilateral CI performers, suggesting that they might use monaural cues for localisation at better than unbiased guessing range (see Section 7.4.3).

7.4.2 Comparison with previous studies on DSPB implants

The two previous studies on the localisation performance with DSPB implants reported an average $\overline{D}$ error of about 35.0° for broadband noise (Verhaert et al., 2012) and 49.9° for words (Bonnard et al., 2013). The overall $\overline{D}$ error reported in the current study was within the range of scores reported by the previous two studies. The overall localisation error reported in the current study for broadband noise ($\overline{D}$ error=41.1°) and speech ($\overline{D}$ error=43.1°) was broadly comparable to that reported by the previous studies, although the comparison between these studies is complicated by many factors.

Firstly, the localisation set-up used by the current study consisted of 11 loudspeakers separated by 18°, whereas only five loudspeakers separated by 45° were used by Bonnard et al. (2013) and Verhaert et al. (2012). It is possible that localisation performance of the DSPB implant subjects in the current study was underestimated by the use of a higher number of loudspeakers, which might result in a more difficult task than when a smaller number of loudspeakers is used. However, it was reported by Hartmann et al. (1998) that the $\overline{D}$ error reached a plateau when there were at least six loudspeakers and the angular separation was greater than 5% of the span (as with the current study). When the angular separation between loudspeakers is greater than 20% of the span (as with the above two studies), the $\overline{D}$ error becomes extremely insensitive to the number of loudspeakers. Another factor that may complicate the comparison is that the stimulus representation level was roved by ±4 dB in the current study, whereas in the previous two studies it was fixed at 60 dB SPL (Bonnard et al., 2013) or at 65 dB SPL (Verhaert et al., 2012). Thus, the extent to which the monaural level cues were accessed by the subjects could have been different between the studies.

A third factor that complicates comparison across studies is the higher variability in the characteristics of the subjects between studies. Examination of the characteristics of the DSPB implant subjects of the studies showed that the subjects of the current study had less experience with their implant than those in previous studies. It is possible that the shorter duration of CI experience with DSPB implant subjects in the current study might have limited their performance. Although Grantham et al. (2007) reported no significant change in localisation performance between about 4-6 to 12-16 months after receiving bilateral CIs, two of their 12 subjects showed a very considerable improvement over a 5- to 15-month period. Thus, it is possible that some subjects in the current study might need more experience with bilateral listening in order to reach their best performance. In fact, the best DSPB implant performer ($\overline{D}$ error=34.1°) was the one who had worn the implant for a longer time, about 18 months. It is worth mentioning that all the DSPB implant subjects of the current study will be retested in our laboratory at least 18 months post-implantation, in order to determine whether their abilities can be improved through additional everyday listening experience.

With regard to the effects of stimulus, the current study seems to be the only study that has investigated the effects of the type of stimulus on localisation performance with the DSPB implants. However, there is an indication of inconsistent findings between the current study and the other studies. Given that Verhaert et al. (2012) and Bonnard et al. (2013) both used a similar set-up, their findings seem to indicate that broadband noise was localised with better accuracy than speech. As noted earlier, an overall localisation error of 35.0° was reported for broadband noise by Verhaert et al. (2012) and 49.9° for words by Bonnard et al. (2013). The current study, however, shows a similar overall error for speech (43.1°) and broadband noise (41.1°). One might expect that the difference in performance between stimuli reported by the previous studies may be attributed to the difference in the characteristics of the subjects in the two studies. Examination of the subjects' information presented in Table 1 in their articles reveals that at least five out of six subjects tested by Bonnard et al. (2013) seem to have been already tested by Verhaert et al. (2012). Although this was not mentioned by Bonnard et al. (2013), the fact that they recruited their subjects from a centre that had already been involved, among three other centres, in the study of Verhaert et al. (2012) may support that they mostly the same subjects. Given that Verhaert et al. (2012) have not defined their subjects, this means the comparison of localisation performance for speech and broadband noise for each subject was not possible.

7.4.3 Comparison of localisation performance with DSPB implants and unilateral CIs

One of the key findings of the current study is that the most of the DSPB implant subjects whose overall error scores were better than chance range of unbiased guessing could still show lower scores than those from the ‘’good’’ unilateral CI performers. As documented previously in section 6.3.1, some unilateral CI subjects can show overall error scores at better than chance range of unbiased guessing, which are more unlikely to have been achieved by biased guessing. This suggests that the better than unbiased guessing performance (i.e. chance range) by the DSPB implant subjects may not necessarily reflect the ability to use binaural cues. Thus, it is not clear whether the localisation performance of the DSPB implant subjects in the studies of Bonnard et al. (2013) and Verhaert et al. (2012) was based on monaural or binaural cues. The current study provides evidence that five of the DSPB implant subjects tested in the current study were able to localise both speech and broadband noise with more accuracy than that of good unilateral CI performers who relied on monaural cues to identify the locations of sound sources. This finding is of great importance, as it may indicate that some of the DSPB implant subjects can take advantage of binaural cues that are not available for unilateral CI users.

Few of the DSPB implant subjects who showed overall error scores at better than unbiased guessing performance, however, showed scores within the range of those from the good unilateral CI performers. This may suggest that the localisation performance of such DSPB implant subjects (subject D3 for broadband noise and D5 for speech and broadband noise) is based on the use of monaural cues and thus the DSPB implant does not provide any bilateral advantage for them. However, it might be possible that the performance of those particular DSPB implants were affected by the characteristics of these subjects. For example, the two DSPB implant subjects who showed similar localisation performance to that of the good unilateral CI performers were older than 65 years, whereas the good unilateral CI subjects were aged between 22 to 54 years (their mean age was 35.5 years). Given that the aging-related auditory and cognitive processing factors generally begin to occur in 60-year-olds (Gates, 2012), it might be possible that the localisation ability of these DSPB implant subjects was affected by such age-related factors. More importantly, the shorter duration of CI experience with DSPB implants may limit the subject’s performance. Given that the two DSPB implant subjects had on average 8 months experience with their implants, this may suggest that more time with bilateral listening is needed to develop their spatial listening abilities.

7.4.4 Comparison of localisation performance with DSPB implants and conventional bilateral CIs

Another key finding of the current study emerged from the comparison of localisation performance by subjects implanted bilaterally with DSPB implants to that of subjects implanted with conventional CIs (Verschuur et al., 2005). Re-examination of the Verschuur et al. (2005) data confirmed that all the 20 conventional bilateral CI sujects can show overall error scores at better than chance range of unbiased guessing, in which they are more likely to reflect some ability than biased guessing. The findings of the current study show a significantly superior localisation performance for the conventional bilateral CI subjects than the DSPB implant subjects although this was only for speech, but not for the broadband noise. This contrasts with the findings of Bonnard et al. (2013) who reported no significant difference in localisation performance with the DSPB implants and the conventional bilateral CIs for speech. The significant difference in performance with speech in the current study might result from the higher variability in performance with speech than with broadband noise. Only one DSPB implant subject performed within the unbiased guessing performance with broadband noise, whereas two subjects did so with speech. When only considering the DSPB implant subjects whose overall error scores were at better than unbiased guessing performance, it seems that the performance of the majority of the DSPB implant subjects falls within the range of performance exhibited by the subjects implanted with the conventional bilateral CIs.

The findings of the current study also showed that none of the good DSPB implant performers approached the best performance of conventional bilateral CI subjects. Given that the DSPB implant subjects were tested with a short duration of bilateral experience (mean =10 months), this may have limited their performance and a longer experience with the implant might be needed to improve their performance. The extent to which the duration of bilateral experience could explain why none of the DSPB implant subjects approached the better performance of Verschuur et al.'s subjects is not clear, given that the exact length of bilateral experience was not given for their subjects. Verschuur et al. (2005) reported conflicting information regarding the duration of bilateral experience of their bilateral CI subjects; they reported that the inclusion criteria for their subjects was to have at least 9 months experience with their second device and then they reported that their subjects were tested between 3 and 9 months after initial tuning of the second device.

As with the current study, similar localisation performance was reported for speech and broadband noise by previous stiudes on conventional bilateral CI subjects (Neuman et al., 2007; Verschuur et al., 2005). Verschuur et al. (2005) reported no significant differences in overall localisation error scores between speech and broadband noise presented at 60 dB SPL. Their result is promising, given that the characteristics of speech and broadband noise used in their study and the current study were almost identical. It should be noted that Verschuur et al. (2005) only reported a significantly higher score for broadband noise presented at 70 dB SPL over that for speech stimulus, and this is possibly due to the effect of activation the automatic gain control (AGC) and compression circuitry at the input stage of the CI system. Inconsistently with that finding, Grantham et al. (2007) reported significantly better localisation performance for speech stimulus than for broadband noise stimulus by their conventional bilateral CI subjects. Grantham et al. (2007) suggest that the superior localisation performance with speech might be the result of the use of spectral or temporal cues in the speech or the involvement of central factors related to the social relevance and salience for communication. However, they acknowledged that this possibility needs to be investigated by further research.

Within the narrowband stimuli, there is a trend of the DSPB implant subjects to localise low-pass noise with lower accuracy than the other stimuli. This finding may indicate that removing the high-frequency portion of the stimulus degrades localisation performance. This may suggest that localisation performance of the DSPB implant subjects is mainly mediated by the ILDs in the high-frequency portion of the stimulus. Results from studies investigating the contribution of binaural cues to localisation with conventional bilateral CI users also showed that bilateral CI users predominantly relied on ILDs for localising all types of sounds (Grantham et al., 2007; Seeber and Fastl, 2008; van Hoesel, 2004; Verschuur et al., 2005). Grantham et al. (2007) for example, found that localisation performance of conventional bilateral CI users with broadband noise deteriorated when the high-frequency portion of the stimulus was removed, indicating a strong contribution of ILDs.

In summary, the findings of the current study show statistically similar localisation performance between those with DSPB implants and those with conventional bilateral CIs for one stimulus, but not for the other. Such findings may indicate that the way the stimulation is synchronised with the DSPB implant is not enough to offer any further spatial hearing benefit than that from two separate CIs.

7.4.5 Comparison of localisation performance with DSPB implants and that of normal-hearing listeners

The localisation performance of normal-hearing subjects presented in Chapter 4 was much better than that of the bilateral CI subjects, including both those with the DSPB implants and the conventional bilateral CIs. These results are in line with previously reported studies on adults with bilateral CIs (e.g. Grantham et al., 2007; Verschuur et al., 2005).

There are several factors that limit localisation performance of bilateral CI users. The first group are limitations due to pathology in the auditory system which are likely arise from degeneration in both the peripheral and central auditory systems due to lack of stimulation. Another factor limiting the performance of bilateral CI users is the restricted availability of binaural cues by the current speech processors. The current signal processing strategies do not represent ITDs in the fine structure of the stimulus. Although the ITDs in the envelopes are presented by the CI processors, this provides rather variable and unreliable cues for spatial hearing (van Hoesel, 2004). The accuracy with which the ILDs are represented is limited by the independent processing of sounds between ears. Although the speech processor in the DSPB implant processes the sounds from both ears synchronously in time, it still processes the sound from each ear independently in two signal processing lines. Thus, the limited ILD accuracy experienced with two independent CI processors is more likely to be experienced with the DSPB implants. In addition, mismatching of the place of stimulation between the ears might also reduce the ILD sensitivity. Difference in either anatomical positioning of the electrode array in the cochlea and/or the insertion depth of electrode arrays between the ears might result in differences in the place of stimulation across ears, which may limit the binaural cues in bilateral CI users (more details can be found in Section 2.6.4).

7.4.6 Real-world implications of the good localisation ability with DSPB CIs

Although the finding of the current study in which most DSPB implant subjects can show overall error scores at better than unbiased guessing performance is promising, such an ability does not necessarily translate into usable localisation ability in everyday life. Localisation ability shown by the subjects was tested in a controlled laboratory environment, where their localisation ability with stationary sound sources and a stationary listener were assessed. This might not, however, reflect real-world situations where multiple sounds are presented at once, leaving it unclear to what extent the cues that have been used by the DSPB implant subjects to do the task can provide reliable cues with multiple sound sources. Given that the ILDs are more likely to dominate the localisation performance with bilateral CI users, it might be possible that such cues can no longer provide reliable cues for localisation with multiple sound sources. In support of this is that the localisation performance shown by the DSPB implant subjects was found to not correlate with their ratings of residual ability on spatial hearing in everyday life. More positively, however, their localisation performance was found to be significantly correlated with their ratings on their localisation ability in everyday life (as will be presented in Chapter 9).

Given the findings reported in Chapter 6, in which the ability of unilateral CI subjects to identify the location of sound sources at a better than unbiased guessing performance was not related to their actual perceived location of sound sources, it is unclear whether the better than unbiased guessing performance by the DSPB implant subjects does actually reflect the appropriate perceived locations or not. A previous study by Shub et al. (2008) suggests that when the subjects were instructed to report the location of a sound source (as with current study), they were asked to use all available information to get the correct locations, whereas asking them to report the perceived location of the source would probably have measured localisation ability in more realistic situations. Apparently, two of the DSPB implant subjects (D2 and D4) reported that they pointed to lateral loudspeakers, although they actually heard the sounds coming from behind. Further research is required to determine whether the DSPB implant users can perceive the actual locations of sound sources and whether they can still perform at better than unbiased guessing in more realistic situations (i.e. sounds coming from multiple locations and with reverberation).

7.5 Conclusions

Limited to the sample tested in the current study, the conclusions of the present study are as follows:

- Most of the DSPB implant subjects can show overall localisation error scores on a simple identification task at better than chance range of unbiased guessing, for different types of stimuli. The better than unbiased guessing performance shown by the DSPB implant subjects in the current study seems to reflect some ability to identify sounds rather than biased guessing.

- There is a trend, albeit not statistically significant, for low-pass noise to be localised with worse accuracy than the other stimuli.

- With the exception of two subjects, the DSPB implant subjects could localise sounds with better accuracy than that shown by the good unilateral CI performers. This may indicate that the DSPB implant subjects can take advantage of binaural cues that are not available for unilateral CI users.

- Localisation performance of the DSPB implant subjects seems to be significantly comparable to that of subjects with conventional CIs, for broadband noise but not for speech. Their localisation performance, however, was still much worse than that of normal-hearing listeners.

Chapter 8: Speech perception in noise with synchronised bilateral and unilateral cochlear implants

8.1 Introduction

In the previous chapter, it was demonstrated that six out of the eight synchronised bilateral cochlear implant (CIs) subjects can show overall localisation error scores at better than chance range of unbiased guessing for different types of stimuli. These scores were also found to be lower than those shown by the ‘‘good’’ unilateral CI performers for all, but one, of the six synchronised bilateral CI subjects. The current research project also aimed to assess the ability of the synchronised bilateral CI users to understand speech in the presence of noise, as one of the potential measures of spatial hearing benefits. Prior to starting this project and to this researcher’s knowledge, no study has been conducted on the speech perception ability of synchronised bilateral CI users; however, two studies have been published within the time span of this project (Bonnard et al., 2013; Verhaert et al., 2012).

The above two studies measured the percentage of words reported correctly by the subjects implanted with Digisonic® SP Binaural (DSPB) implants at a fixed signal-to-noise ratio (+10 dB SNR). Verhaert et al. (2012) compared the percentage of words reported correctly by their DSPB implant subjects (*n*=14) when listening bilaterally and unilaterally. The target was Fournier’s list of French disyllabic words presented from 0°, while the noise was presented at +10 dB SNR from 0°, -90° or +90° azimuth, to measure the spatial hearing benefits. Their results showed that the average benefit was 13.6%, 12.0% and 14.0% for squelch, head shadow, and summation effects respectively; all were statistically significant. The benefit of spatial release from masking (SRM) was, however, not reported. Bonnard et al. (2013), on the other hand, used Fournier’s list of French disyllabic words with five competing noises to estimate the proportion of correct responses. The target words were presented from 0° and the noise was presented simultaneously from all five loudspeakers at -90°, -45°, 0°, 45° and +90°. The average percentage of words correctly recognised by their seven DSPB implant subjects was 55.7%, statistically comparable to the 43.3% reported by six subjects who had conventional bilateral CIs implanted.

Although both studies concluded that DSPB implant subjects generally had some ability to perceive speech in noise, none reported whether the subjects can obtain binaural benefit from SRM. It was also impossible to estimate the SRM from Verhaert et al.’s study, given that they did not report the percentage of correct words by the DSPB implant subjects listening bilaterally for noise at +90° or -90° azimuth. Additionally, both studies measured the proportion of correct words presented at a fixed SNR. This makes a comparison between the results of the DSPB implant users to those in the published studies on conventional bilateral/unilateral CI users or normal-hearing listeners more difficult, for two reasons. First, the above two studies reported results as the percentage of correct responses rather than thresholds. Binaural benefits, for example, are widely reported in terms of dB for CI users (Culling et al., 2012; van Hoesel and Tyler, 2003) and normal-hearing listeners (Hawley et al., 2004). Secondly, both studies used a fixed SNR procedure, whereas an adaptive procedure was often used to measure the speech perception abilities of CI users (e.g. Loizou et al., 2009; Litovsky et al., 2004; van Hoesel and Tyler, 2003) and normal-hearing listeners (e.g. Hawley et al., 2004; Smits et al., 2013). One advantage of the adaptive procedure over the fixed SNR is that the adaptive procedure is targeting a predetermined performance level on the psychometric function and thus avoiding the occurrence of ‘‘ceiling’’ and ‘‘floor’’ effects that may occur if a fixed SNR is used (Leek, 2001; Liu and Eddins, 2012). Indeed, Verhaert et al. (2012) reported that one subject showed a floor performance effect and three subjects showed a ceiling performance effect, and therefore the spatial benefits to such subjects might be underestimated. Further studies are needed to determine all the spatial benefits, including SRM, binaural squelch, head shadow and summation effects in terms of improvements in speech perception thresholds (SRTs) in dBs for the DSPB implant users, using an adaptive procedure.

In addition to the above spatial hearing benefits that might be provided by the bilateral CIs for speech perception in noise, it was also reported that implanting two ears can potentially provide implanted users with more ease of listening. Noble et al. (2008), for example, reported a significantly lower self-rated listening effort for bilateral CI users than for unilateral CI users. Dunn et al. (2011) also found that bilateral CI users had better SRTs than the unilateral CI users while attending to other simultaneous tasks, such as when visual input was added. Both studies concluded that listening with two CIs might possibly help to separate the attention between speech and noise. This might also suggest that the attention necessary to separate speech from noise would be lower for spatially separated speech and noise than for co-located speech and noise. There is a possibility that bilateral CI users who had similar SRTs for co-located versus spatially separated speech and noise might experience lower listening effort to understand spatially separated speech and noise. It is therefore important to take into consideration listening effort as a variable when determining the possible benefit of spatially separated speech and noise for CI users.

Given the potential limitations of the two studies on DSPB implants described above and that the benefit of SRM has not yet been reported for DSPB implant users, an experiment was conducted with the aim of assessing the ability of DSPB implant users to understand speech in noise and to address the limitations of the above studies. Spatial benefits for speech perception in noise were measured with an adaptive threshold estimation procedure. The speech perception ability of unilaterally implanted users was also tested in order to determine whether DSPB implants provide any additional advantages over unilateral CIs for speech perception. The possible benefit in terms of listening effort that might be associated with spatially separating speech and noise was also measured for both the DSBP implant and the unilateral CI users.

8.1.1 Summary of objectives

The objectives of this study were as follows:

1. Measure the spatial hearing benefits for speech perception, including SRM, binaural squelch, head shadow and summation effects with the DSPB implant users. The hypothesis is that DSPB implant users might probably show SRM which is more likely to result from the head shadow effect. Based on the results of normal-hearing listeners presented in Chapter 5, it would be practically and statistically impossible to determine binaural squelch in the DSPB implant users and perhaps also the summation effect.

2. Determine whether the DSPB implant users experience benefit in terms of listening effort when speech and noise are spatially separated versus when they are co-located. The hypothesis is that spatially separating speech and noise might lead to lower listening effort experienced by the CI users.

3. Compare all the spatial hearing benefits of the DSPB implant users to those of unilateral CI users, using the same test set-up and speech material, in order to assess whether the DSPB implant provides any advantage over the unilateral CIs. The hypothesis is that DSPB implants might provide advantages over unilateral CIs when the unilateral CI subjects happen to have the noise at their implanted ear.

4. Compare the spatial hearing benefits for speech perception of DSPB implant users to those with normal-hearing listeners (Chapter 5). The hypothesis is that the spatial benefits of the DSPB implant users would still be worse than those of normal-hearing listeners, although the difference between the two groups, particularly SRM, binaural squelch and head shadow effects, might be of great difficulty to detect in the current study (given the results of normal-hearing listeners).

8.2 Additional methods

As with the localisation test, testing of speech perception was approved by the National Research Ethics Service (REC reference: 12/SC/0421) as well as the University of Southampton Research Governance Office and the University Hospitals Birmingham Clinical Research Office. Approval of the Institute of Sound and Vibration Research Human Experimentation Safety and Ethics Committee (reference number: 2915), where the experiment was conducted, was also obtained prior to the start of testing. All the ethical approvals can be found in Appendix C.1 and C.2 for testing unilateral CI subjects and in Appendix D.1 and D.2 for DSPB implant subjects.

8.2.1 Participants

All CI subjects who participated in the localisation experiment also took part in the speech perception in noise experiment. The participants were eight adults implanted with DSPB implants and eight adults implanted with a single CI, all from the University of Southampton Auditory Implant Service (USAIS). Participant information is listed for the unilateral CI subjects in Table 6.2 and for the DSPB implant subjects in Table 7.1.

The eight unilateral CI subjects were tested with their clinical speech processors that they had been using in everyday life. For the DSPB implant subjects, however, a spare processor was used, so that a change in the mapping software could be made prior to testing, to enable switching off the side receiving the speech processor (i.e. ipsilateral side). Three different maps had been downloaded in the spare processor: bilateral implants, right implant only and left implant only. The right ear map, for example, was used when the subject was supposed to listen with right ear only. This was carried out by turning the most comfortable levels (i.e. M levels) of all electrodes on the left ear to the minimum, so that nothing could be heard from the left side. Each of the DSPB implant subjects was asked in advance to inform the researcher which program they use in everyday listening, so that the subject could be provided with a spare speech processor with the program they were most accustomed to use.

Before the start of testing, new batteries were provided. Subjects were also instructed to select the volume settings on the spare processor that they were most accustomed to use. Neurelec paid for subjects' transportation to the University of Southampton and for their lunch during their visit, and it also provided two spare speech processors to use during testing. Subjects were also paid £15 at the end of the testing day, after completion of both localisation and speech perception experiments. Subjects are identified by numbers assigned in the order in which they were tested for the DSPB implant subjects and in the order of the performance for unilateral CI subjects.

8.2.2 Procedure

Subjects each took part in two sessions on a single day, separated by a lunch break. Sound localisation and speech perception in noise were each tested in one session, selected at random. Subjects were fully informed and provided written consent before the first session. For the speech perception portion of testing, subjects each took part in one session lasting 2 hours, for the DSPB subjects, and one hour, for the unilateral CI subjects, including frequent rest intervals. The test procedure was similar to the procedure described in Section 3.4. An overview of the basic points is presented in this section.

Subjects were seated individually in the centre of the loudspeaker array, facing the frontal loudspeaker at 0° azimuth. The speech material used in the current study was the Triplet Digit Test (TDT), where digits were always presented nominally at 65 dB (A) from the frontal loudspeaker. The noise was presented using the adaptive procedure either from the frontal loudspeaker (N0°) or the loudspeaker placed at +90° (N+90°) or -90° (N-90°) of the subject. The adaptive procedure of two-down/one-up adaptive rule with a theoretical asymptote of 71% was used to estimate SRTs, as described in Section 3.4.4.

Table 8.1 summarises the measurements conducted on each CI subject. Fourteen SRTs were obtained for each of the DSPB implant subjects: 3 listening modes (bilateral CIs, right CI only and left CI only) x 3 or 2 noise locations (listening bilaterally at N0°, N+90° and N-90°; listening unilaterally at N0° and at the contralateral side of the activated implant, N-Contra) x 2 repetitions. When switching between bilateral and unilateral listening modes, the DSPB implant subjects were engaged in a 5-10 min conversation in order to allow brief acclimatisation to the new listening condition. For unilateral CI subjects, six SRTs were measured by each subject: one listening mode (unilateral CI) x 3 noise locations (N0°, N+90° and N-90°) x 2 repetitions. The order of noise location was counterbalanced across subjects, as was the order of listening mode for the DSPB implant subjects.

The listening effort required to perform the test was measured using two tests: the listening effort scale (Appendix A.1) and response time. Once the SRTs were determined for noise at N0°, N+90° or N-90° locations for the DSPB implant subjects listening bilaterally and unilateral CI subjects, they were asked to rate their listening effort required to understand speech on a scale which ranged from 1 (‘’Extreme effort’’) to 7 (‘’No effort at all’’). The total time each subject spent to determine SRT with N0°, N+90° and N-90° was also determined, based on the calculations implemented on MATLAB code. Two listening effort measurements were obtained for each noise location (N0°, N+90° and N-90°) on both listening effort scale and response time. The session started with practice to familiarise the subjects with the task.

Table 8.1: Overview of the measurements for speech perception obtained for the DSPB and the unilateral CI subjects.

Noise location	DSPB CI (*n*=8)			Unilateral CI (*n*=8)
	Both CIs	Right CI	Left CI	Unilateral CI
N0°	2	2	2	2
N+90°	2	-	2	2
N-90°	2	2	-	2
Total SRTs	**14**			**6**

8.3 Results

The results on speech perception in noise of the DSPB implant subjects and unilateral CI subjects are presented in this section. Test-retest reliability of the two SRTs obtained for each noise location and listening mode are first examined (Section 8.3.1) and then the SRTs averaged across the two replications are presented in Section 8.3.2 for the DSPB implant and the unilateral CI subjects. Spatial benefits including SRM, binaural squelch, summation and head shadow effects, as well as the listening effort benefit are described in Section 8.3.3. The spatial benefits experienced by the DSPB implant subjects are compared to those of the unilateral CI and normal-hearing subjects, in Section 8.3.4.

8.3.1 Test-retest reliability

Two SRTs were obtained for each CI subject, using the adaptive TDT for each noise location and listening mode. The difference in mean SRTs between the two replications are presented in Table 8.2. The greatest difference between mean SRTs of the two replications was found for the DSPB implant subjects listening bilaterally and the noise placed at N0° location. The mean bilateral SRT for noise at N0° was lower (i.e. better) for the second replication, by 3.08 dB, than for the first one. For the unilateral CI subjects, the greatest difference in mean SRTs of the subjects in the two replications was only 1.32 dB and was for noise at the ipsilateral side of their implants. The standard deviation of the difference between SRTs of the two replications is also given in Table 8.2 (indicated by σ_δ) for each noise location and listening mode. This standard deviation, which represents the stability of SRTs between the two replications, was generally greater for the DSPB implant group than the unilateral CI groups.

Statistical results for reliability, including paired *t*-tests and inter-class correlation (ICC) of the SRTs from the two replications are also presented in Table 8.2. The distributions of the SRTs of the two replications were at least approximately normally distributed for both the DSPB implant and the unilateral CI groups (Shapiro-Wilk normality test: $P >$ 0.05). Paired *t*-tests with a Bonferroni correction were used to determine if the differences in mean SRTs between the two replications were statistically significant. A Bonferroni correction gave a criterion probability of 0.007 for the DSPB implant (0.05/7) and 0.01 for the unilateral CI group (0.05/3). Single asterisks in Table 8.2 indicate statistically significant SRTs between the two replications.

Results indicate that the mean SRT marginally significantly improved for the second replication compared with the first one only for the DSPB implant subjects listening bilaterally for N+90° (P=0.006), and listening unilaterally with their right CI for N-90° (P=0.008). The mean SRT between the two replications for these conditions was, however, found to be both highly and statistically significantly correlated for the DSPB implant group. The relationship between the SRTs of the two replications was highly and statistically significant for the DSPB implant subjects. For the unilateral CI subjects, no statistical difference in SRTs was found between the two replications for each noise location. However, the mean SRT between the two replications for noise at the ipsilateral side of their implants was not highly correlated (r = 0.5) nor statistically significant ($P > 0.1$). Taking the above results together, the SRTs determined adaptively using the TDT seem repeatable without a significant learning effect for the DSPB implant group, although this was not necessarily true for the unilateral CI group, in at least some conditions.

Table 8.2: Test-retest statistics of the SRTs between the two replications for the DSPB and unilateral CI subjects for different noise locations: 1) the difference between the mean SRT (in dB SNR) of the two replications (standard deviation of that difference, σ_δ); 2) the paired *t*-test and 3) the two-way mixed intraclass correlation coefficient (with absolute agreement and average measure). Positive values indicate better performance on the second replication than the first one. N-Ipsi: noise at the ipsilateral side of their implanted ear and N-contra: noise at the contralateral side of their implanted ear.

Group		Noise location	Difference in mean SRTs (σ_δ)	*t-test*		ICC	
				t	*P*	*r* (confidence interval)	*P*
DSPB CI	Both CIs	N0°	3.08 (3.10)	2.80	0.03	0.83 (0.12-0.96)	0.018
		N+90°	1.76 (1.29)	3.84	0.006*	0.98 (0.91-0.99)	0.000
		N-90°	-0.57 (3.63)	0.44	> 0.1	0.85 (0.24-0.96)	0.012
	Right CI	N0°	1.79 (4.04)	1.25	> 0.1	0.76 (-0.21-0.95)	0.040
		N-90°	2.11 (1.64)	3.64	0.008	0.98 (0.88-0.99)	< 0.001
	Left CI	N0°	-0.63 (4.50)	0.39	>0.1	0.75 (-0.25-0.95)	0.044
		N+90°	0.41 (2.75)	0.42	> 0.1	0.89 (0.48-0.97)	0.004
Unilateral CI		N0°	0.34 (1.90)	0.59	> 0.1	0.87 (0.39-0.97)	0.006
		N-Ipsi	-1.32 (1.99)	1.88	0.07	0.58 (-1.05-0.91)	> 0.1
		N-Contra	0.11 (1.59)	0.18	> 0.1	0.65 (-0.72-0.93)	0.04

**P with Bonferroni correction < 0.007*

8.3.2 SRTs in noise

This section presents the SRTs, averaged across the two replications, for the DSPB implant (Figure 8.1) and the unilateral CI subjects (Figure 8.2), where lower SRTs reflect an ability to tolerate a more adverse SNR (i.e. better performance). The left panel of Figure 8.1 shows the SRTs of the DSPB implant subjects when listening bilaterally at three noise locations: N0°, N+90° or N-90°. The unilateral SRTs of the DSPB implant subjects are presented in the right panel of the figure, at two noise locations: N0° and noise at the contralateral side of the activated implant (N-Contra).

For the DSPB implant subjects listening bilaterally, Figure 8.1 shows a considerable variation in thresholds across subjects for all noise locations. The thresholds ranged between -5.8 to 3.8 dB SNR for N0° and between about -9.3 to 4.6 dB SNR when noise was shifted to the side (N+/-90°). It appears that, across all noise locations, both N+90° and N-90° noise locations had the lowest thresholds. However, median thresholds were similar for N0°, N+90° and N-90° noise locations, suggesting that no benefit was generally observed when the noise was separated from the target speech (i.e. no SRM benefit).

When the DSPB implant subjects listened unilaterally with one implant only, the thresholds were found to be similar to those observed with bilateral listening. The unilateral thresholds ranged between -4.0 to 7.4 dB SNR for N0° and between -6.5 to 6.1 dB SNR for the N-Contra noise location. Unlike bilateral thresholds where median thresholds were similar across noise locations, unilateral thresholds seem to be higher (i.e. worse) for N0° than N-Contra noise locations. Median unilateral thresholds were 1.3 dB SNR for the N0° location and -1.5 dB SNR for N-Contra location. This indicates that DSPB implant subjects listening unilaterally can generally tolerate more noise when the noise is at the contralateral side of the activated implant than when the noise is at the front to the subject. This may suggest that listening with one implant seems to be sufficient to produce the benefit of separating speech and noise, due to the effect of head shadow (i.e. monaural benefit).

The results of the SRTs for unilateral CI subjects are shown in Figure 8.2 for different noise locations: N0°, N-Ipsi (noise at the ipsilateral side of their implant) and N-Contra (noise at the contralateral side of the implant). It seems that SRTs by the unilateral CI subjects generally improved when the noise was moved to the contralateral side of their implant. The median SRT for the N-Contra noise location was at least 5.2 dB better than the medians of other noise locations. This indicates that unilaterally implanted subjects benefited only when the noise was placed on the contralateral side of their implants (i.e. the head shadow effect). It is worth noting that unilateral CI subjects had generally lower SRTs than the DSPB implant subjects listening bilaterally and unilaterally. The SRTs for N0° were statistically better for the unilateral CI subjects than the DSPB implant subjects, even when they listening with both implants (t (14) =2.20, P =0.04). A parametric statistical analysis test was used, since the SRTs by the DSPB implant and the unilateral CI subjects for co-located speech and noise were at least approximately normally distributed (Shapiro-Wilk normality test: $P > 0.05$).

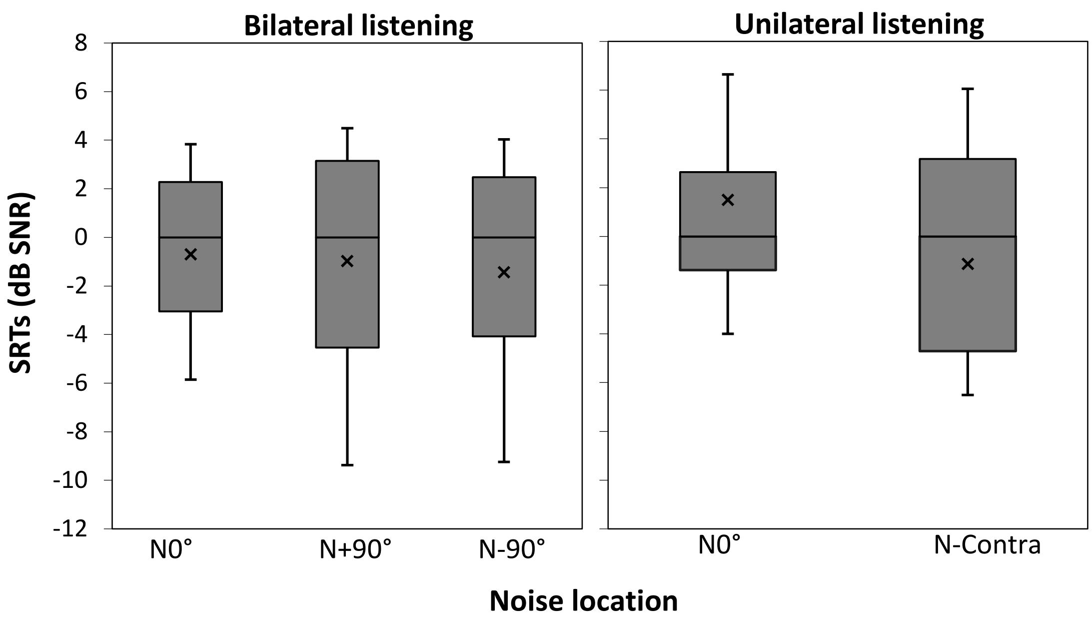


Figure 8.1: Speech reception thresholds (SRTs), in dB SNR, by the eight DSPB implant subjects. Left panel shows bilateral SRTs for the different noise locations (N0°: noise at the front; N+90°: noise at 90° to the right; N-90°: noise at 90° to the left). Right panel shows unilateral SRTs for the different noise locations (N0°: noise at the front; N-Contra: noise at the contralateral side of the activated implant). Each box represents the two middle quartiles (end of boxes), separated by median (horizontal line), mean (cross inside the box), maximum and minimum values (horizontal lines at the end of whiskers).

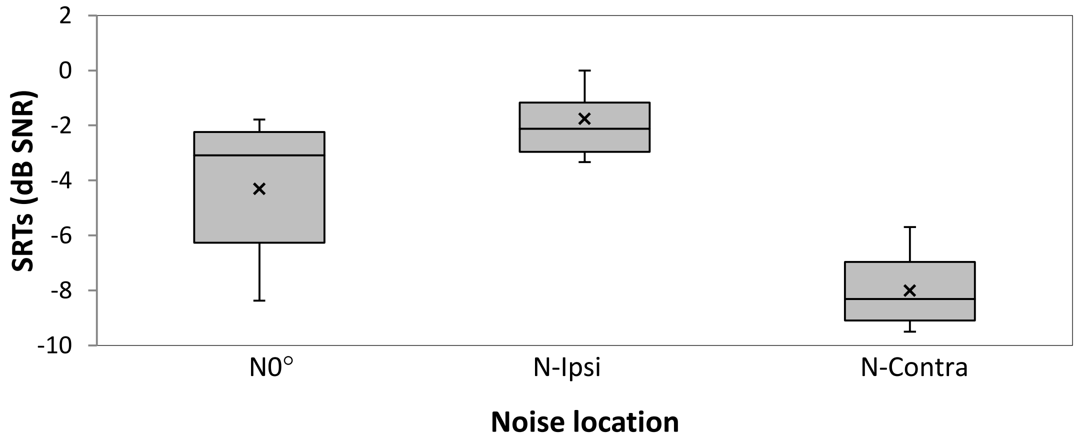


Figure 8.2: SRTs, in dB SNR, by the eight unilaterally implanted subjects for N0° (noise at the front), N-Ipsi (noise at the ipsilateral side of their implants) and N-Contra (noise at the contralateral side of their implants). The characteristics of the box plots are described in Figure 8.1.

8.3.3 Spatial benefits

Spatial benefits for speech perception are presented in this section for the DSPB and the unilateral CI subjects. Figure 8.3 shows SRM, binaural squelch, binaural summation and head shadow for the DSPB implant subjects. Spatial benefits including SRM and head shadow for the unilateral CI subjects are presented in Figure 8.4. To provide an estimation of the population mean, and therefore enable comparisons with the results of previous studies, mean spatial benefit and its 95% confidence intervals are presented in Figure 8.5 for the DSPB implant subjects (upper panel) and the unilateral CI subjects (lower panel). The description of the measures of these benefits was presented above in Section 2.3.2. The values of these benefits are derived by comparing the SRTs presented Figures 8.1 and 8.2 for different noise locations and listening modes (as shown in Figure 2.6).

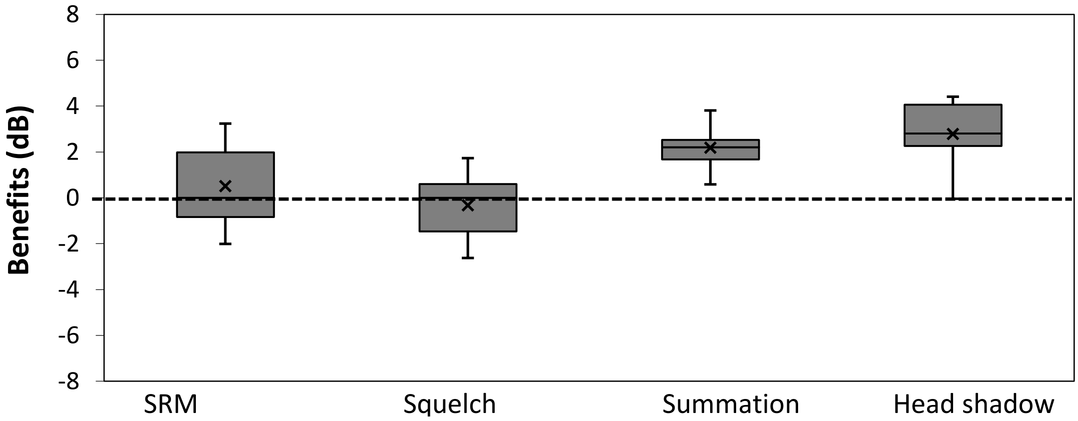


Figure 8.3: Spatial benefits for speech perception in noise, in dB, for the DSPB implant subjects: speech release from masking (SRM), binaural squelch, summation, and head shadow. The characteristics of the box plots are described in Figure 8.1. The horizontal dashed line indicates no benefit.

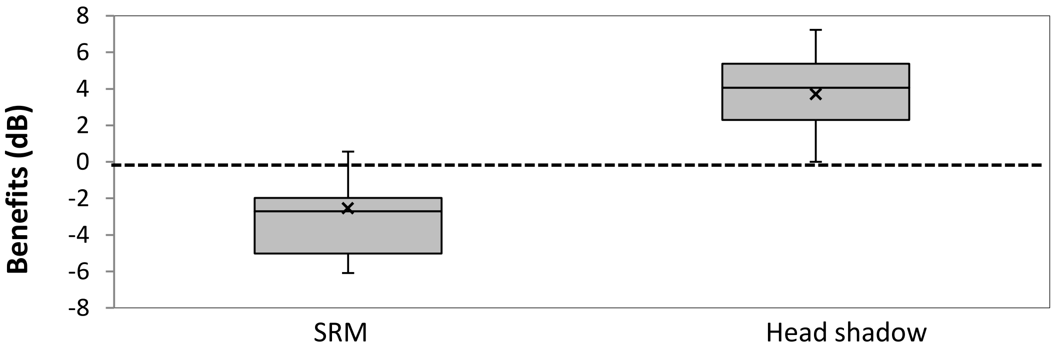


Figure 8.4: Spatial benefits for speech perception in noise, in dB, for the unilateral CI subjects. The characteristics of the box plots are described in Figure 8.1. The horizontal dashed line indicates no benefit.

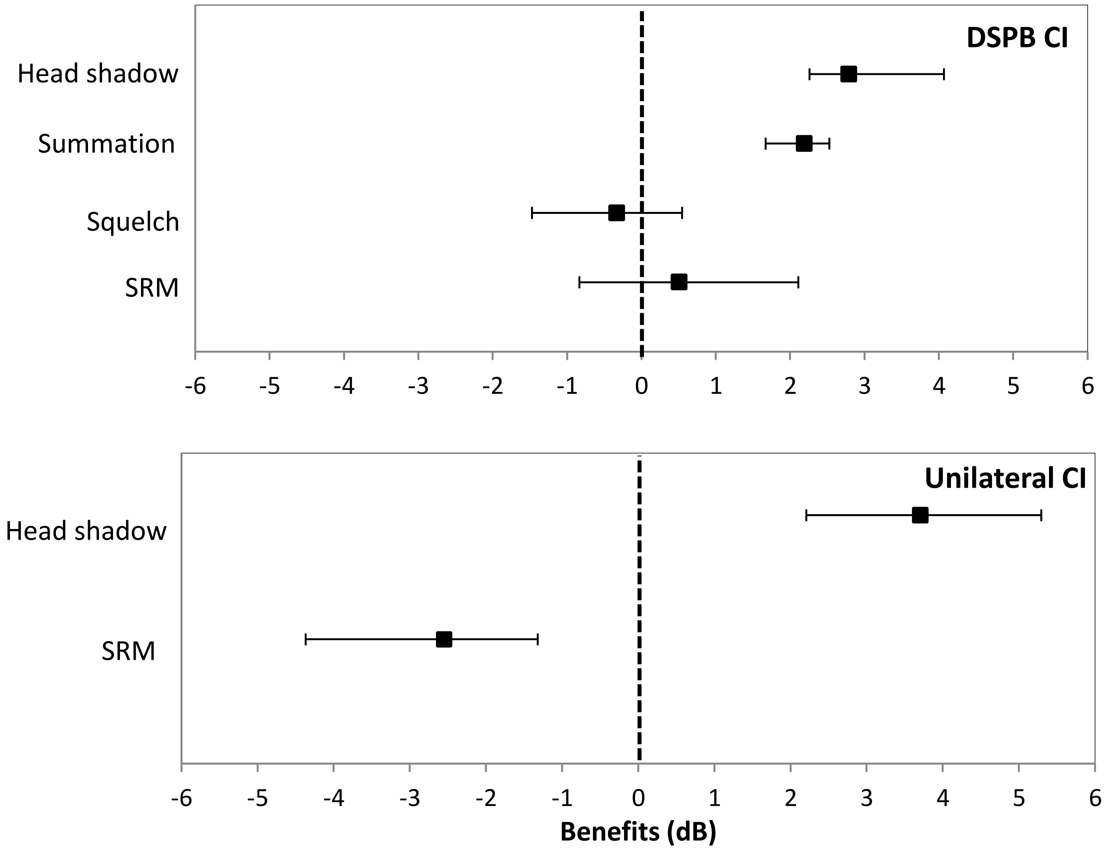


Figure 8.5: Mean spatial benefit, in dB, for the DSPB implant (upper panel) and the unilateral CI groups (lower panel). Error bars represent 95% confidence intervals of the mean. The vertical dashed line indicates no benefit.

8.3.3.1 Binaural benefit: SRM

The median SRM shown by the DSPB subjects was only 0.10 dB, which means that the DSPB subjects had similar SRTs whether speech and noise were spatially separated or co-located. The mean SRM was 0.50 dB and the 95% confidence intervals ranged from -0.84 to 2.10 dB, indicating no significant SRM was experienced by the DSPB subjects.

Given that the current study was only testing eight DSPB implant subjects (as opposed to 14 subjects, as planned in Section 6.2.1), it might be possible that the lack of statistical evidence for SRM reflects the insufficiency of the small sample. It is also possible that the above result could have been strongly influenced by the large variation between the eight subjects. For example, one of the eight subjects was prelingually deaf. Figure 8.6 plots the SRM for each of the DSPB implant subjects. To determine whether each DSPB implant subject experienced SRM, a statistical criterion was set based on the test-retest reliability results, in particular the values of σ_δ. The amount of SRM for each subject is considered significant at the $P < 0.05$ level if it is greater than $1.96\sigma_{\delta}$. The results for normal-hearing listeners presented in Table 5.2 were used for a better estimating of test-retest reliability, for two reasons. Firstly, it was difficult to accurately estimate test-retest reliability of such a small number of DSPB implant subjects. Secondly, even in a best-case scenario, in which the CI user showed large amount of SRM, it would not exceed the amount of SRM experienced by normal-hearing listeners. Based on the results of normal-hearing listeners, the σ_{δ} of bilateral SRTs for N0°, N+90 and N-90 was of the order 1.8 dB SNR, and therefore the amount of SRM is considered significant at the $P < 0.05$ if it is greater than 3.5 dB (1.96* 1.8 dB). The figure reveals that none of the DSPB implant subjects experienced significant SRM.

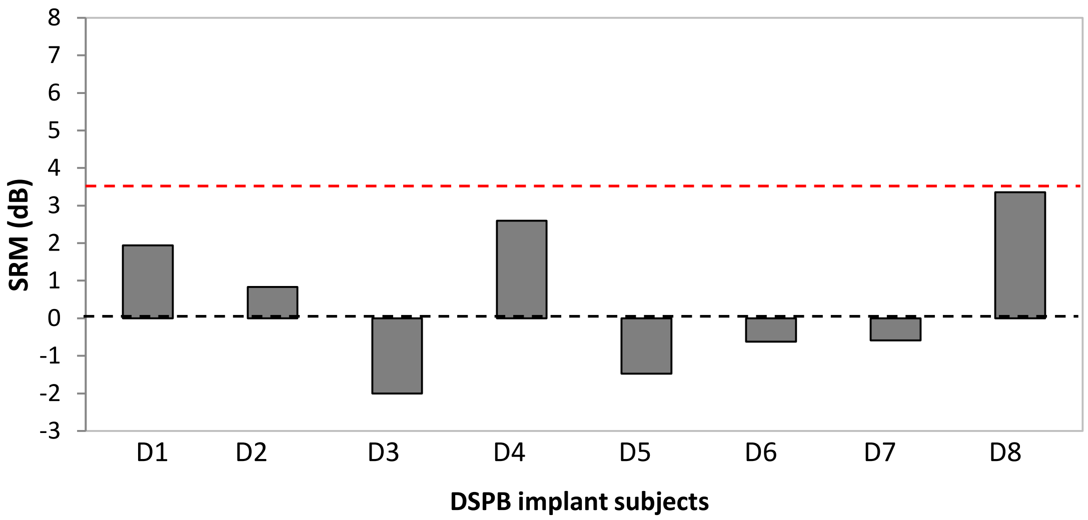


Figure 8.6: Spatial benefits for speech perception in noise, in dB, for each of the eight DSPB implants. The horizontal black dashed line indicates no benefit. The horizontal red dashed line indicates statistically significant benefit at $P < 0.05$.

With reference to unilateral CI subjects, the median SRM was -2.05 dB, indicating that unilateral CI subjects had higher SRTs (i.e. worse) with noise at the side of their implants than at the front. The mean SRM was -2.54 dB (95% confidence intervals -4.36 to -1.32 dB), indicating no significant SRM was experienced by the unilateral CI subjects.

8.3.3.2 Monaural benefit: head shadow effect

The median head shadow experienced by the DSPB subjects was 2.66 dB, which means that they had better unilateral SRTs when the noise moved to the contralateral side of their implants than at the front. The mean head shadow was 2.79 dB (95% confidence intervals 2.26 to 4.06 dB), indicating significant head shadow effect.

The median head shadow shown by the unilateral CI subjects was 3.98 dB, indicating that the unilaterally implanted subjects had better SRTs with noise at the contralateral side of their implants than at the front. The head shadow effect for the unilateral CI subjects was also significant, as indicated by the 95% confidence intervals of the mean, which ranged between 2.20 to 5.29 dB.

Although the amount of head shadow seems greater for the unilateral CI subjects than the DSPB implant subjects, the difference in the amount of head shadow between the unilateral CI and the DSPB implant groups was, not statistically significant, as indicated by the overlapping 95% confidence intervals.

8.3.3.3 Binaural benefit: Squelch effect

The median binaural squelch benefit was -0.06 dB, indicating that the DSPB implant participants had no benefit from adding a second ear with a poorer SNR. The mean squelch effect was -0.33 dB (95% confidence intervals -0.47 to 0.55 dB), indicating that DSPB implant subjects did not significantly experience a binaural squelch benefit.

8.3.3.4 Binaural benefit: Summation effect

The median summation effect, or the benefit from adding an ear with equal SNR, was 2.21 dB. The mean summation effect was 2.19 dB (95% confidence intervals 1.67 to 2.53 dB), indicating a significant summation effect. However, when comparing SRTs with N0° when the DSPB implant subjects were listening bilaterally versus when they were listening with their better ears (the best unilateral CI thresholds), no significant difference was found (mean 1.4 dB at 95% confidence intervals of 0 to 1.72 dB).

8.3.3.5 Other benefits: Listening effort

As shown in Section 8.3.3.1, none of the DSPB implant subjects showed significant SRM. It is of interest to determine whether they experienced any benefit in terms of listening effort (i.e. less listening effort to understand speech with noise at the side than at the front). Table 8.3 shows the mean and the 95% confidence intervals of the possible listening effort benefits of separating speech and noise. The benefit was determined as the difference in self-rating score or response time in conditions with spatially separated versus co-located speech and noise. Positive values indicate lower listening effort being required to understand speech when noise is at the side than at front (i.e. benefit), whereas negative values indicate no benefit.

It seems that the DSPB implant subjects did not show listening effort benefits when listening bilaterally with the noise placed from either +/-90° of the subject. The difference in listening effort required in conditions with spatially separated versus co-located speech and noise was almost 0 on self-rating score and 0 second on response time (i.e. no benefit). Similar results were also found for the unilateral CI subjects when noise was placed at the ipsilateral side of their implant, suggesting no overall benefit in terms of listening effort. When noise was placed at the contralateral side of the implanted ear for the unilateral CI subjects, they had a better self-rated score by about 0.43 of a point than when noise was at the front, possibly due to head shadow effect. However, no benefit for response time was found (difference= 0.03 second). Apparently, both CI groups experienced similar listening effort benefits, as indicated by the overlapping confidence intervals between the two CI groups.

Table 8.3: Mean (95% confidence intervals) of listening effort benefits experienced by the DSPB implant and the unilateral CI groups. Results from paired t-tests analysis are also listed.

		Self-rated score (points)		Response time (sec)	
		Mean	***t* (*P*)**	**Mean**	***t* (*P*)**
DSPB CI	N+90°	0.06 (-0.62-0.62)	0.16 (>0.1)	-0.02 (-0.41-0.32)	0.25 (>0.1)
	N-90°	0.00 (-0.5-0.25)	0.00 (>0.1)	0.04 (-0.17-0.39)	0.25 (>0.1)
Unilateral CI	N-Ipsi	0.06 (-0.12-0.50)	0.35 (>0.1)	0.02 (-0.25-0.24)	-1.17 (>0.1)
	N-Contra	0.43 (0.00-0.62)	2.96 (0.02)	0.03 (-0.25-0.08)	-1.20 (>0.1)

Although no listening effort benefit was found based on group performance, there might be some subjects who experienced listening effort benefits. As with SRM, a criterion based on test-retest reliability was also applied for listening effort benefit. Listening effort benefit is considered significant if it is greater than 1.6 points (1.96*0.8 points) for listening effort scale and 0.8 sec (1.96*0.4 sec) for response time. The results reveal that none of the DSPB implant or the unilateral CI subjects showed benefit in terms of listening effort; all the individual listening effort benefit was far below the significant level (Appendix E.1).

In summary, the above findings show that the DSPB implant subjects seemed not to experience the spatial benefit of SRM for speech perception in noise. The only benefit showed by the DSPB subjects was head shadow effect, though this benefit was still much lower the head shadow benefit reported for unilateral CI subjects. There was also no benefit in terms of listening effort for either the DSPB implant or unilateral CI groups.

8.3.4 Spatial benefits of the DSPB implant versus normal-hearing listeners

This section compares the spatial speech perception benefits reported in the previous section for the DSPB implant subjects to those from normal-hearing listeners reported in Chapter 5. Figure 8.7 plots the spatial benefits, including SRM, binaural squelch, summation and head shadow effects obtained from the DSPB implant subjects and normal-hearing subjects. The figure shows that the spatial benefits, particularly SRM, were greater for normal-hearing subjects than the DSPB subjects, except for the summation effect. The summation benefit was larger for the DSPB subjects than for the normal-hearing subjects.

Table 8.4 presents statistical results of the comparison between the DSPB implant and normal-hearing groups. Unequal variance was only apparent between the summation effect of the DSPB implant and the normal-hearing groups (Levene's test: P=0.02) and so homogeneity was not assumed for summation. The statistical results confirmed the above observations, in that the spatial benefits, including SRM, squelch and head shadow, were either significantly or marginally significantly greater for normal-hearing subjects than for the DSPB subjects. Although the summation effect experienced by DSPB implant subjects seems to be greater than that by normal-hearing subjects, this difference did not reached the significance. It should be noted that also when considering the summation effect with reference to the better unilateral CI ears, no significant difference in such benefit between the DSPB and normal-hearing subjects was found (t (36) =0.91, $P > 0.1$; mean difference=0.71 dB).

Compared to unilateral CI subjects, normal-hearing subjects experienced significantly larger benefit for SRM (t (36) =10.91, P <0.001; mean difference=8.60 dB), but not for head shadow effect. The head shadow was similar for the normal-hearing and unilateral CI subjects (t (36) =1.35, $P > 0.1$; mean difference=1.17 dB). Equal variance was assumed (Levene's test: $P > 0.05$).

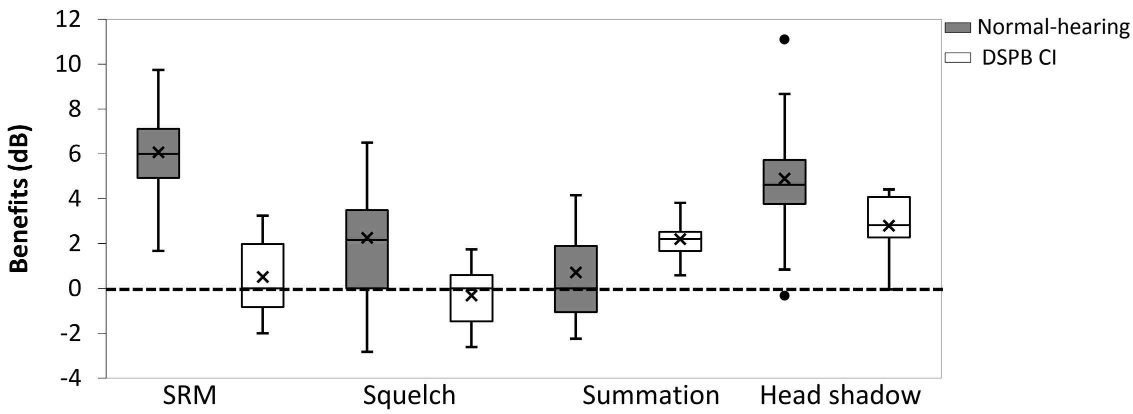


Figure 8.7: Spatial benefits for the DSPB implant subjects from this study and the normal-hearing listeners reported in Chapter 5. The characteristics of the box plots are described in Figure 8.1. The circles represent outliers, which are values that lie between 1.5 and three times the interquartile range below the lower quartile or above the upper quartile. The horizontal dashed line indicates no benefit.

Table 8.4: Results of *t*-test analysis on the difference in spatial benefits between DSPB implant and normal-hearing subject groups.

Spatial benefit	Mean difference (dB)	*t*	*P*
SRM	5.55	7.18	0.00*
Squelch	2.57	2.98	0.005*
Summation	-1.49	2.18	0.035
Head shadow	2.09	2.63	0.01*

**P with Bonferroni correction < 0.01*

8.4 Discussion

The present study was intended to assess the spatial hearing benefits for DSPB implant users in terms of speech perception in noise in more detail than in previous studies. The current study was designed to answer the question of whether DSPB implant users do benefit from the spatial separation of target speech and noise. The extent to which DSPB implants provide spatial benefits was compared with those from unilateral CI users and normal-hearing listeners, who were also tested with the same material and procedures.

The results of the current study revealed that none of the DSPB implant subjects experienced statistically significant binaural benefit for spatially separating speech and noise while listening bilaterally (i.e. SRM). The DSPB implant subjects only showed significant head shadow and summation effects, though the significant summation effect disappeared when the bilateral SRTs for co-located speech and noise were compared to those while listening with their better ears (the best unilateral CI thresholds). The significant head shadow effect showed by the DSPB subjects was similar to that shown by the unilateral CI subjects who were chosen to have very good speech scores in noise. The unilateral CI subjects, however, showed better thresholds for co-located speech and noise than the DSPB implant subjects listening bilaterally. Normal-hearing subjects still experienced statistically greater spatial hearing benefits for speech perception in noise, except for the summation effect. A similar amount of summation effect was experienced by normal-hearing subjects and the DSPB implant subjects. The above results are discussed in detail in the following sections.

As with the localisation test, the above findings are only limited to the sample of subjects tested in the current study, in which only eight subjects were tested (as opposed to 14 subjects as planned in Section 6.2.1) who also showed a considerable variation in their characteristics. It should be stressed that it was not possible to recruit the planned 14 DSPB implant users, as the CI centres involved in the current study abruptly ceased providing DSPB implants during the time span of this project. A larger study with many more DSPB implant subjects might able to detect an improvement in

SRTs when speech and noise are separated, compared to when they are co-located (i.e. SRM).

8.4.1 SRTs in co-located speech and noise

When the speech and noise were directly in front of the DSPB implant users, the DSPB implant subjects showed median SRT of about -0.7 dB SNR. Although one of the previous two studies on speech perception ability of DSPB implant subjects (Verhaert et al., 2012) reported the performance of their DSPB implant subjects for co-located speech in noise, they reported the results as the percentage of correct responses (mean= 60%) rather than thresholds. This makes the comparison between the results of the current study and their study is very difficult.

Compared to those for users implanted with conventional bilateral CIs, the median SRT reported for the DSPB implant subjects in the current study seems in the lower range (i.e. better) reported by previous studies for conventional bilaterally implanted users. A mean SRT of about -1.2 (Schleich et al., 2004) to 7 dB SNR (Litovsky et al., 2006) was reported for conventional bilateral CI users using sentences as speech material. Although this indicates that DSPB subjects demonstrated comparable performance to those with conventional bilateral CIs, it is not clear whether the DSPB implant subjects would still perform well if they were tested with sentences. Previous results showed that better SRTs can be achieved by normal-hearing listeners if they are tested with TDT than with sentences (i.e. Bamford-Kowal-Bench, BKB) (see Appendix B.1 for more details). It should be noted that it was impossible to test the DSPB implant subjects with BKB sentences at the time of testing, since they generally had scores of less than 70% for testing BKB in quiet. Given that the conventional bilateral CI users in the above two studies were able to do sentences in noise, this might, however, suggest that they were clinically performing better than the DSPB implant subjects. If so, the results for the DSPB implant subjects seem encouraging, as these may indicate that they can still perform similarly to the conventional bilateral CI users, who were more likely to have better scores on testing in quiet than the DSPB implant subjects.

8.4.2 SRM with the DSPB implant

The findings of the current study show that when the noise moved 90° to one side, bilateral listening offered no significant advantage of separation (i.e. SRM) for the DSPB implant subjects. To the best of this researcher’s knowledge, the current study is the first to report the SRM for the DSPB users and, therefore, it is impossible to compare the SRM between studies. The mean SRM of about 0.5 dB in the current study, however, had a confidence interval (95% at -0.84 to 2.10 dB) that did not include the mean SRM reported previously for conventional bilateral CI users. Previous studies on bilateral CI users reported a mean SRM of about 3 dB (Schleich et al., 2004) to 4.5 dB (van Hoesel and Tyler, 2003). An SRM of about 3.6 dB was also predicted by a model developed by Culling et al. (2012) for noise at 90°.

Although it is not entirely clear why the DSPB subjects did not show SRM in the current study, several factors might account for the lack of significant SRM obtained by DSPB subjects. Firstly, the current study was underpowered to detect the spatial hearing benefits associated with bilateral implantation. As noted earlier, the current study only tested eight DSPB implant subjects as opposed to 14 subjects originally planned in Section 6.2.1. Secondly, the differences in SRTs between different spatial configurations with the DSPB subjects seem to be in the order of SRTs for test-retest reliability. It should be acknowledged that at the time of testing DSPB implant subjects, the spatial benefits of normal-hearing subjects presented in Chapter 5 were not fully analysed. After reflecting the normal-hearing data, it appears that, due to the small effects and large between subjects variability, the aims the researcher intended to achieve with CI users in this study were not possible. Thirdly, it might be possible that the speech perception with the TDT was relatively easy for the DSPB subjects, leading to good performance in the more difficult listening situations. For instance, the good SRTs obtained by the DSPB implant subjects in the relatively difficult reference condition, with both speech and noise were presented directly in front of the listener, might have suppressed benefits from spatially separated speech and noise. However, Schleich et al. (2004) also showed lower SRTs for co-locating speech and noise (Section 8.4.1), and still showed an SRM of about 3 dB, thought a statistical analysis was not performed to determine whether such SRM was significant or not.

Fourthly, the differences in the subjects' characteristics may also play a role in the lack of SRM reported for the DSPB implant subjects in the current study. For example, the subjects in the current study had only from 4 to 18 months bilateral experience with use of their DSPB implants (median= 10 months). Conventional bilateral CI subjects in the previous studies were required to have at least 9 months, in Litovsky et al.'s study, and at least 12 months in the study of van Hoesel and Tyler (2003). The fact that the DSPB subjects can generally show overall localisation error scores at better than chance range of unbiased guessing and that their localisation performance was found not to be correlated with their amount of SRM (Kendall's tau: r= 0.4, $P > 0.1$) may support the possibility of the effect of bilateral CI experience. Previous studies showed that speech perception of bilateral CI users gradually improves over the first 12 months after implantation (Dorman and Ketten, 2003; Tyler and Summerfield, 1996), whereas localisation performance reached its asymptote by 4 to 6 months after implantation (Grantham et al., 2007). Therefore, more experience might be required for the DSPB implant subjects to show spatial benefits for speech perception. It is worth mentioning that all the DSPB implant subjects in the current study will be retested at least 18 months post-implantation in order to determine whether their abilities can be improved through additional everyday listening experience.

8.4.3 Binaural summation

When both speech and noise were presented at the front of the DSPB subject, a significant summation effect of about 2.19 dB was reported for the DSPB implant subjects. The summation effect reported for the DSPB implant subjects in the current study was in the higher range reported for conventional bilateral CI users, which ranged between 1 to 2 dB (Laszig et al., 2004; Litovsky et al., 2006; van Hoesel and Tyler, 2003). Given that the cues available when listening unilaterally for co-located speech and noise are the same as in listening bilaterally, the possible explanation for the summation effect in bilateral CI users is that complementary information about the stimulus can be obtained from both implants, through the asymmetrical electrode insertions or nerve survival.

There is, however, no statistical evidence that bilateral listening with the DSPB implant provides any spatial advantage over unilateral listening with the better ear only. van Hoesel and Litovsky (2011) recommended the use of the better ear as reference condition to assess the binaural summation effect, in order to avoid overestimating binaural benefit due to better ear contribution. Although one might expect that the use of the better ear as reference condition for unilateral listening could lead to underestimating the binaural benefit, due to the statistical bias that favours the unilateral condition, it has been demonstrated that this effect is likely to be very small (van Hoesel and Litovsky, 2011). The finding of the current study shows that the performance of the DSPB subjects with bilateral listening was better by 1.4 dB than with the better ear only, although it was not statistically significant. The above finding agreed with previous finding, in that the performance of conventional bilateral CI subjects was not statistically different for listening bilaterally or with their better ear only for co-locating speech and noise (van Hoesel and Tyler, 2003). It does, however, contrast with the findings of other studies on conventional bilateral CI users (Ramsden et al., 2005) and the previous study on the DSPB implant users (Verhaert et al., 2012), which reported a significant summation effect, in percentage, for bilateral listening over listening with the better ear only. Verhaert et al. (2012), for example, reported a significant summation effect of about 14% for the DSPB implant subjects.

Although the summation benefit reported in the current study was in the range of benefits reported in the previous studies, it might be possible that the lack of statistical evidence for the summation effect in the current study reflects the insufficiently of the sample size and/or the variation in thresholds between subjects. It is also possible that the the statistically significant summation effect reported by some studies may be attributable to their subjects' characterestics or experimental methods. For example, the current study allowed for a brief acclimatisation period of about 5-10 mins when switching to new listening conditions, as with the study of van Hoesel and Tyler (2003). It is possible that the acclimatisation period for the unilateral listening condition may lead to better unilateral performance and would, therefore, reduce the observed binaural benefit, including that in terms of binaural summation. Since bilateral listening is the condition used in everyday life, it is possible that not offering any acclimatisation periods for unilateral listening (as with the study of Verhaert et al., 2012) may lead to an overestimation of the binaural benefits. In any case, results of normal-hearing subjects reported in Chapter 5 showed a non-signifcant summation effect of about 0.69 dB (95% at -1.06 to 2.00 dB).

8.4.4 Binaural squelch

The squelch effect was also absent for the DSPB subjects. The lack of binaural squelch was also reported in previous studies (Loizou et al., 2009; Schleich et al., 2004; van Hoesel and Tyler, 2003). Loizou et al. (2009) reported a non-significant binaural squelch of about 1 dB. Athough a 2 dB binaural squelch was reported for five bilaterally implanted users in the study by van Hoesel and Tyler (2003), it was only marginally significant (P=0.04). A 0.9 dB binural squech was alo reported by Schleich et al. (2004). The finding of no squelch effect was, however, in contrast with the findings of Litovsky et al. (2006) for conventional bilateral CI users and Verhaert et al. (2012) for DSPB implant users. In the study of Litovsky et al. (2006), a significant squelch effect of 2 dB was reported for their bilaterally implanted subjects. A close inspection of their data shows that the overall binaural squelch can be attributed to the large squelch effect that was shown by only a few subjects. Similar considerations might also apply for the study of Verhaert et al., who reported a significant squelch effect of about 13.6%, although this could not be examined, as the individual scores of their DSPB subjects were not reported. Generally, the binaural squelch reported in the majority of studies is relatively small and variable across bilateral CI users. Such a finding is not surprising, given that the current CI processors do not preserve ITDs. Bronkhorst and Plomp (1988) suggest that binaural squelch with broadband noise is largely attributable to good ITD sensitivity, particularly at low-frequencies.

8.4.5 Head shadow

Although bilateral listening with DSPB Implants does not seem to provide binaural advantages for speech perception in noise, the DSPB implant can still offer benefit if the DSPB implant user is listening unilaterally and noise is at the contralateral side of the listening ear. The present study revealed that the DSPB subjects showed a head-shadow effect, with a median effect of 2.6 dB. This indicates that listening with either ear was sufficient to produce an advantage when the noise source was placed on the contralateral side of the listening ear. Verhaert et al. (2012) also reported significant head shadow effect for the DSPB subjects, though the head shadow effect was reported as a percentage (mean= 12.0%), making the comparison between their finding and the finding of the current study not straightforward.

The significant head shadow found in the present study is consistent with that found in other studies on conventional bilateral CI users. A head shadow in the range of 4.7 to 6.8 dB was reported by van Hoesel and Tyler (2003) and Schleich et al. (2004). Loizou et al. (2009) reported a 3.8 dB head shadow effect. It should be pointed out that the head shadow effect in the first two studies was defined slightly differently from that in the study of Loizou et al. and the current study. In the studies of Hoesel and Tyler and Schleich et al., this effect was calculated as the difference in unilateral SRT when the noise was on the contralteral side of the implant and when the noise was at the ipsilateral side of the implant. As with the current study, Loizou et al. (2009) determined the head shaodw by comparing unilateral SRT when the noise was at the contralateral side of their activated implant with when the noise was at the front. This difference in the way the head shadow was calculated may explain the difference in the amount of head shadow effect reported by the above studies.

Since the SRM was not determined with the DSPB subjects, it is possible that the head shadow effect contributing to the SRM was much smaller than the isolated head shadow effect. In the SRM condition, the SNR improved at one ear and degraded at the other ear, because of the spatial separation of speech and noise. It might be possible that the DSPB subjects, due to their short experience with the DSPB implant use, were not fully able to use information from the ear with the better SNR.

In summary, with the small effect of the spatial benefits and the large variation across the DSPB subjects, it is difficult to draw a solid conclusion. Further study with a larger sample size might allow the different benefits of bilateral listening to be detected. A follow-up study on the DSPB subjects would also allow the possible effect of longer experience with the DSPB implant use to be determined.

8.4.6 Listening effort

The current study showed that that the listening effort required by the DSPB subjects was similar for spatially separated versus co-located speech and noise. This finding is surprising, as it was expected that the DSPB subjects might experience a reduction in listening effort for spatially separated speech and noise, as they did not show SRM. The results of the current study, however, indicate that the DSPB subjects did not show SRM or listening effort benefits.

One possible reason for the lack of listening effort benefit for spatially separated speech and noise is that the current study was underpowered to detect the difference in the listening effort, as with thresholds, for different noise locations. Another possibility is that the DSPB subjects may have overestimated their capabilities, and then had similar self-rated scores for different noise locations. Ford et al. (1988) reported that listeners tend to overestimate their capacities, specifically older adults. It is well established that both age and hearing impairment influence the listening effort required to understand speech in noisy situations (Larsby, et al., 2005; Scialfa, 2002). However, the results of the response time measure indicate that there was no benefit experienced by the DSPB subjects in terms of listening effort. It might be possible that the measures used in this project may not give accurate measurements, and this limitation is acknowledged. An objective measure that is more sensitive to listening effort for speech perception could therefore be considered as a measure for listening effort benefits, such as dual-task paradigms and pupillometric measures. It should be stressed that the current study aimed to get an overall indication of listening effort benefit using clinically and practically established measures and it is beyond the scope of the current project to provide an accurate and sensitive measurement for listening effort.

8.4.7 Do DSPB implants offer advantages over unilateral CIs for speech perception?

The findings of the current study showed that both the DSPB implant subjects and unilateral CI subjects did not experience significant SRM. Culling et al. (2012), however, reported that the true benefit of bilateral implantation can be indicated as the difference in SRM between bilateral and unilateral CI users. Given that consideration, the DSPB implants seem to offer a SRM advantage of about 3 dB over unilateral CI subjects who happen to have the noise on the side of their implanted ear. This advantage seems to be significant, as indicated by the non-overlapping confidence intervals of the SRM reported for DSPB implant subjects and unilateral CI subjects (Figure 8.5). The DSPB implant, however, offered users, no advantages over unilateral CI when the noise was on the contralateral side of their implanted ear. The head shadow effect was similar for both the DSPB implant and the unilateral CI subjects.

When both the speech and noise were directly in front of the subject, unilateral CI subjects performed significantly better than the DSPB subjects listening bilaterally (mean difference=3.5 dB). The superior performance of unilateral CI subjects might result from the characteristics of the subjects. Unilaterally implanted subjects were chosen based on specific criteria to reflect the best performance that one could be expected from unilateral CI users. All had very good speech scores in noise. The DSPB subjects were, however, chosen based on more relaxed criteria in order to include more subjects. The fact that the unilateral CI subjects had a maximum of 7 dB SNR for clinical speech testing in noise, whereas the maximum score for speech in noise was 12 dB SNR for the DSPB subjects may explain the superior performance of unilateral CI users. Given the fact that the ability of conventional bilateral CI users to perceive speech in noise improves with time (Litovsky et al., 2009), it is also possible that the shorter duration of CI experience with the DSPB subjects limited their performance. Median CI experience was less than a year for DSPB implant subjects, compared to about 9.5 years for unilateral CI subjects. It is possible that the DSPB subjects might achieve better performance if they were exposed to longer experience with their implants.

In summary, the current study showed that the DSPB implants seem to provide no significant SRM, as with unilateral CIs. Both the DSPB implants and unilateral CIs provide similar head shadow effect, which is significant. This may indicate that the CI subject has to turn her/his head to optimise SNR at the better ear, although this may make lip reading impossible. Other potential benefits such as better localisation performance needs to be also considered when counting the advantages offered by the DSPB implant over unilateral CIs.

8.4.8 Spatial benefits of bilateral CIs versus normal-hearing listeners

Generally, the spatial benefits obtained by bilateral CI users were found to be lower than those obtained by normal-hearing listeners who were tested previously in Chapter 5 with similar procedures. With the exception of the summation effect, it was found that the amount of SRM, binaural squelch and head shadow effect with DSPB subjects were significantly lower than that of normal-hearing listeners. Although DSPB subjects tended to have a larger summation effect than normal-hearing listeners, this difference did not reach the significance level

The factors that limit localisation ability of bilateral CI users also applied for speech perception in noise. Briefly, these factors related to the limitations due to pathology in the auditory system, the difference in anatomical positioning of the electrode array in the cochlea and/or the insertion depth of electrode arrays and the restricted availability of binaural cues by the current speech processors. Limitations due to pathology in the auditory system are likely to have arisen from degeneration in both peripheral and central auditory systems due to lack of stimulation. Differences in either anatomical positioning of the electrode array in the cochlea and/or the insertion depth of electrode arrays between the ears might result in differences in the place of stimulation across ears, which may limit the binaural cues in bilateral CI users. Although such a mismatch could negatively affect the ITD processing (Long et al., 2006), some have argued that, for CI users, this mismatch can provide slightly different information about the signal for each implant, thus resulting in them receiving more benefit from the summation effect (Culling et al., 2012; Schleich et al., 2004). It was argued that stimulating different regions in the cochlea across ears might transfer complementary information to the cochlear nerves, providing a larger summation effect. This could explain why DSPB implant users from the current study showed higher, but not significant, summation benefits than normal-hearing listeners.

Moreover, the representation of binaural cues by the implants and current speech processors is not accurate. Technical limitations are expected to restrict the availability of binaural cues to the CI user. The fine structure information of signals is not presented to the CI users, although it has an important role in binaural squelch for speech perception (see Section 2.2.1). The accuracy with which the ILDs are represented is limited by the independent processing of sounds between ears. Although the speech processor in the DSPB implant processes the sounds from both ears synchronously in time, it still processes the sound from each ear independently in two signal processing lines. Thus, the limited ILD accuracy experienced with two independent CI processors is more likely to be experienced with the DSPB implants.

In addition to the above factors, the current spreads over a wide range of channels (i.e. channel interaction), which may also limit the ability of bilateral CI users to understand speech in noise. With a directly stimulated single pair of electrodes, a substantially larger binaural masking level difference (BMLD) of about 9 dB was reported for adults (Long et al., 2006) and 6.4 dB for children (Van Deun et al., 2009). Such large BMLDs were, however, much reduced to a few dB when additional masking noise was presented to nearby electrodes (Lu et al., 2011; Van Deun et al., 2011). Similarly, a difference in binaural intelligibility level of speech interaurally delayed by 700 µs in broadband noise has not yet been demonstrated in bilateral CI users (van Hoesel et al., 2008). Findings of van Hoesel et al. (2008), Lu et al. (2011) and Van Deun et al. (2011) may support the effects of the spread of current and channel interactions that are known in CIs on speech perception of bilateral CI users. Lu et al. (2011), indeed, reported that the BMLD was significantly and negatively correlated with the degree of channel interactions estimated from auditory nerve evoked potentials.

8.5 Conclusions

Limited to the sample of DSPB implant subjects, the conclusions of the present study are as follows:

- The DSPB subjects showed no significant binaural benefits including SRM, squelch effect and summation effect with reference to the better ear. They did, however, show significant head shadow effect.

- The DSPB subjects did not also experience listening effort benefit for spatially separated rather than co-located speech and noise.

- The DSPB implants seem to offer no advantages over unilateral CIs for speech perception in noise.

- The spatial benefits experienced by the DSPB implant subjects were much smaller than those from normal-hearing listeners, except in the case of the summation effect. The summation effect experienced by the DSPB implant subjects and normal-hearing subjects was not significantly different.

Chapter 9: Self-reported assessment with synchronised bilateral and unilateral cochlear implants

9.1 Introduction

The current project aimed to explore spatial hearing benefits that might be provided by the synchronised bilateral cochlear implants (CIs) called Digisonic® SP Binaural implants (DSPB). Spatial benefits of the DSPB implant were assessed with tests on sound-source localisation (Chapter 7) and speech perception in noise (Chapter 8) and the results showed that the DSPB implant can only offer spatial advantages for localisation. There is, however, still no clear evidence that the DSPB implant can offer spatial advantages for speech perception in noise. Although the above laboratory tests provide insights into the spatial benefits with the DSPB implant, such tests are much less predictive for listening in everyday life situations and hence they only reflect a limited sample of ability. The test of localisation in this project, for example, only involves stationary sound sources and a stationary listener with no head movement. Similarly, for speech perception which involves testing the perception of a single voice in a single noise, both are stationary and predictable.

Despite the limited ability tested with the laboratory tests, the link between ability measured in the laboratory and ability experienced in everyday life has still not been established. Although Van Esch et al. (2015) reported significant relationships between the measured spatial hearing ability by their hearing-impaired subjects determined by the minimum audible angle (MAA) and spatial release from masking (SRM) and their self-reported spatial hearing ability in everyday life, such correlations were found to be relatively weak. The correlation coefficient reported in their study has a mean of about 0.3 only. A similar result was also reported by Noble et al. (2008), who found significant correlations, but again weak, between the measured spatial ability by their conventional bilateral CI subjects in sound-source localisation and speech perception in noise and their reported spatial hearing ability in everyday life. It is, therefore, necessary to go to a more comprehensive measurement that assesses a generality of everyday life situations, using self-report measures in order to determine to what extent the performance in laboratory tests relates to functioning in everyday life. Additionally, there is growing interest in the outcomes from the perspective of the CI users themselves, in terms of their experience in everyday life. Investigating outcomes from the perspective of DSPB implant users can lead to more understanding of how they are coping with their implants in everyday life and identifying where benefits of implantation arise for them in everyday life as well as where the ongoing difficulties remain.

Only one study that the researcher is aware of has assessed abilities of DSPB implant users in terms of their experience in everyday life by using self-report measures (Bonnard et al., 2013). In that study, self-rated abilities by subjects implanted with DSPB implants (*n*=7) were reported compared to those from subjects implanted with conventional bilateral CIs (*n*=6). Two measures were used: a specific measure of hearing performance using the Abbreviated Profile of Hearing Aid Benefit (APHAB) and a more generic measure of quality of life using the Glasgow Benefit Inventory (GBI), which was developed especially to evaluate any otorhinolaryngological intervention. Results from the GBI, where subjects were asked to rate the changes in their health status after implantation, showed that the DSPB subjects generally reported an overall reduction in the impact of their hearing disability after being implanted, on all levels, including general, physical, social and psychological subscales of the GBI. The reported level of an improvement in their health status following implantation was statistically similar for both the DSPB implant subjects and the conventional bilateral CI subjects (Bonnard et al., 2013).

With regard to APHAB, Bonnard et al. (2013) reported the percentage of hearing disability experienced by DSPB implant subjects in everyday life, where 100% corresponded to maximal disability. The mean hearing disability reported by the DSPB subjects was lowest for listening in background noise subscale (30.1%) and highest for listening in reverberant subscale (46.1%). As with the GBI, similar levels of hearing disability were reported by both the DSPB implant subjects and the conventional bilateral CI subjects. Although the study of Bonnard et al. (2013) provides insights into the effect of DSPB implants on everyday life, the measures used in their study did not cover some important functions that might be greatly affected by hearing deficits. For example, the contribution of hearing functions that are presumed to be served by spatial hearing was not covered, even by the hearing-specific APHAB. The majority of items of the APHAB assume that both the space and time are predictable, and therefore, the spatial and dynamic aspects of hearing were not investigated. Furthermore, the relationship between the outcomes from the APHAB and the laboratory tests was not statistically examined, although the DSPB subjects in the Bonnard et al.'s study were also tested on localisation and speech perception in noise.

The current study aims to provide a better insight into the ability of the DSPB implant users over wide aspects of hearing, rather than the simple and static aspect. The Speech, Spatial and Qualities of Hearing scale (SSQ) was selected to be used in the current project (Gatehouse and Noble, 2004) as it covers a wide range of functions, with some emphasis on functions that are assumed to depend on spatial hearing. The SSQ covers the spatial hearing function that is critical to the aims of investigating spatial hearing benefits of the DSPB implant, in addition to speech and other qualities of hearing. As with the laboratory tests, the spatial benefits with the DSPB implant were also qualified by determining whether the DSPB implant provided any additional advantages over unilateral CIs. Self-rated abilities of the DSPB implant users were compared to those with the unilateral CIs. Self-rated abilities with normal-hearing listeners were also assessed, with the aim to determine how the DSPB users do in everyday life compared to normal-hearing listeners. Comparing the self-rated abilities with DSPB implants, unilateral CIs and with normal hearing would help to expose similarities and differences over a range of functions among different group of subjects.

9.1.1. Summary of objectives

The objectives of this study were as follows:

1. Explore how the DSPB users were coping with their implants in everyday life, using SSQ. Similarly to what has been reported for bilateral CI users (Noble et al., 2008), it was hypothesised that the DSPB implant users would probably show similar benefits on all the three subscales of the SSQ, including speech, spatial and qualities of hearing subscales.

2. Determine how the self-rated abilities of the DSPB users in everyday life related to their performance on laboratory tests (i.e. sound-source localisation and speech perception). It was hypothesised that the self-rated abilities in everyday life by the DSPB implant users would not necessarily be strongly correlated with their performance on laboratory tests.

3. Compare the self-rated abilities of the DSPB users to those with unilaterally implanted users. It was hypothesised that the DSPB implant users would rate their abilities more highly (i.e. better) than the unilaterally implanted users, particularly for the spatial hearing subscale.

4. Compare the self-rated abilities of the DSPB users to those with normal-hearing listeners. The hypothesis is that self-rated abilities of DSPB implant users would still be worse than that of normal-hearing listeners across all the three subscales of the SSQ.

9.2 Additional methods

As with localisation and speech perception tests, the current study was approved by the National Research Ethics Service (REC reference: 12/SC/0421) as well as the University of Southampton Research Governance Office and the University Hospitals Birmingham Clinical Research Office. Approval of the Institute of Sound and Vibration

Research Human Experimentation Safety and Ethics Committee (reference number for CI subjects: 2915; for normal-hearing subjects: 4164) was also obtained prior to the start of testing. All the ethical approvals can be found in Appendix C.1 and C.2, for testing unilateral CI subjects, and in Appendix D.1 and D.2 for DSPB implant subjects.

9.2.1 Participants

All the DSPB subjects and unilateral CI subjects who participated in the localisation and speech perception experiments also took part in this study. In addition, normal-hearing listeners who participated in the localisation experiment reported in Chapter 4 took part in the current study. The criteria for choosing the normal-hearing subjects were described in Section 4.3.1.1: they all had normal hearing and reported no ear problems within the past 12 months and were otologically normal on the day of testing.

Demographic information about subjects is given in Table 9.1. Detailed individual information on the unilateral CI subjects and DSPB subjects was presented previously in Tables 6.2 and 7.1. It is worth reminding, here, that the unilaterally implanted subjects in this project were chosen to represent the best performance that could be expected from unilateral CI users. Clinical data showed that the unilateral CI subjects had a maximum of 7 dB signal-to-noise ratio (SNR) for speech in noise, whereas the maximum score for speech in noise was 12 dB SNR for the DSPB subjects. Results from Chapter 8 also showed that the SRTs for co-located speech and noise were significantly better, by about 3.5 dB, for the unilateral CI subjects than the DSPB subjects.

Table 9.1: Gender distribution, median age and time since implantation (interquartile range) for DSPB, unilateral CI and normal-hearing subject groups.

	DSPB CI	**Unilateral CI**	**Normal-hearing**
Number	8	8	20
% female; % male	50%; 50%	50%; 50%	50%; 50%
Age in years	65.5 (29)	45 (21.7)	25 (5.25)
Post-implantation time in months	10 (8)	114 (93)	_

9.2.2 Procedure

Self-rated abilities in everyday life were explored using the SSQ, which is presented in Appendix A.2. The SSQ seems a promising tool for assessing the difficulties that listeners may have over a wide range of functions. The SSQ is a 50-item scale covering three main subscales that measure hearing for speech (14 questions), spatial hearing (17 questions) and qualities of hearing (19 questions). Previous studies have shown that the SSQ is sensitive and reliable enough to detect the differences in abilities among CI and hearing aid users (Singh and Pichora-Fullera, 2010). It is also considered a useful measure to investigate any additional benefits of bilateral CIs over unilateral implants (Noble and Gatehouse, 2006). It has been extensively used to assess abilities with unaided and aided hearing aids (Gatehouse and Noble, 2004) and CI users (Noble et al., 2008; Summerfield et al., 2006).

Each subject was asked to complete the SSQ on their own prior to their visit to our laboratory to test their performance on localisation and/or speech perception in noise, to ensure that their rating was not affected by their performance on laboratory tests. Subjects were asked to fill out the SSQ based on their real-world experience in everyday life. They were asked to rate their ability by marking each item using a horizontal visual-analogue scale (VAS) ranging from 0 to 10, where 0 stands for least ability and 10 for greatest ability.

9.3 Results

The SSQ was returned by all subjects without any missing data. Self-rated abilities of the DSPB and unilateral CI subjects, as well as normal-hearing subjects, are presented in Section 9.3.1. The relationship between the outcomes on the SSQ and laboratory tests of spatial hearing was also examined and results are presented in Section 9.3.2.

9.3.1 SSQ: Self-assessment with different groups

The average self-rated score in each of the three main subscales of the SSQ, including speech, spatial and quality of hearing, was calculated for each subject. The average score across all the main subscales was also calculated for each subject, to reflect overall SSQ. Figure 9.1 presents the self-rated scores on the overall SSQ and each of the three subscales, speech, spatial and qualities of hearing, for different groups of subjects: DSPB implant, unilateral CI and normal-hearing subjects, where the higher the score (maximum 10), the greater the ability. Individual average scores of the overall SSQ and each of the three subscales are also presented in Figure 9.2 for the DSPB implant group (upper panel) and the unilateral CI group (lower panel).

The upper panel of Figure 9.1 shows that the median overall SSQ score of the DSPB group was higher (i.e. better), by only about one point, than that of the unilateral CI group. The median overall SSQ score was 5.3 points for the DSPB implant groups, while it was 4.4 points for the unilateral CI groups. The median score of the normal-hearing group was, however, almost double the median of the CI groups (median= 8.7 points). Statistical analysis was conducted to examine the above observation. The data of the scores for the overall SSQ and the three subscales were found to be normally distributed (Kolmogorov-Smirnov: $P > 0.05$). One-way independent ANOVA was performed on the overall SSQ scores, with the subject group as the independent variable. Results showed a significant effect of subject group on the overall SSQ scores

(F (2) =22.6, $P < 0.001$). Results from *post hoc* pairwise comparisons revealed that both the DSPB implant and unilateral CI groups had similar self-rated scores on the overall SSQ ($P > 0.1$), and their scores were statistically lower than those reported by the normal-hearing group ($P < 0.001$).

Scores on the three subscales of the SSQ, including speech, spatial and qualities of hearing are shown in the lower panel of Figure 9.1. Two main trends can be observed. First, there are differences in the scores reported for the three subscales among each of the DSPB and unilateral CI groups. Generally, the DSPB implant subjects seem to have higher (i.e. better) scores for the spatial subscale and lower scores for the speech subscale. The variation in the scores of the spatial subscale of the DSPB implant subjects was, however, greater than in the other subscales; it includes the worst and the best scores across all the subscales. The unilateral CI group, on the other hand, tends to have higher scores for qualities and lower scores for the spatial subscale. These results may suggest that, in general, the DSPB implant subjects experienced lower hearing disability in the spatial aspects of hearing, whereas the unilateral CI subjects experienced lower disability in the qualities of hearing. The scores of normal-hearing subjects were generally similar across the three subscales.

The second trend was that the difference in scores between the two CI groups appears to be greater for the spatial subscale. The median score of the DSPB group was higher (i.e. better) by about 3 points than that of the unilateral CI group. For the other two subscales, the median score seems similar for the two CI groups. Normal-hearing subjects had generally higher scores than the CI groups on all the three subscales. It is worth noting that the best scores reported by normal-hearing subjects were 9.7, 9.9 and 9.8 points for speech, spatial and qualities of hearing subscales. Although this indicates that some normal-hearing subjects approached the maximum score (i.e. perfect hearing), none of them reported a maximum score. In fact, a few normal-hearing subjects had scores that overlapped with the scores of a few CI subjects. Three subjects from each CI group had similar scores to the scores of four normal-hearing subjects.

Statistical analyses were conducted to examine the above trends. A repeated measures ANOVA was conducted on SSQ scores with the type of subscale as within-subjects factors and subject group as the between-subjects factor. Given the number of main effects and interactions, a Bonferroni correction of 0.016 was applied. Results showed a significant effect of the type of subscale (F (2) =7.85, P=0.003) and subject groups (F (2) =22.6 P=0.001). Results from *post hoc* pairwise comparisons showed that the scores for qualities was significantly higher than that for speech ($P < 0.001$) and spatial subscale (P= 0.009). With regard to the effect of subject group, no significant difference in scores was observed between the DSPB and unilateral CI groups ($P > 0.1$), in which both had significantly lower scores than those reported by the normal-hearing group (*P* <0.001). Significant interaction between type of subscale and subject group was found (*F* (4) =6.46, *P* =0.001), indicating significantly higher scores for qualities than for speech for the DSPB group (*F* (2) =3.91, *P*=0.012) and significantly higher scores for qualities than for spatial for the unilateral CI group (*F* (2) =4.99, *P*=0.013).

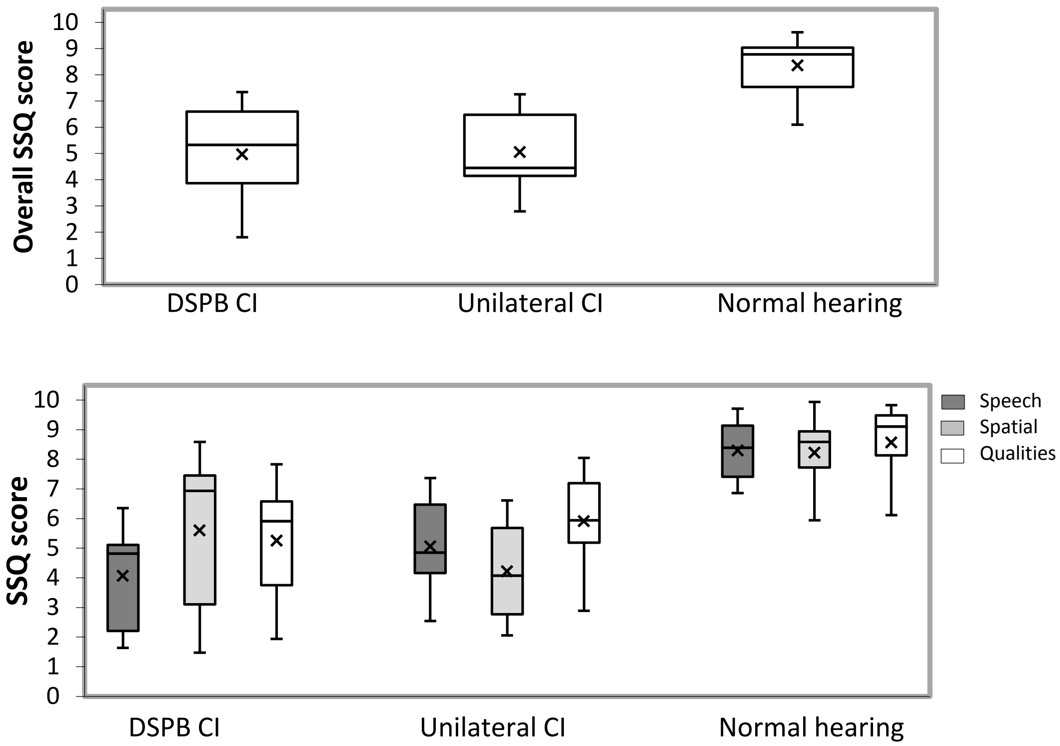


Figure 9.1: Scores on the overall SSQ (upper panel) and each of the three subscales: speech, spatial and qualities of hearing (lower panel) for subjects with DSPB implants (*n*=8), unilateral CIs (*n*=8) and normal-hearing (*n*=20). Each box represents the two middle quartiles (end of boxes), separated by median (horizontal line), mean (cross inside the box), maximum and minimum values (horizontal lines at the end of whiskers).

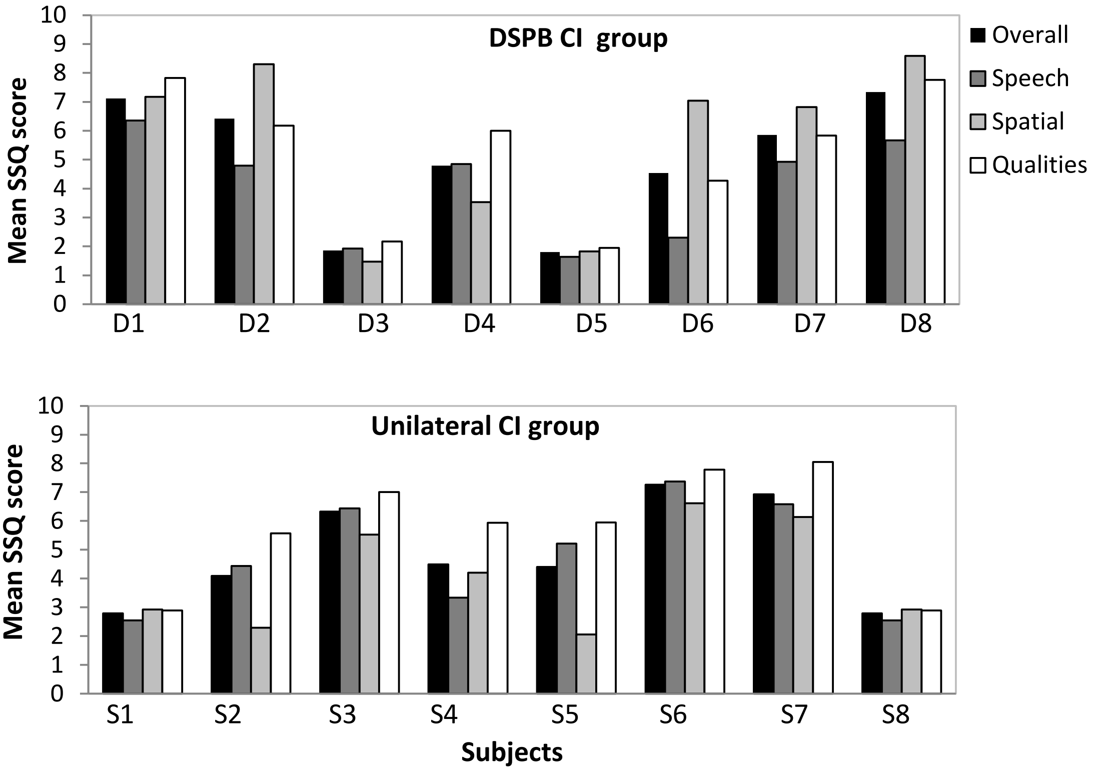


Figure 9.2: Mean ratings on the overall SSQ and speech, spatial and qualities of hearing subscales for individual DSPB implant (upper panel) and the unilateral CI group (lower panel). The order of subjects along the abscissa is the same as that shown in Figure 6.4, for unilateral CI subjects, and Figure 7.4, for DSPB implant subjects.

Since the above three subscales cover a wide range of items, each subscale was divided into a set of smaller subscales, as reported by Gatehouse and Akeroyd (2006), with the aim to provide a clearer understanding of the subjects' abilities. The assignment of individual SSQ items to each of the smaller subscale labels is reported in Table 9.2, with the median self-ratings on these subscales for the three subject groups. The results showed that the speech hearing disability of both CI groups significantly increased as contexts became more challenging (F (3) =44.9, P < 0.001). The DSPB implant group had about a similar rating on localisation and distance and movement for the spatial hearing. Although unilateral CI subjects seemed to have better ratings on distance and movement than localisation, this difference did not reach the significance level (F (1) = 0.31, P > 0.1). With regard to qualities subscales, similar ratings were reported among the subscales by both the DSBP implant and the unilateral CIs (F (3) = 0.76, P > 0.1).

Compared to the unilateral CI group, the median rating of the DSPB group was found to be greater for the localisation subscale of the spatial hearing by 4.2 points. This difference did not, however, reach the significance level. Apparently, no significant differences in scores were reported between the DSPB implant and the unilateral CI groups. Scores of the normal-hearing group were, however, associated with higher ratings than both the DSPB implant and unilateral CI groups, on nine subscales. *Post hoc* pairwise comparisons showed that normal-hearing rating on the segregation of sound subscale of the qualities of hearing was only significantly higher than the unilateral CI group (*P* <0.001), but not of the DSPB implant group (*P* >0.1).

Table 9.2: Median scores for the DSPB implant, unilateral CI, and normal-hearing subjects on each of the SSQ subscale labels. Double asterisks indicate where a group's score was statistically significantly different from both the other two groups, whereas the single asterisks indicate where a group's score was statistically significantly different from one of the two groups at *P* <0.005)

	SSQ subscale label	**Contributing items**	**Median**		
			DSBP	**Unilateral CI**	**Normal-hearing**
Speech	Speech in quiet	Speech items 2 and 3	6.2	8.4	9.6**
	Speech in noise	Speech items 1, 4, 5 and 6	4.7	4.9	8.3**
	Speech in speech contexts	Speech items 7, 8, 9 and 11	4.5	5.0	8.2**
	Multiple speech-stream processing and switching	Speech items 10, 12 and 14	1.0	2.3	7.3**
Spatial	Localisation	Spatial items 1, 2, 3, 4, 5, 6 and 7	7.0	2.8	8.4**
	Distance and movement	Spatial items 8, 9, 10, 11, 12, 13, 15, 16 and 17	6.4	4.8	8.0**
Qualities	Sound quality and naturalness	Qualities items 8,9,10,11 and 12	6.1	6.9	8.9**
	Identification of sound and objects	Qualities items 4,5,6,7 and 13	5.7	5.9	8.7**
	Segregation of sounds	Qualities items 1,2 and 3	7.5	5.8	8.7*
	Listening effort+	Qualities 14, 18 and 19	6.5	6.6	7.9**

+The higher the value the lower the level of rated listening effort.

Taken together, the above results indicate that the ability experienced by the CI subjects seems statistically similar for both the DSPB implant and unilateral CI subjects. Although it did not reach the significance level, the DSPB subjects rated their localisation ability better by 4.2 points than unilateral CI subjects. Normal-hearing subjects reported statistically higher self-rating ability than the CI subjects.

9.3.2 SSQ: Correlations with laboratory spatial hearing measures

This section examines the correlation between the SSQ and the performance on laboratory tests of spatial hearing for CI subjects described in previous chapters. Spatial hearing ability was represented by the overall error with speech stimulus for the localisation test and SRM for the speech perception in noise test.

Figure 9.3 shows the individual mean score on the overall SSQ for the DSPB and unilateral CI groups versus their results on localisation (overall localisation error with speech stimulus, left panel) and speech perception in noise (SRM, right panel). The figure shows that the DSPB subjects who exhibited relatively better ability on sound localisation and/or speech perception did not necessarily experience better ability in everyday life and vice versa. For example, a DSPB implant subject who had poor measured localisation ability (subject D3) reported similar self-rated ability to subject D5 who exhibited relatively good localisation ability at better than chance unbiased guessing performance. Although the measured localisation ability of subject D3 was similar to that of subject D7, in which they had overall error scores that fall in the range of unbiased guessing, subject D7 reported much better self-rated ability than subject D3. The same was found for unilateral CI subjects, where those who showed overall error scores at better than unbiased guessing performance reported similar self-rated ability to the other subjects. A similar observation was also noted for the relationship between overall SSQ scores and the binaural benefit on speech perception in noise (i.e. SRM). For both CI groups, subjects who showed similar SRM values had considerable differences in their SSQ scores.

Table 9.2 shows the statistical analyses of correlations between the SSQ and its three subscales and the performance on the laboratory tests, with a Bonferroni correction. In addition to the SRM for speech perception, the correlation for the speech perception thresholds (SRTs) when speech and noise were in front of the listeners was also examined. The only significant correlation indicated that the amount of SRM shown by the DSPB implant subjects tended to be highly related to their scores on the speech and qualities subscales of SSQ. The results of the 95% confidence intervals of the correlation coefficient indicate that the SRM was also significantly correlated to the overall SSQ. The scores shown by the DSPB implant subjects on localisation and SRTs were, however, not significantly correlated with each of the SSQ subscales (although the correlation between their scores on localisation and spatial SSQ was statistically significant before the Bonferroni correction was applied). The statistical analyses of correlations for normal-hearing subjects, which are presented in Table 1 of Appendix F.1, also showed no significant relationship between their scores on overall SSQ and its three subscales and their performance on the laboratory tests.

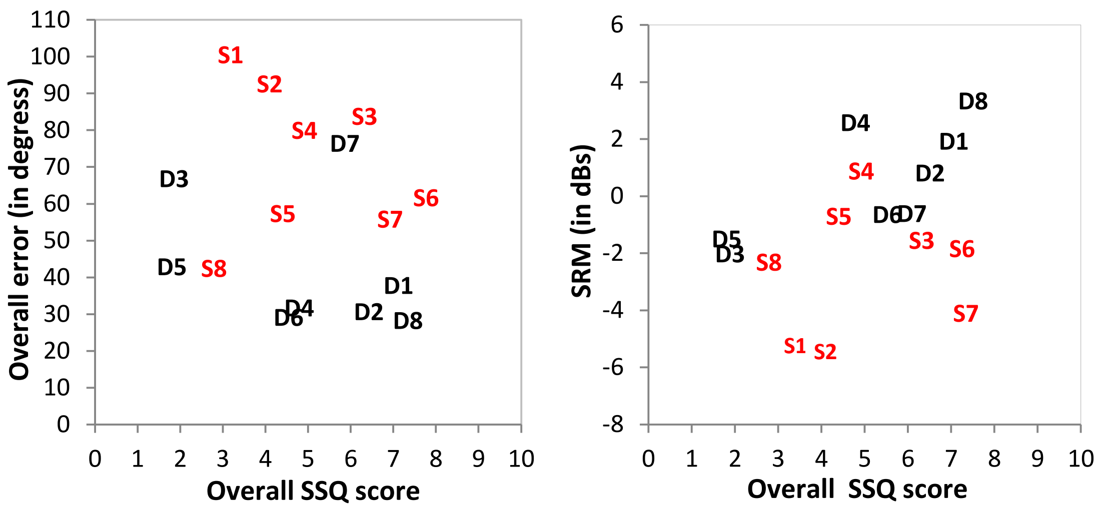


Figure 9.3: Mean rating on overall SSQ versus binaural hearing benefits: left panel: localisation represented by overall error ($\overline{D}$ error with speech stimulus), right panel: spatial release from masking (SRM) for individual DSPB implant subjects (D letter) and unilateral CI subjects (S letter).

Table 9.3: Results of correlation analyses between SSQ scores and laboratory test (localisation with speech, SRM and SRT for co-located speech and noise). The correlation coefficients (95% confidence intervals) are listed. The Pearson correlations were used, with the exception of correlation between localisation with the DSPB implant and SSQ, where Kendall's tau was used (as localisation data of the DSPB implant were not normally distributed).

	DSPB CI			Unilateral CI		
	Loc	SRM	SRT	Loc	SRM	SRT
Overall SSQ	-0.35 (-0.8-0.4)	0.80 (0.07-0.8)	-0.38 (-0.8-0.4)	-0.42 (-0.8- 0.4)	0.23 (-0.6-0.8)	0.69 (-0.1-0.8)
Speech SSQ	-0.21 (-0.8-0.6)	0.83* (0.2-0.8)	-0.06 (-0.7-0.7)	-0.51 (-0.9-0.3)	0.15 (-0.6-0.8)	0.58 (-0.2-0.8)
Spatial SSQ	-0.37 (-0.8-0.5)	0.55 (-0.2-0.8)	-0.62 (-0.8-0.7)	-0.32 (-0.8-0.5)	0.18 (-0.6-0.8)	0.56 (-0.2-0.8)
Quality SSQ	-0.37 (-0.8-0.4)	0.87* (0.2-0.8)	-0.24 (-0.8-0.6)	-0.34 (-0.8-0.5)	0.29 (0.5-0.8)	0.71 (0.0-0.8)

**P with Bonferroni correction* < 0.01

The correlation between the smaller subscales of the SSQ and the laboratory tests was also examined. As the likelihood of detecting statistically significant correlations becomes very small after applying the Bonferroni correction, only the subscales that related to the measured spatial ability on the laboratory test were analysed. Localisation performance of the DSPB implant subjects was significantly correlated with their ratings on the localisation subscale of the spatial SSQ (r=-0.69, P=0.018). As regard speech perception in noise, the DSPB implant subjects ratings on speech in noise subscale of the speech SSQ were marginally significantly correlated with their amount of SRM (r=0.77, P=0.024). The correlations between each of the smaller subscales of the SSQ and the laboratory tests are presented in Appendix F.1 for the DSPB implant subjects (Table 2) and unilateral CI subjects (Table 3).

9.4 Discussion

The current study aimed to explore self-rated abilities of the DSPB implant subjects in everyday life compared with those of the unilateral CI and normal-hearing subjects. The outcomes were measured using the SSQ, as it was reasoned that this scale is particularly relevant to the aim of the project of evaluating the spatial benefits of DSPB implants. The results indicated that the DSPB implant subjects generally rated their everyday life ability in the mid-range on the SSQ scoring scale (0-10 points). Their self-rated ability on the qualities of hearing subscale was statistically significantly better than on the speech subscale, with median difference of about 1 point. There was also a trend for the scores of DSPB implant subjects to be higher on the spatial hearing subscale than for the speech subscale, with median difference of about 2 points, though such difference did not reach a significance level (Section 9.4.1). The above pattern of results seems to be different from that reported by Noble et al. (2008) on conventional bilateral CI subjects (Section 9.4.2).

Unilateral CI subjects tested in the current study, on the other hand, rated their ability in the low- to mid-range on the SSQ scoring scale. They rated their ability on the qualities of hearing subscale statistically significantly better than on the spatial subscale (Section 9.4.3). The self-rated ability reported by the DSPB subjects and the unilateral CI subjects was found to be statistically similar. It is, however, worth noting that the self-rated ability of DSPB subjects tended to be better than that of unilateral CI subjects for the spatial hearing subscale (median difference= 2.8 points). In particular, the DSPB subjects seem to have a greater self-rated localisation ability, by 4.2 points, than the unilateral CI subjects. The outcomes of both CI groups were still lower than those of normal-hearing subjects, across all the three subscales (Section 9.4.4).

9.4.1 SSQ: Self-rated abilities with the DSPB implants

The current study showed that the ratings of the DSPB implant subjects were generally in the mid-range on the SSQ scoring scale. This suggests that the DSPB implant subjects can show some ability in everyday hearing functions with respect to speech, spatial hearing and qualities, yet they still experience some difficulties with hearing with their implants.

One of the main findings of the current study is that the DSPB implant ratings were statistically significantly lower (i.e. indicating greater disability) for speech than for the qualities subscale. There was also a trend, albeit not significant, for the DSPB implant ratings for speech hearing to be lower than for the spatial subscale. The median scores by the DSPB implant subjects were 4.9, 6.9 and 6.2 points for the speech, spatial and qualities subscales. The lack of significant differences in scores between spatial and speech subscales might be postulated to be due to the small sample size and the considerable variation in the scores shown by the DSPB implant subjects. The current study was underpowered, as only eight DSPB implant subjects were tested, as opposed to the 14 subjects planned originally. Despite that, the DSPB implant subjects showed surprisingly considerable variation in scores, particularly for the spatial subscale.

It is not entirely clear whether there is any reason behind the general decline in the DSPB implant ratings when moving from spatial hearing to speech hearing. It might, however, indicate that interaural differences in the level of sounds (ILDs) preserved by the current CI speech processing may enable the DSPB implant subjects to perform, to some extent, some of the tasks described on the spatial hearing subscale. However, such speech processing does not preserve the fine structure information of signals, which would be required to perform tasks involving distinguishing simultaneous streams of audible information for speech hearing. It is well documented that fine structure information has an important role in binaural squelch for speech perception (see Section 2.2.1). In fact, the greater disability reported for the DSPB implant subjects for speech hearing was found to be more driven from questions involving multi-stream listening. It seems that the DSPB implant subjects struggle to rapidly switch between speech and other structured sound streams. The median score for the speech-stream processing and switching was just one out of 10 points, suggesting that the DSPB implant subjects were not able at all to follow more than one speech stream at the same time or switch from one to another. Such a possibility, however, might be excluded given the previous study of Noble et al. (2008) who reported similar self-rated ability for speech and spatial hearing by the conventional bilateral CI users (see Section 2.4.2 for more details).

There is another possibility that the lower ability for speech hearing than the spatial and qualities might simply reflect the overall confidence of the subjects. It may be that DSPB implant subjects who had had only short bilateral experience with their CIs were less confident on tasks described in the questions on speech hearing and therefore reluctant to make higher ratings for such questions. It may also reflect the role of listening experience with their implants, with median bilateral experience of about 10 months. It might be possible that the DSPB implant subjects need longer bilateral experience to do, with more confidence, some of the tasks described in speech hearing which involve monitoring of signals and switching speech and other sound streams than tasks described in spatial and qualities of hearing. Given that all the DSPB implant subjects of the current study will be retested in our laboratory at least 18 months post-implantation, this may help to determine whether and to what extent their self-rated ability reported in the current study was affected by their short listening experience with their implants. It may also relate to the duration of deafness and the age at onset of deafness. The DSPB implant subjects of the current study had many years of deafness and one was congenitally deaf. It may also be the tougher demands of cognitive processing the DSPB implant subjects required to perform some tasks on speech hearing. It is well documented that a significant amount of speech understanding involves attention and cognitive resources (Fraser et al., 2010). Given that the aging-related auditory and cognitive processing factors generally begin to occur in the 60-years-olds (Gates, 2012), and that the DSPB implant subjects in the current study were generally older than 65 years, it might be possible that the DSPB implant ratings for speech hearing were affected by such factors.

Another finding of the current study is that that the self-rated ability in everyday life of the DSPB implant subjects may not be represented by the measured ability in laboratory tests. The findings of the current study indicated no statistically significant correlation between the ability in everyday life and the measured ability in laboratory tests (localisation and speech perception). It should be stressed that this finding may also be influenced by the limited statistical power due to the small sample size and/or the variation in scores between subjects. The 95% confidence intervals on correlation coefficients shown in Table 9.3 indicate that the SRM was significantly correlated with overall SSQ and two of its subscales, including speech and qualities, but not for spatial hearing. Neither the performance of the DSPB implant subjects on localisation nor their performance on speech perception for co-located speech and noise was correlated with their ability in everyday life. Such findings contrast with the findings reported by van Esch et al. (2015) that the measured spatial ability determined by SRM and MAA can predict everyday spatial hearing ability. Van Esch et al. (2015) found significant correlations between the results of normal-hearing and hearing-impaired listeners on spatial hearing tests of MAA and SRM and self-reported spatial ability. The correlation coefficients reported in their study were, however, in the order of 0.31 for MAA and only 0.4 for SRM, which may lead us to question the robustness of such correlations.

Nevertheless, the finding of the current study that the spatial hearing measures may not reflect ability in everyday life is not surprising, given that the SSQ covers the contributions of some functions that are not revealed by laboratory tests. Given that the ILDs are more likely to dominate the spatial hearing performance with bilateral CI users and that they lose the redundancy to rely on other cues for spatial hearing, it might be possible that with multiple sound sources the ILDs would provide unreliable cues in real-world situations, similarly to the deterioration of speech understanding in the presence of background noise. However, more positively, the results of the current study showed that self-rated localisation ability is significantly related to the localisation performance.

The current study, therefore, sheds more light on the DSPB implant's ability in real-life situations than that reported by Bonnard et al. (2013). The results of Bonnard et al. (2013) showed an overall benefit in health status after cochlear implantation, as indicated by a positive score of about 35.7 points at GBI. More importantly, their results showed that the residual hearing disability experienced by the DSPB implant users was below 50 % on all the subscales of the APHAB, and that the lowest-level of disability was for background noise (30.1%), compared to the ease of communication, reverberant listening conditions and aversiveness to sounds subscales of the APHAB. Although the comparison between their study and the current study is complicated due to the use of different measures, both studies showed that the DSPB implant users had some abilities to do tasks in listening situations that are static in space and time. The current study, most importantly, is the first study that provides insight on the spatial abilities of the DSPB implant users in real-life situations that vary in space and time, although further research with a larger sample size might be required to draw solid conclusions on the ability of the DSPB implant users in everyday life.

9.4.2: SSQ: Self-rated abilities for DSPB implant versus conventional bilateral CIs

The findings of the current study replicate previously published results, in that bilaterally implanted subjects can show some self-rated ability in everyday life (Noble et al., 2008; Summerfield et al., 2006). The median overall SSQ reported for the DSPB implant subjects of 5.3 points was found to be broadly consistent with previous studies on conventional bilateral CI users. Noble et al. (2008), for example, reported a mean score of 6 points on overall SSQ for their 36 bilaterally implanted subjects (the mean listening experience with bilateral CIs was 22.9 months). Summerfield et al. (2006) also reported a mean overall SSQ of about 5.9 points for their 24 subjects, after nine months of bilateral experience. The finding reported for the DSPB implant subjects in the current study seems encouraging, given that they had been using their implant for between 4 to 18 months (median bilateral listening experience was 10 months).

The findings of the current study, however, contrast with the study of Noble et al. (2008) who reported higher ratings for qualities of hearing than speech and spatial subscales, although the statistical analysis of the differences between subscales was not reported. Noble et al. (2008) reported a mean score of 5.8, 5.7 and 6.4 points for the speech, spatial and qualities of hearing subscales, whereas the current study showed median scores of 4.9, 6.9 and 6.2 points. While the current study showed relatively higher ratings, albeit not significantly, for spatial than for the other subscales, particularly speech hearing, the study of Noble et al. (2008) showed slightly higher ratings for qualities of hearing than the speech and spatial subscales, in which both had similar ratings. Nevertheless, the mean ratings by the DSPB implant subjects in the current study had confidence intervals that included the mean rating reported by the previous study for spatial and qualities of hearing, but not for speech. The mean ratings were 4.0 (95% at 2.2 to 5.1), 5.5 (95% at 3.1 to 7.4) and 5.2 points (95% at 3.7 to 6.5) for speech, spatial and qualities of hearing subscales. It should be noted that the study of Summerfield et al. (2006) only reported the mean rating for the spatial subscale of 5.8 points, which also included in the confidence interval of the mean spatial hearing score reported in the current study.

Although the above findings may indicate that the DSPB implant subjects experienced lower ability for speech hearing than that of conventional bilateral CI users, such a comparison may be complicated by the differences in the CI subjects of the two studies. It might be possible that the DSPB implant ratings for speech hearing were limited by factors such as age at onset of deafness and duration of deafness. For example, the DSPB implant subjects in the current study had been profoundly deaf for many years (median=16 years), including one who was congenitally deaf. The extent to which such factors could explain the lower ability for speech hearing for the DSPB implant subjects than that for conventional bilateral CI users is, however, not clear, given that Noble et al. (2008) did not report this information for their subjects. Another possible explanation for the lower self-rated speech ability reported by the DSPB implant subjects is that the DSPB implant subjects in the current study had shorter bilateral listening experience (median CI experience was 10 months) than the conventional bilateral CI subjects of Noble et al.'s study (mean CI experience was 22.9 months). Given the fact that the speech performance improves with time (Litovsky et al., 2009), it might be possible that longer experience with the DSPB implant is required by the subjects in order to show higher ability for speech hearing.

9.4.3: SSQ: Self-rated abilities for the unilateral CIs and normal-hearing listeners

This section considers the self-rated ability of unilateral CI and normal-hearing subjects in the context of previous studies. The self-ratings of the unilateral CI subjects were found to be in the low- to mid-range on the SSQ scoring scale (0-10). The median scores reported for the unilateral CI subjects were 4.4, 4.8, 4.0 and 5.9 points for overall, speech, spatial and qualities SSQ, respectively. The self-rated ability reported by the unilateral CI subjects for spatial hearing may reflect the role of audibility; it might be possible that unilateral CI subjects learn to use monaural level and spectral cues between implanted and non-implanted ears to show some limited ability on spatial hearing. Ratings of unilateral CI subjects in the present study were broadly comparable with those found in previous studies (Noble et al., 2008; Summerfield et al., 2006). Noble et al. (2008) reported mean speech, spatial and qualities scores of 5.0, 4.1 and 5.3 points for their unilateral CI subjects (n=70 subjects with CI experience of 42.2 months). Summerfield et al. (2006) also reported a mean spatial score of 3.8 points for their unilateral subjects (n=12 subjects with CI experience of 2.7 years), although the scores for the other subscales were not reported. As found by Noble et al. (2008), the unilateral CI subjects' ratings in the current study for spatial were lower than for the speech (though not significantly) and qualities subscales.

The broadly comparable ratings of unilateral CI subjects of the current study and those in other studies suggests that the ''good'' unilateral CI performers in the current study rated their spatial hearing ability in everyday life no differently from the other unilateral CI users. This finding may support the findings reported previously in Chapter 6, in which the ability of unilateral CI subjects to identify the locations of sound sources at better than chance range of unbiased guessing does not necessarily mean that the listener's perceived locations are appropriate. Shub et al. (2008) suggest that asking the subjects to identify the correct locations would encourage the subjects to use any information to identify the correct locations, whereas asking the subjects to report the perceived location of the source would probably have measured localisation ability in more realistic situations. A further support of this is that lack of a relationship reported in the current study between the unilateral CI subjects' performance in laboratory tests and their rating scores.

Concerning normal-hearing subjects, the findings of the present study were in line with the results of previous studies (Banh, 2012; Demeester et al., 2012; Singh and Pichora-Fuller). For example, Banh et al. (2012) and Demeester et al. (2012), reported the SSQ scores of young normal-hearing listeners (Banh et al.: n=48, mean age=19 years; Demeester et al.: n=108, mean age= 19.5 years). The average scores of speech, spatial and qualities were 8.5, 8.6 and 9.4 points (Banh et al., 2012) and 8.7, 8.5 and 9.3 points (Demeester et al., 2012). Thus, the outcomes of these two studies appear to be quite comparable to those of the current study. Among normal-hearing subjects tested in Banh et al.'s study and the current study, no one had a perfect score (i.e. 10 points). This is an important point to note, as it may have implications for clinical applications. For example, it would assist clinicians to set realistic expectations for adults with auditory prostheses Although there is still a possibility that the normal-hearing subjects in the current study were underestimating their ability, the finding of the current study that the scores of normal-hearing subjects were less than 10 points is not surprising, as even normal-hearing listeners could face some difficulties with listening in more challenging situations such as those described in the SSQ.

9.4.4: SSQ: Does the DSPB implant offers advantages over unilateral CIs?

This section examines whether the DSPB implant provides any advantages over unilateral CIs in terms of the self-rated abilities experienced in everyday life. It is worth remembering the differences between the characteristics of the DSPB implant subjects and unilateral CI subjects who participated in the current study. Unilaterally implanted subjects were chosen based on specific criteria to reflect the best performance that one could be expected from unilateral CI users. All had very good clinical speech scores in noise with a maximum of 7 dB SNR. The DSPB subjects were, however, chosen based on more relaxed criteria, in order to include more subjects. The maximum score for speech in noise was 12 dB SNR for the DSPB subjects. Moreover, the unilateral CI subjects in the current study had much longer CI experience (median: 9.5 years) than the DSPB implant subjects (median: 10 months).

The finding in the present study showed that the DSPB implant subjects rated their ability as not statistically different from the unilateral CI subjects. However, there is an important trend for DSPB implant ratings to be higher than the unilateral CI subjects for spatial hearing. The difference between median scores of the DSPB implant and the unilateral CI groups was 0.9, 0, 2.8 and 0 points on overall SSQ, speech, spatial and qualities of hearing subscales (negative value indicates better scores for unilateral CI subjects). Closer analysis of the outcomes indicated that the DSPB implant group showed higher self-rated ability, albeit not significant, than the unilateral CI group, by about 4.2 points for localisation and 1.6 points for the distance and movement subscales of spatial hearing. The DSPB implant subjects also showed higher ability on segregation of sounds, by about 1.7 points, than the unilateral CI subjects. Such findings seem to indicate that the DSPB implants had better self-rated ability than unilateral CI subjects on spatial hearing. It is possible that the current study was underpowered to detect differences in spatial scores between the DSPB implant subjects and unilateral CI subjects. The current study tested only a group of eight DSPB implant subjects, in which they showed considerable variation in scores, particularly for spatial SSQ.

In addition to localisation, one might expect that speech perception in the presence of competing speech/noise is among the areas that would be influenced by bilateral implantation, the DSPB implant group had, however, lower ability on speech hearing than the unilateral CI subjects. In particular, the DSPB implant ratings were lower than unilateral CI subjects, by about 2.2 points for speech in quiet. Such a result is perhaps not surprising, given the better clinical speech scores of the unilateral CI group compared to the DSPB implant group. The results on speech perception ability reported in Chapter 8 also indicate that the unilateral CI subjects performed significantly better, by 3.5 dB, than the DSPB subjects for co-located speech and noise (Section 8.3.2).

Self-rated ability by both CI subjects was still significantly lower than that of normal-hearing subjects on all the three subscales (as with laboratory tests). Closer inspection of the outcomes indicated that the DSPB implant group had lower ability than normal-hearing on all the smaller subscales, except for segregation of sounds. The DSPB implant subjects rated their ability to segregate input streams into discrete acoustic entities as not statistically different from that of the normal-hearing subjects. Although this may suggest that both the DSPB implant and the normal-hearing groups experienced similar ability to segregate sounds, there is still a possibility that the normal-hearing subjects in the current study were underestimating their ability to segregate sounds. A previous study by Banh et al. (2012), however, reported the ratings of 48 normal-hearing subjects to show only a slightly higher rating, by about 0.6 points, on segregation of sounds to those of the normal-hearing subjects in the current study.

In summary, the current study has explored the similarities and differences in the ability experienced in everyday life among the DSPB implant and the unilateral CI subjects. It showed that the DSPB implant group had statistically similar self-rated abilities to those with one implant, although the non-significantly higher rating of the DSPB implant for spatial ability, particularly on localisation, is worth noting. The DSPB implant subjects had higher localisation ratings (i.e. greater ability) than unilateral CI subjects, by about 4 points. Ratings of both the DSPB implant and the unilateral CI groups were still behind those reported for normal-hearing subjects.

9.5 Conclusions

The current study has shed light on the ongoing difficulties subjects experience when implanted with the DSPB implant or unilateral CIs. Within the limitations of the subjects tested in this study, the conclusions of the current study are as follows:

- The DSPB implant subjects rated their ability in everyday life in the mid-range on the SSQ scoring scale (0-10). Their self-rated ability on the qualities of hearing subscale was statistically significantly better than on the speech subscale. Although it was not significant, their self-rated ability on the spatial hearing seems to be also better than on the speech subscale.

- The DSPB implant subjects tended to have better self-rated spatial hearing ability than unilateral CIs, though this was not statistically significant. In particular, the DSPB implant subjects seem to have better localisation ratings than unilateral CI subjects.

- The DSPB implant ratings were still significantly behind those reported for normal-hearing subjects.

Chapter 10: Summary, conclusions and future research

10.1 Introduction

This research project aimed at exploring spatial hearing abilities with the synchronised bilateral cochlear implant (CI) system implemented in the Digisonic® SP Binaural cochlear implants (DSPB CIs). Prior to starting this project and to this researcher's knowledge, no study on spatial benefits with this kind of cochlear implant has been conducted. However, two studies have since been published over the time span of this project (Bonnard et al., 2013; Verhaert et al., 2012). Both studies reported that adults with the DSPB implants performed similarly to users of conventional bilateral CIs on sound-source localisation and speech perception in noise. Verhaert et al. (2012) also reported a significantly better performance for the DSPB implant subjects when they were listening with both implants than when one implant was deactivated, leading the authors to suggest that the DSPB implant subjects can take advantage of binaural cues that are not available when either implant is deactivated.

There were, however, some uncertainties regarding whether these conclusions were justified (see Table 2.5). It is not clear, for example, if the apparent improvement in performance when listening with both DSPB implants compared to only one device was actually related to spatial hearing ability. The fact that the study by Verhaert et al. (2012) did not provide any acclimatisation periods for unilateral listening may have led to overestimation of bilateral performance. Most importantly, neither study took into account the chance level and its range, assuming the appropriate guessing behaviours, when analysing localisation data of their subjects. It is, therefore, not clear whether their synchronised bilateral CI subjects could localise sounds at better than the chance range expected from guessing (unbiased and biased guessing). With respect to speech perception in noise, neither of the two studies reported whether the subjects can show a binaural benefit of spatial release from masking (SRM). This research project was motivated by the possibility of providing deeper insights into spatial hearing ability with the synchronised bilateral CIs and the possible potential benefits for clinical practice.

Spatial hearing benefits were assessed in this project through measures of sound-source localisation in the horizontal plane, speech perception in noise and self-report assessment. Performance of normal-hearing listeners on such measures was first assessed in order to evaluate the suitability of the methodology used for investigating spatial hearing abilities of CI users in this project (Chapters 4 and 5). The spatial hearing abilities of adults implanted with DSPB implants were assessed on three measures and compared to the ability of adults implanted with single CIs, who were chosen to reflect the ‘‘better’’ unilateral CI performance (Chapters 6 to 9). This comparison was intended to determine whether the DSPB implants can offer advantages over unilateral CIs for spatial hearing.

This chapter summarises the findings of the studies reported in this thesis (Section 10.2) and discusses the implications of these findings (Section 10.3). The main conclusions driven by these findings are presented in Section 10.4. The final section presents some suggestions for possible further research.

10.2 Summary

The spatial hearing abilities of the DSPB implant users were explored in this project through three measures. In the first two investigations, psychoacoustic measures, including horizontal sound-source localisation and speech perception in noise, were assessed in order to give an indication of how DSPB implant users were performing with their CIs. It should be stressed that the findings of the current research project should be considered in the context of the limitations associated with this project. The current study tested only eight DSPB implant subjects, in which a considerable variation in their characteristics was apparent between subjects. For example, one of the eight subjects was prelingually deaf. Although the current study was intended to test 14 DSPB subjects, it was not possible to achieve the intended sample size, as the CI centres involved in the current study abruptly ceased providing DSPB implants during the time span of this project.

Results for horizontal plane localisation showed that the majority of the postlingually DSPB implant subjects can show overall localisation error scores at better than chance range expected from guessing (unbiased and biased guessing). There is a trend, albeit not statistically significant, for low-pass noise to be localised with worse accuracy than other stimuli containing high frequencies, which might point to the dominance of ILD cues for localisation. The overall localisation error reported in the current study was within the range of scores reported by the previous two studies for broadband stimuli (Bonnard et al., 2013; Verhaert et al., 2012). The results for speech perception in noise, however, indicated that the DSPB implant subjects might not able to take advantage of spatial hearing in separating target speech from noise. When the noise moved 90° to one side, the DSPB implant offered no statistically significant binaural advantage of separation (i.e. SRM), irrespective of whether the noise was on the right or left. To the best of this researcher’s knowledge, no previous studies on SRM for DSPB implant users have been conducted, and so it is impossible to compare the SRM benefit between studies. The DSPB implant subjects did, however, experience a significant head shadow effect, consistent with the findings of Verhaert et al. (2012).

The present study also showed that the DSPB implant subjects who localised at a better than chance range of guessing may not necessarily obtain better speech perception thresholds when speech and noise were spatially separated versus co-located. Although it is not entirely clear why the ‘‘good’’ DSPB implant localisers did not show binaural benefits for speech perception, the factor of the experience-dependent emergence of spatial hearing abilities should be considered. Given that binaural mechanisms involved in localisation and speech perception measures are not the same (Blauert, 1997), this may suggest that the duration of bilateral experience needed to exhibit benefit on one measure is not necessarily the same as for the other. It is well known that signal detection (as with localisation) and speech understanding (as with speech perception) are tasks involving different mechanisms that may rely on different auditory and cognitive processes (Blauert, 1997). Previous studies on conventional bilateral CI users demonstrated that CI users generally reached asymptote performance in speech perception after a longer duration of bilateral experience than that for localisation (Grantham et al., 2007; Litovsky et al., 2009; Tyler and Summerfield, 1996). Performance of bilateral CI users in speech perception was found to gradually improve over the first 12 months after implantation (Dorman and Ketten, 2003; Tyler and Summerfield, 1996), whereas localisation performance reached its asymptote by 4 to 6 months after implantation (Grantham et al., 2007). Given that the bilateral experience with the DSPB implant subjects ranges from just 4 to 18 months, it might be possible that a longer experience with bilateral listening is required in order to show benefits for speech perception in noise.

Given that the above psychoacoustic measures assess a limited sample of ability that does not necessary reflect the ability in everyday life, subjective outcomes from the perspective of DSPB implant subjects themselves were also assessed. Results from the Speech, Spatial and Qualities of Hearing scale (SSQ) indicated that the self-ratings of the DSPB implant subjects were generally in the mid-range on the SSQ scoring scale (0-10). The DSPB implant subjects showed statistically significantly lower ratings (i.e. greater disability) for the speech of hearing subscale than for the qualities of hearing subscale of the SSQ. Although it was not significant, there was also a trend for the DSPB implant ratings for speech hearing to be lower than those for the spatial subscale of the SSQ. The correlation between the self-rated spatial abilities on the SSQ and the measured abilities on localisation and speech perception was found to be not statistically significant. The lack of significant correlation seems unsurprising, given that the SSQ covers the contributions of some functions that that are not revealed by the psychoacoustic measures.

With the aim to provide evidence of whether the DSPB implant did offer advantages over unilateral CIs, a group of unilaterally implanted subjects who had become acclimatised to listening with one implant in everyday life was also assessed on all the above measures. The criteria for unilateral CI subjects in this project were restricted to include only those who might be more likely to reflect the ‘‘better’’ unilateral CI performers, in order to determine whether the DSPB implant subjects still perform better. The results indicated that the majority of the DSPB implant subjects whose overall localisation error scores were better than chance range of guessing can still show lower scores than those of the ‘‘good’’ unilateral CI performers. This finding may indicate that the DSPB implant subjects could take advantage of binaural cues that are not available to unilateral CI users. With regard to speech perception, the DSPB implant seemed to offer a statistically significant difference in their SRMs of about 3 dB over that of unilateral CI subjects who happened to have the noise on the side of their implanted ear. The DSPB implant offered, however, no advantages over unilateral CIs when the noise was on the contralateral side of their implanted ear. The head shadow effect was similar for both the DSPB implant and the unilateral CI subjects. It is, therefore, impossible to tell with accessible evidence whether the DSPB implant can provide advantages over unilateral CIs for speech perception in noise. Self-rating outcomes showed that the DSPB implant subjects had statistically similar self-rated abilities to those with unilateral CIs, although the non-significantly higher rating of the DSPB implant for spatial ability, particularly on localisation, is worth noting. The DSPB implant subjects had higher localisation ratings (i.e. greater ability), by about 4 points, than unilateral CI subjects.

Despite the lower performance shown by the unilateral CI subjects than the DSPB implant subjects, the results of localisation performance of unilateral CI subjects seem interesting. These results indicated that four out of the eight unilateral CI subjects tested can show overall error scores on a simple sound-identification task at better than chance range of guessing, which is consistent with the findings of Grantham et al. (2008). One of the main findings of the current project is that the better than guessing performance of unilateral CI subjects on a simple identification task is still achievable with stimulus presentation level roves of ±4 dB and ±8 dB and no spectral-shape roving. Such a result suggests that the level rove used in this research project, as well as in other localisation studies, might not be sufficiently large to discourage subjects from using monaural cues for localisation. The finding of better than guessing performance by unilateral CI subjects in the current project does not necessarily mean that the listener’s perceived locations are appropriate. Neither of the two unilateral CI subjects who showed some ability to identify the locations of sound sources at better than guessing performance could actually tell where the source was actually perceived.

Given that the DSPB implants seem to provide advantages over unilateral CIs for localisation, the next question is how the DSPB implants perform compared to the conventional bilateral CIs, where two independent processors are used. Results indicated that localisation performance of the DSPB implant subjects was significantly similar to that reported previously with conventional bilateral implant subjects for broadband noise, but not for speech (Verschuur et al., 2005). The significant difference in localisation performance with speech stimulus might result from the higher variability in performance with speech than with broadband noise by the DSPB implant subjects. With respect to speech perception in noise, the DSPB implant does not seem to offer similar advantages to the conventional bilateral CIs. The mean SRM reported for the DSPB implant subjects had a confidence interval (95% at 0.84 to 2.10 dB) that did not include the SRM reported previously for conventional bilateral CI users. Given that the DSPB implant subjects were tested with a short duration of bilateral experience, this may have limited their performance and a longer experience with the implant might be needed to exhibit SRM comparable with that of conventional bilateral CI subjects. Self-rating outcomes indicated that the DSPB implant subjects seem to have generally comparable ratings to those reported for conventional bilateral CI subjects (Noble et al., 2008; Summerfield et al., 2006). Taken together, the above findings suggest that the spatial benefits provided by the DSPB implants and the conventional bilateral CIs seem broadly comparable, though not for speech perception, and that the synchronised processing with the DSPB implant seems to not offer any better accuracy for binaural cues than two separate CIs. With the aim of providing a more complete picture of the effect of the DSPB implants, a Consultant Otolaryngologist at the University of Southampton Auditory Implant Service (USAIS) was contacted by email to determine whether there were any postoperative complications with the DSPB implants, but no response was received.

Although bilateral CI subjects, including both those implanted with the DSPB and the conventional CIs, have demonstrated better spatial hearing ability than unilateral CI subjects, they still do not perform as well as normal hearing listeners. The spatial hearing ability reported for normal-hearing subjects in the current project was way better than that reported for the bilateral CI subjects. Such a finding is not surprising, given the factors limiting performance in bilateral CI subjects, which were discussed in Section 2.6.4. Briefly, these factors include limitations in the areas of pathology of the auditory system, surgical positioning of the electrode arrays in the cochlea and signal processing strategy. The degeneration in the peripheral and central auditory systems, due to auditory deprivation, is likely to limit spatial hearing in CI users. Although bilateral CI users might be able, through training and experience, to learn how to utilise altered cues, the extent to which the neurons that mediate binaural cues are affected by experience is still unknown. It is also not clear whether the role of experience can be manifested with the altered cues introduced by the mismatch of the place of stimulation between ears. Difference in either anatomical positioning of the electrode array in the cochlea and/or the insertion depth of electrode arrays between the ears might result in differences in the place of stimulation across ears, which may limit the binaural cues in bilateral CI users. Another factor limiting the performance of bilateral CI users is the restricted availability of binaural cues by the current speech processing strategy. The current speech processing strategy does not preserve fine structure ITDs, although localisation performance of normal-hearing listeners is strongly dominated by such cues for localising sounds containing low frequencies. Although the ITDs in the envelopes are presented by the CI processors, this provides rather unreliable cues for spatial hearing (van Hoesel, 2004). Moreover, it has been demonstrated that, as with normal-hearing listeners, bilateral CI users assign less weight to ITDs in the envelope (Grantham et al., 2007; Seeber and Fastl, 2008). The independent processing of sounds between ears can also distort binaural cues. Although the speech processor in the DSPB implant processes the sounds from both ears synchronously in time, it still processes the sound from each ear independently in two signal processing lines. The ILD experienced with two independent processors is more likely to be still apparent with the DSPB implants.

10.3 Implications for spatial hearing

The current research shows that the DSPB implant seems to provide better measured and self-rated localisation abilities than unilateral implantation. These abilities of subjects with the DSPB implants seem to be broadly consistent with the existing literature on conventional bilateral CIs. Such findings may potentially have important implications for clinical populations. Given that the current policy in the UK is to offer only a single CI for severely-profoundly deaf adults, the DSPB implant might be considered an alternative option for deaf adults. Since the DSPB implant is designed to have two electrodes driven by a single internal receiver and a single speech processor, the cost of such an implant is significantly lower than for two separate implants. The DSPB implant stimulates both ears for the cost of one implant. This also ensures that the ear with the best postoperative performance is implanted, as with the conventional bilateral CIs. Unlike the conventional bilateral CIs, however, the DSPB implant does not provide users with a back-up in case of device failure.

As anticipated, the DSPB implant seems to provide no additional advantage for spatial hearing over conventional bilateral CIs. The insensitivity of the DSPB implant subjects to ITDs is not surprising, given that the fine-structure ITDs in the signal are still not preserved in the current CI strategies. Envelope ITDs also did not seem to contribute to the performance of the DSPB implant subjects, since their localisation performance did not deteriorate when the rise time of the signal was made more gradual. Given that the DSPB implant processes the sound from each ear independently in two signal processing lines, it seems that the distorted ILDs experienced with the conventional bilateral CIs would still be the same for the DSPB implants. Although Verhaert et al. (2012) suggest that the DSPB implant might offer better accuracy for binaural cues, since the random ITDs and ILDs experienced with the two separate CIs are reduced, the current study shows no spatial advantages with the DSPB implants than conventional bilateral CIs. This was expected, since the timing in the signal envelope experienced with the conventional bilateral CIs is replaced by a fixed timing in the DSPB implants (15 µs), and the processing is still independent between ears.

Practically speaking, the measured and self-rated localisation abilities with the DSPB implant seem better than that provided by a single CI. Localisation performance with the DSPB implant is broadly consistent with the existing studies on conventional bilateral CIs, in which both groups of implanted subjects still perform worse than normal-hearing listeners. Further research is required with the aims to explore how to optimise binaural hearing sensitivity through electrical stimulation and to bridge the gap in performance between bilateral CI users and normal-hearing listeners.

10.4 Conclusions

Limited to the small number of subjects tested in the current project and the complexity of their characteristics, the conclusions of this thesis are as follows:

- An individual's overall error score for horizontal sound-source localisation can appear to be better than the conventional statistical account of guessing behaviour, which assumes unbiased guessing, through *biased* guessing.

- Adults implanted with either bilateral DSPB or unilateral CIs do not perform as well as normal-hearing adults for horizontal sound-source localisation, speech perception in noise and self-reported assessment.

- Some unilateral CI adults can show overall localisation error scores on a simple sound-source identification task that are better than expected from guessing (unbiased and biased), despite level roves of ±4 dB and ±8 dB. This may indicate that the level rove used in this project as well as in similar previous studies is not sufficiently large to guard against CI users using monaural cues.

- The DSPB implants seem to provide advantages for horizontal sound-source localisation over unilateral CIs for the majority of postlingually deaf DSPB adults.

- There is no evidence that the DSPB implants offer any advantages over conventional bilateral CIs in terms of horizontal sound-source localisation.

- There was a strong trend for the DSPB implant to be associated with better self-rated spatial hearing ability than unilateral CIs, although this was not statistically significant. In particular, the DSPB implant subjects tended to rate their localisation ability in everyday life better than unilateral CI subjects.

The results for speech perception in noise were otherwise inconclusive.

10.5 Future research directions

It is possible that the current research project was underpowered to detect significant spatial hearing benefits with the DSPB implants, due to the small sample size. The current study tested only a group of eight DSPB implant subjects, in which a considerable variation in their characteristics was apparent between subjects. As pointed out previously, it was not possible to recruit the intended number of subjects. A larger study with many more DSPB implant subjects might be able to detect a difference in performance between stimuli and among groups. Data from more DSPB implant adults is therefore required to draw solid conclusions about the spatial hearing benefits and the possible effect of factors such as duration of CI experience.

Another limitation of this research project comes from the fact that a non-randomised research design was used in this project. The outcomes of the DSPB implant group were compared with a separate group of subjects with unilateral CIs. Although such a research design can provide some evidence about the effectiveness of bilateral implantation, the results reported in the current research project are at risk of selection bias. There were confounding differences between the DSPB implant and unilateral CI groups, other than the number of implants. For example, the DSPB implant group had a longer duration of deafness, shorter CI experience and higher (i.e. worse) clinical speech score in noise. While the bilateral CI subjects implanted with the DSPB implant using the Main Peak Interleaved Sampling (MPIS) strategy, the unilateral CI subjects were implanted with different types of CI and with different speech processing strategies. Thus, it is not clear to what extent the differences in performance between the DSPB implant and unilateral CI groups was not due to the existing differences between the groups. To control all the confounding variables between groups, one would need to conduct a randomised research design in which only the effect of the number of implants can be assessed.

10.5.1 Progress in spatial hearing abilities with the DSPB implants

The current thesis described spatial hearing abilities with the DSPB implant subjects that were measured at 4-18 months post-implantation. A further goal of this research is to explore whether these abilities can be improved through additional everyday listening experience. As shown in Chapter 7 and Chapter 8 of this thesis, a large variation was observed in the performance of the DSPB implant subjects, and it is possible that some subjects needed more time to master their performance. Moreover, the lack of significant SRM by the DSPB implant subjects might be postulated to be due to the short duration of bilateral experience. In an attempt to measure changes in spatial hearing abilities with time, all the DSPB implant subjects will be retested at least 18 months post-implantation.

10.5.2 Spatial hearing with synchronised stimulation

The current study shows that the way synchronised stimulation is implemented in the DSPB implants seems insufficient to provide better binaural hearing ability than conventional bilateral CIs. Since there were many factors that might have led to underestimating the effect of the synchronised stimulation, it would be helpful if the DSPB implant subjects could also be tested when the stimulation across two ears is not synchronised. Comparing the performance of the same DSPB implant user when the stimulation is synchronised and not synchronised would help to accurately represent the benefit of synchronised stimulation. It is worth noting that Dr. Brad Backus, who is in charge of research projects in the UK at Neurelec, was contacted to check the possibility of setting the stimulation across ears as unsynchronised; however, it seems that this cannot be done. It would be very helpful if this could be done since any difference in performance shown when the stimulation is synchronised or not synchronised would solely reflect the actual effect of stimulation. Additionally, the research group attempted to measure the output of the DSPB implant-in-a-box, which is a CI receiver that is connected to resistors rather than implanted in a real subject. However, the DSPB implant-in-a-box was not available during the time span of this project. It would be interesting to test the DSPB implant-in-a-box when it is available, as this would help to investigate the effect of synchronised stimulation.

10.5.3 Spatial hearing with cochlear implantation in everyday life

Although the finding of the current study that most DSPB implant subjects could localise at better than chance range of guessing is promising, this ability does not necessarily translate into usable localisation ability in everyday life. Given that the ILDs are more likely to dominate the localisation performance with bilateral CI users and that they lose the redundancy to rely on other cues for localisation, it might be possible that, with multiple sound sources, the ILDs would provide unreliable cues, leading to considerable difficulty in real-world situations. In support of that is the lack of correlation between the measured and self-rated spatial ability with the DSPB implant users (Section 9.3.2). It is possible that the self-rated ability of DSPB implants would correlate with the measured ability if the tests were conducted in an environment that more closely represents real-world situations. Furthermore, it has been suggested by Shub et al. (2008) that when the subjects were instructed to identify the apparent location of a sound source (as with the current study), they were asked to use all available information to get the correct locations, whereas asking them to report the perceived location of the source would probably have measured localisation ability in more realistic situations. When the ''good'' unilateral CI subjects in the current project were asked to report the perceived location of the sound source rather than identifying the correct loudspeaker, they seemed to perceive the location of every sound source as coming from different directions (Section 6.4.2). Further research could assess the localisation and speech perception of DSPB implant users in real-world situations such as noisy and reverberant environments.

10.5.4 Comparison with unilateral and bilateral CIs

In the current project, the spatial hearing ability of unilaterally implanted subjects was assessed. The reason for this was to investigate whether the DSPB implant offers spatial advantages over a unilateral CI. Although the results showed a better, not necessarily statistically significant, performance for the DSPB implant group for localisation and self-rated measures, data from a large group of unilaterally implanted subjects is required. A larger study of unilateral CI users would also help to determine the possible predictors of good localisation ability with unilateral CIs. Additionally, since the results presented in Chapter 6 indicate that some unilaterally implanted subjects can show overall localisation error scores at better than chance range of guessing, it would be interesting to investigate in more depth what exact cues they might be using. From a first attempt to investigate what cues they were using, it seems more likely that their localisation performance was based, at least partly, on monaural level cues. Further research on localisation ability of unilateral CI users with different stimuli paradigms is required to investigate in more depth the exact cues that good unilateral CI performers are using to localise sounds.

The spatial hearing abilities of the DSPB implant subjects should also be compared with those of conventional bilateral CI users. The current project showed indirect evidence that localisation performance of the DSPB implant subjects was broadly comparable to that of those with conventional bilateral CIs who have been tested previously in our lab using a similar set-up. However, those subjects were not matched on factors such as age at implantation and duration of experience.

In summary, spatial hearing abilities with the DSPB implant were assessed in this research project in terms of sound-source localisation, speech perception in noise and self-reported measures. Based on the limited number of subjects tested in the current study, the results showed that some spatial hearing abilities can be accessed through the DSPB implant. This research project also provides evidence that a DSPB implant can offer spatial advantages over unilateral implantation for localisation. Although the DSPB implant is designed to provide synchronised stimulation in both ears, the results showed that this system of implantation does not seem to provide any additional advantages for localisation over conventional bilateral CIs, where two independent processors were used.

Appendices

Appendix A. Questionnaires

Appendix A.1: Listening effort scale

Rate your listening effort

How much effort did this exercise require from you?

1 EXTREME EFFORT
2 A GREAT DEAL OF EFFORT
3 QUITE A LOT OF EFFORT
4 SOME EFFORT
5 A LITTLE EFFORT
6 NOT MUCH EFFORT
7 NO EFFORT AT ALL

Appendix A.2: The Speech, Spatial and Qualities of Hearing Scale (SSQ)

1. You are talking with one other person and there is a TV on in the same room. Without turning the TV down, can you follow what the person you're talking to says?	*Not at all* *Perfectly* 0 1 2 3 4 5 6 7 8 9 10	Not applicable ☐

Speech 1	You are talking with one other person and there is a TV on in the same room. Without turning the TV down, can you follow what the person you're talking to says?	Not at all-perfectly
Speech 2	You are talking with one other person in a quiet, carpeted lounge-room. Can you follow what the other person says?	Not at all-perfectly
Speech 3	You are in a group of about five people, sitting round a table. It is an otherwise quiet place. You can see everyone else in the group. Can you follow the conversation?	Not at all-perfectly
Speech 4	You are in a group of about five people in a busy restaurant. You can see everyone else in the group. Can you follow the conversation?	Not at all-perfectly
Speech 5	You are talking with one other person. There is continuous background noise, such as a fan or running water. Can you follow what the person says?	Not at all-perfectly
Speech 6	You are in a group of about five people in a busy restaurant. You *cannot* see everyone else in the group. Can you follow the conversation?	Not at all-perfectly
Speech 7	You are talking to someone in a place where there are a lot of echoes, such as a church or railway terminus building. Can you follow what the other person says?	Not at all-perfectly
Speech 8	Can you have a conversation with someone when another person is	Not at all-perfectly

	speaking whose voice is the same pitch as the person you're talking to?	
Speech 9	Can you have a conversation with someone when another person is speaking whose voice is different in pitch from the person you're talking to?	Not at all-perfectly
Speech 10	You are listening to someone talking to you, while at the same time trying to follow the news on TV. Can you follow what both people are saying?	Not at all-perfectly
Speech 11	You are in conversation with one person in a room where there are many other people talking. Can you follow what the person you are talking to is saying?	Not at all-perfectly
Speech 12	You are with a group and the conversation switches from one person to another. Can you easily follow the conversation without missing the start of what each new speaker is saying?	Not at all-perfectly
Speech 13	Can you easily have a conversation on the telephone?	Not at all-perfectly
Speech 14	You are listening to someone on the telephone and someone next to you starts talking. Can you follow what's being said by both speakers?	Not at all-perfectly
Spatial 1	You are outdoors in an unfamiliar place. You hear someone using a lawnmower. You can't see where they are. Can you tell right away where the sound is coming from?	Not at all-perfectly
Spatial 2	You are sitting around a table or at a meeting with several people. You can't see everyone. Can you tell where any person is as soon as	Not at all-perfectly

	they start speaking?	
Spatial 3	You are sitting in between two people. One of them starts to speak. Can you tell right away whether it is the person on your left or your right, without having to look?	Not at all-perfectly
Spatial 4	You are in an unfamiliar house. It is quiet. You hear a door slam. Can you tell right away where that sound came from?	Not at all-perfectly
Spatial 5	You are in the stairwell of a building with floors above and below you. You can hear sounds from another floor. Can you readily tell where the sound is coming from?	Not at all-perfectly
Spatial 6	You are outside. A dog barks loudly. Can you tell immediately where it is, without having to look?	Not at all-perfectly
Spatial 7	You are standing on the footpath of a busy street. Can you hear right away which direction a bus or truck is coming from before you see it?	Not at all-perfectly
Spatial 8	In the street, can you tell how far away someone is, from the sound of their voice or footsteps?	Not at all-perfectly
Spatial 9	Can you tell how far away a bus or a truck is, from the sound?	Not at all-perfectly
Spatial 10	Can you tell from the sound which direction a bus or truck is moving, for example, from your left to your right or right to left?	Not at all-perfectly
Spatial 11	Can you tell from the sound of their voice or footsteps which direction a person is moving, for example, from your left to your	Not at all-perfectly

	right or right to left?	
Spatial 12	Can you tell from their voice or footsteps whether the person is coming towards you or going away?	Not at all-perfectly
Spatial 13	Can you tell from the sound whether a bus or truck is coming towards you or going away?	Not at all-perfectly
Spatial 14	Do the sounds of things you are able to hear seem to be inside your head rather than out there in the world?	Inside my head-Out there
Spatial 15	Do the sounds of people or things you hear, but cannot see at first, turn out to be closer than expected when you do see them?	Much closer-Not closer
Spatial 16	Do the sounds of people or things you hear, but cannot see at first, turn out to be further away than expected when you do see them?	Much further-Not further
Spatial 17	Do you have the impression of sounds being exactly where you would expect them to be?	Not at all-perfectly
Qualities 1	Think of when you hear two things at once, for example, water running into a basin and, at the same time, a radio playing. Do you have the impression of these as sounding separate from each other?	Not at all-perfectly
Qualities 2	When you hear more than one sound at a time, do you have the impression that it seems like a single jumbled sound?	Jumbled-Not jumbled
Qualities 3	You are in a room and there is music on the radio. Someone else in the room is talking. Can you hear the voice as something	Not at all-perfectly

	separate from the music?	
Qualities 4	Do you find it easy to recognise different people you know by the sound of each one’s voice?	Not at all-perfectly
Qualities 5	Do you find it easy to distinguish different pieces of music that you are familiar with?	Not at all-perfectly
Qualities 6	Can you tell the difference between different sounds, for example, a car versus a bus; water boiling in a pot versus food cooking in a frying plan?	Not at all-perfectly
Qualities 7	When you listen to music, can you make out which instruments are playing?	Not at all-perfectly
Qualities 8	When you listen to music, does it sound clear and natural?	Not at all-perfectly
Qualities 9	Do everyday sounds that you can hear easily seem clear to you (not blurred)?	Not at all-perfectly
Qualities 10	Do other people’s voices sound clear and natural?	Not at all-perfectly
Qualities 11	Do everyday sounds that you hear seem to have an artificial or unnatural quality?	Unnatural-Natural
Qualities 12	Does your own voice sound natural to you?	Not at all-perfectly
Qualities 13	Can you easily judge another person’s mood from the sound of their voice?	Not at all-perfectly
Qualities 14	Do you have to concentrate very much when listening to someone or something?	Concentrate hard-Not need to concentrate
Qualities 15	If you turn one cochlear implant off, and do not adjust the other, does everything sound naturally	Too quiet-Not too quiet

	quiet? (not relevant for unaided condition)	
Qualities 16	When you are the driver in a car can you easily hear what someone is saying who is sitting alongside you?	Not at all-perfectly
Qualities 17	When you are a passenger can you easily hear what the driver is saying sitting alongside you?	Not at all-perfectly
Qualities 18	Do you have to put in a lot of effort to hear what is being said in conversation with others?	Lot of effort-No effort
Qualities 19	Can you easily ignore other sounds when trying to listen to something?	Not easily ignore-Easily ignore

Appendix A.3: Health Questionnaire

Participant Identification Number for this trial:

A) *Personal details:*

1	Your age	
2	Your sex	
3	Your first language	
4	Your daily communication language	

B) Ears and Hearing:

		Yes	**No**
1	Do you think you have difficulty hearing in either ear?		
2	Do you wear or have ever been advised to wear a hearing aid?		
3	Does your hearing fluctuate other than when you have a cold?		
4	Have you ever had surgery to either ear?		
5	Do you suffer from tinnitus (noise, such as ringing, whistling or		
6	Do you have trouble with your balance or do you get vertigo?		
7	Are you experiencing or have you recently had any of the following: Pain in either ear Discharge (running) from either ear Inflammation in either ear A blockage in either ear An injury to either ear A cold or flu		
8	Are you currently on medication or have been recently taking		
9	Have you ever had a head injury requiring a stay in hospital?		
10	Have you been exposed to loud noise in the past 2 days?		

C) History of listening tests:

		Yes	**No**
1	Do you have any previous experience with listening or hearing		
2	Do you have any previous experience with localisation tests in		
3	Do you have any previous experience with speech recognition		

Appendix B. Results of speech perception with normal-hearing listeners

Appendix B.1: SRTs across different speech materials

The following experiment was conducted by the researcher with the aim to assess speech perception in noise with Bamford-Kowal-Bench (BKB) and Automated Toy Test (ATT) at different noise locations. Testing was approved by the Institute of Sound and Vibration Research Human Experimentation Safety and Ethics Committee (reference number: 1241).

Participants

Thirty normal-hearing adults were recruited from the student population at the University of Southampton (23 females and 7 males); all were native speakers of English. Participants all have normal hearing and ranged in age from 18 to 30 years. All participants completed all testing on the required conditions in a single session lasting for approximately one hour.

Setup

Testing was performed in a double-walled sound booth with carpeting. The participant was seated in a chair, with three loudspeakers positioned at 0°, +90° and -90° azimuths. All loudspeakers were 1 m from the approximate centre of the head and were at ear height of 1.2 m which is the approximate height of the ears of a typical adult when seated in a chair. Loudspeakers were connected to a Laptop with custom-made MATLAB software and an external Creative Extigy sound-card via a small switch box. The level of the stimulus was controlled through an Ariston AX-910 amplifier. All hardware was located in the booth where the participant was tested.

Stimuli

Two speech materials were used: BKB sentences and ATT words presented in a steady white noise that had the same long-term average spectrum of the sentences or words. Noise was presented nominally at a level 55 dB SPL (A-weighted). The level of sentences or words was varied adaptively using a standard adaptive procedure (Levitt, 1971). All stimuli were generated digitally at a sampling rate of 44.1 kHz that was used also for localisation task. The MATLAB code was written by Dr Daniel Rowan.

A sound level meter (Brüel & Kjaer 2260) and microphone (Brüel & Kjaer 4189) were used to calibrate the output of each of the three loudspeakers. The sound level meter was positioned with the microphone facing forwards. The level of noise was adjusted via the amplifier volume control until the sound level meter reached 55 dB (A).

Procedure

During testing, participants were seated in the centre of the array, facing the frontal loudspeaker. Participants were asked to keep their heads as still as possible during the test. Their head movements were also monitored visually by the tester to minimise head movement.

Sentences/words were always presented from a loudspeaker placed directly in front of the participant at 0° azimuth. The noise was played from one of two locations: front (0º, the same loudspeaker as the digits), side either at +90º or -90º of the participant (chosen at random). Each run of trials contained presenting noise from one location, so that the location of noise either at front or side was fixed during the run. Two runs, once at each noise location either at front or side, was included within a single block. Four blocks were administered for normal-hearing listeners. A set of 8 runs were completed by normal-hearing listeners for each speech material. In total, 16 measurements were obtained for each participant (2 speech materials x 2 noise location x 4 repetitions). The order of speech materials was randomised for each participant as well the order of noise location within each block, using the Latin square design.

Participants were instructed to respond by repeating the sentences or words aloud and to ignore the noise as much as possible. They were encouraged to guess when they were not sure of what they had heard. For BKB testing, participant's responses were considered correct if two or more key words in each sentence were repeated correctly, and recorded by the experimenter. Loose scoring method was used so that any error, in tense and plurals for instance, were ignored as long as the word root was correct. No repeats were allowed and no feedback was given. Before starting testing, practice trials were presented for each participant to familiarise the participant with the task.

A speech reception threshold (SRT) was determined for each run. The adaptive procedure was used to estimate SRTs. The level of sentences/words was initially presented at 70 dB SPL and continued to decrease until the participant responded incorrectly. Subsequent levels were determined following a two-down/one-up adaptive rule with a theoretical asymptote of 71%. The step size used was, respectively, 8 dB and 4 dB for the first and second reversals, and was 2 dB for the remaining eight reversals. The SRT was calculated based on the average level presented on the last eight reversals.

A two-down/one-up adaptive rule targeting a 71% correct criterion was used. The step size used was 5dB for the first three reversals and 2dB for the following six. The SRT was calculated based on the average level presented on the last eight reversals. Four runs were administered for each noise configuration in each listening test. To minimise any order effect, the order of noise configuration was randomised using across participants.

Results

Figure 1 shows the SRTs, averaged across all four repetitions, obtained from normal-hearing subjects for different noise locations for BKB and ATT from the current study and Triplet Digit Test (TDT) from the study presented in Chapter 5. Lower SRTs reflect an ability to tolerate more adverse SNR (i.e. better performance).

The figure shows that the SRT was generally lower for the TDT than for BKB and ATT speech materials for both noise locations. The difference in SRTs between TDT and ATT and BKB can be attributed to the nature of the speech test; TDT and ATT are closed set tests whereas BKB is an open set test. Factors attributed to the difference between TDT and ATT are not clear. Although SRTs differed between these three measures, the SRTs improved when the noise was spatially separated from the speech for all speech materials. Similar spatial release from masking was obtained for all the speech materials, as shown in Figure 5.4. It should be noted that the focus of study was only to compare SRM with different speech materials, and it is beyond the scope to discuss the possible differences in SRTs between the different tests.

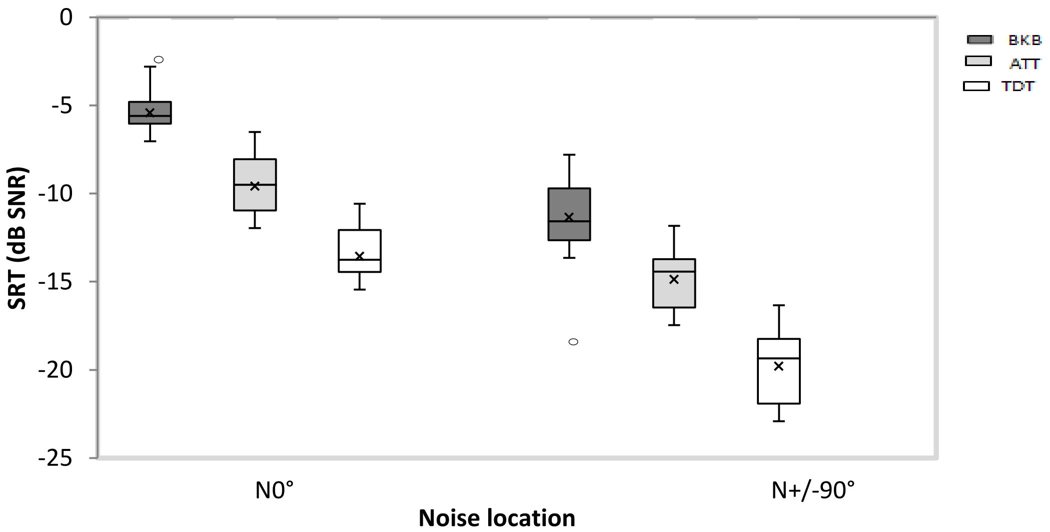


Figure 1: Speech reception thresholds (SRTs), in dB SNR, for the different noise locations (N0° noise at front; NS+/-90° noise at side either 90° to the right or to the left) across different speech materials BKB and ATT (from the current study) and TDT (from the study presented in Chapter 5).

Appendix C. Results of localisation ability with unilateral CIs

Appendix C.1: Ethical approval for unilateral CI study

NHS
Health Research Authority

NRES Committee South Central - Oxford A
Bristol Research Ethics Committee Centre
Whitefriars
Level 3 Block B
Lewins Mead
Bristol
BS1 2NT

Tel: 0117 342 1331
Fax: 0117 342 0445

10 January 2013

Mrs Noura Alothman
Institute of Sound and Vibration Research (ISVR), Building 13, Room 4076
University of Southampton
Southampton
SO17 1BJ

Dear Mrs Alothman

Study title:	**Binaural hearing in adults with Digisonic® SP Binaural cochlear implants**
REC reference:	**12/SC/0421**
Protocol number:	**ISVR S&E approval# 2915**
Amendment number:	**SA2**
Amendment date:	**13 December 2012**
IRAS project ID:	**108112**

The above amendment was reviewed by the Sub-Committee in correspondence.

Ethical opinion

The Committee Members approved the changes :

Additional aim to establish the best performance that would be expected from unilateral cochlear implant adults(adults with a single cochlear implant) and to determine whether adults with Digisonic® SP Binaural cochlear implants still perform better (i.e. examine whether the performance of Digisonic® SP Binaural cochlear implants is better than the performance of unilateral cochlear implant adults who are expected to perform relatively well)(Q A10). Therefore, unilateral cochlear implant adults in the South of England Cochlear Implant Centre (SOECIC) at University of Southampton will be invited to participate in the study. They will be asked to attend only one session (Q A 21)to test them on: 1) Localisation: using the same procedure that has been explained in our protocol (5th October 2012-Version 2). 2) Speech recognition in noise: using the same procedure that has been explained in our protocol (5th October 2012-Version 2) except that unilateral cochlear implant adults will be tested in three conditions (rather than 7 conditions)(Q A13). They are required to meet the following criteria (Q A17-1): * Adult cochlear implant user aged 18- 55 years. * Fitted with a single cochlear implant. * Full time implants users. * Deaf for less than 10 years before implantation. * No cognitive or learning difficulties. * Have at least one year experience with implants. * Have speech score in noise of +5 dB SNR (speech to noise ratio) or less. * Have profound hearing loss in the un-implanted ear. * Have not wear hearing aid in the un-implanted ear since they are implanted. * Have sufficient English to understand informed consent form. Exclusion criteria are (Q A17-2): * Older adults: to make sure the results are not confused by the age-related changes in the central nervous processing. * Adults with cognitive or learning difficulties: this will allow to purely assess binaural hearing ability, and not to be confused by cognitive difficulties affecting the results. * Adults with speech scores in noise exceeding +5 dB SNR: to make sure we are involving adults who are most likely to perform well. * Adults with residual hearing in the un-implanted ear: having residual hearing may help unilateral cochlear implant adults and then can affect the results. A sample size of 17 participants will be recruited. It was decided to invite 40 unilateral cochlear implant adults, assumed that 40% of them are not willing to participate, and 10% might drop out during the study (Q A59 and A60). Each participant will be paid £20 for participating (Q A46).

The Committee Members stated that there is a typographical error in the PIS under the heading "What will happen to me if I take part" "Your will also be paid…" Should be "You…"

The members of the Committee taking part in the review gave a favourable ethical opinion of the amendment on the basis described in the notice of amendment form and supporting documentation.

Approved documents

The documents reviewed and approved at the meeting were:

Document	Version	Date
Evidence for ISVR and RGO approvals		
List of changes		
Participant Consent Form: Informed Consent Form for Unilateral Implants	1	28 November 2012
Participant Information Sheet: Information Sheet for unilateralimplants	1	28 November 2012
Participant Information Sheet: Invitation Letter for Unilateral Implants	1	28 November 2012
Notice of Substantial Amendment (non-CTIMPs)	SA2	13 December 2012
Covering Letter		

Membership of the Committee

The members of the Committee who took part in the review are listed on the attached sheet.

R&D approval

All investigators and research collaborators in the NHS should notify the R&D office for the relevant NHS care organisation of this amendment and check whether it affects R&D approval of the research.

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

We are pleased to welcome researchers and R & D staff at our NRES committee members' training days – see details at http://www.hra.nhs.uk/hra-training/

12/SC/0421:	**Please quote this number on all correspondence**

Yours sincerely

Pp Dr Karen Melham
Chair

E-mail: nrescommittee.southcentral-oxforda@nhs.net

Enclosures: *List of names and professions of members who took part in the review*

Copy to: Martina Prude, University of Southampton
mad4@soton.ac.uk

Appendix C.2: Ethical approval for changing the inclusion criteria of the unilateral CI subjects

NHS
Health Research Authority

NRES Committee South Central - Oxford A
Bristol Research Ethics Committee Centre
Whitefriars
Level 3 Block B
Lewins Mead
Bristol
BS1 2NT

Tel: 0117 342 1331
Fax: 0117 342 0445

14 March 2013

Mrs Noura Alothman
Institute of Sound and Vibration Research (ISVR),
Building 13, Room 4076
University of Southampton
Southampton
SO17 1BJ

Dear Mrs Alothman

Study title:	**Binaural hearing in adults with Digisonic® SP Binaural cochlear implants**
REC reference:	**12/SC/0421**
Protocol number:	**ISVR S&E approval# 2915**
Amendment number:	**SA3**
Amendment date:	**15 February 2013**
IRAS project ID:	**108112**

The above amendment was reviewed at the meeting of the Sub-Committee held in correspondence.

Ethical opinion

The Committee Members approved the following changes:

1) Inclusion criteria for patients with unilateral cochlear implants extended to:
   a. Adult cochlear implant user aged 18- 65 years. (May be extendedto 70 years).
   b. Fitted with a single cochlear implant.
   c. Full time implants users.
   d. Profoundly deaf for less than 10 years before implantation.
   e. No cognitive or learning difficulties. • Have at least 6 months experience with implants.
   f. Have speech score in noise of maximum +8 dB SNR (speech to noise ratio) or less. Will increase SNR 0.5 dB gradually starting from +5.5 dB to +8 dB until sample size is achieved.
   g. Have profound hearing loss in the un-implanted ear.
   h. Have not wear hearing aid in the un-implanted ear since they are implanted.
   i. Have sufficient English to understand informed consent form.

Health Research Authority

2) Obtain the following information from the unilateral cochlear implant patient's medical file (A11):
    a. Most recent speech recognition thresholds in noise post implantation.
    b. Hearing thresholds in the un-implanted ear.
    c. How long the patient used hearing aids before implants
    d. Age at implantation, length of deafness and duration of binaural experience

3) Re-send reminder letters for participants and for those with Digisonic® SP Binaural cochlear implants.

The members of the Committee taking part in the review gave a favourable ethical opinion of the amendment on the basis described in the notice of amendment form and supporting documentation.

Approved documents

The documents reviewed and approved at the meeting were:

Document	Version	Date
Research Governance Approvals		18 February 2013
Reminder letter 2 for patients with Unilateral Cochlear Implants	1	06 February 2013
Reminder letter 1 for patients with Digisonic Binaural Cochlear Implants	1	06 February 2013
Summary of Changes		
Notice of Substantial Amendment (non-CTIMPs)	SA3	15 February 2013
Covering Letter		

Membership of the Committee

The members of the Committee who took part in the review are listed on the attached sheet.

R&D approval

All investigators and research collaborators in the NHS should notify the R&D office for the relevant NHS care organisation of this amendment and check whether it affects R&D approval of the research.

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

We are pleased to welcome researchers and R & D staff at our NRES committee members' training days – see details at http://www.hra.nhs.uk/hra-training/

12/SC/0421:	**Please quote this number on all correspondence**

NHS
Health Research Authority

Yours sincerely

p.p. T. Fairman

Dr Karen Melham
Chair

E-mail: nrescommittee.southcentral-oxforda@nhs.net

Enclosures:	*List of names and professions of members who took part in the review*
Copy to:	*Martina Prude, University of Southampton*

Appendix C.3: Mean absolute error scores of unilateral CI subjects

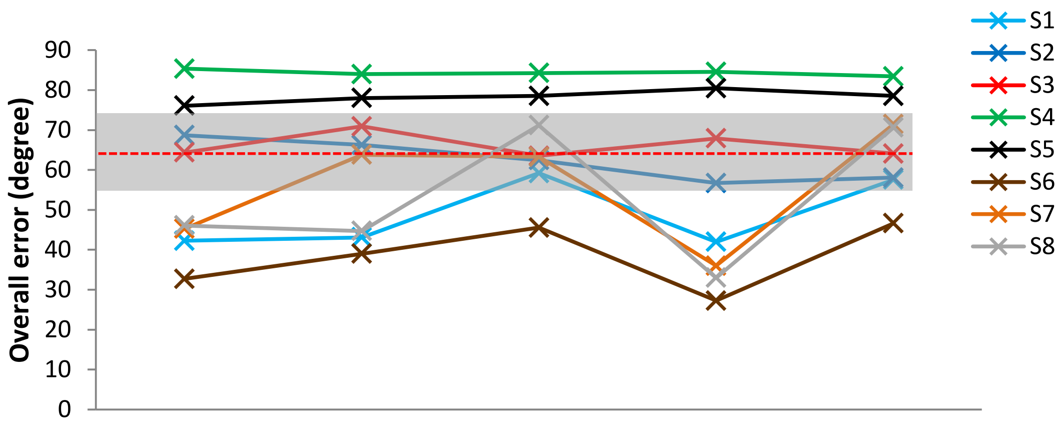


Figure 1: Individual scores of mean absolute error, in degrees, of the eight unilaterally implanted subjects and for each stimulus, averaged across the two repetitions: speech, broadband noise (BBN), low-pass noise (LPN), high-pass noise (HPN) and high-pass noise burst (HPN-burst). Each line represents a separate, numbered listener. The horizontal red line shows the chance level expected from unbiased guessing with the grey area indicating the chance range of unbiased guessing (see Section 4.2.2.1).

Appendix C.4: Overall localisation error scores with each of the two replications

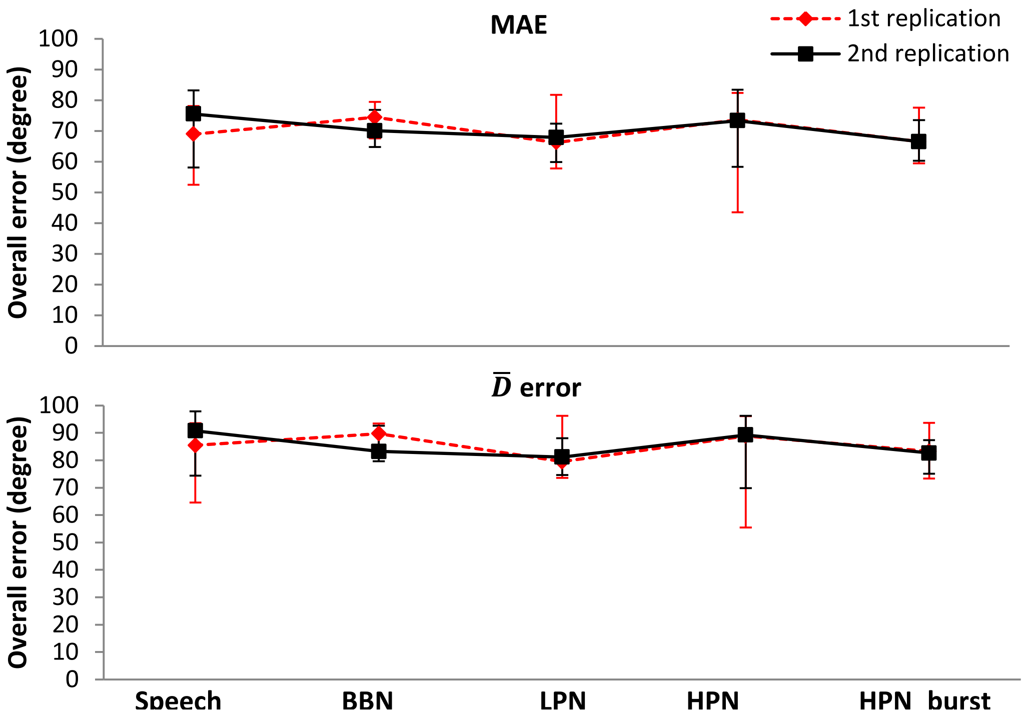


Figure 1: Median overall error with each of the two repetitions for unilateral CI subjects. Error bars represent the upper and lower quartiles

Appendix C.5: Localisation data of unilateral CI subjects for low-pass noise and high-pass noise burst stimuli.

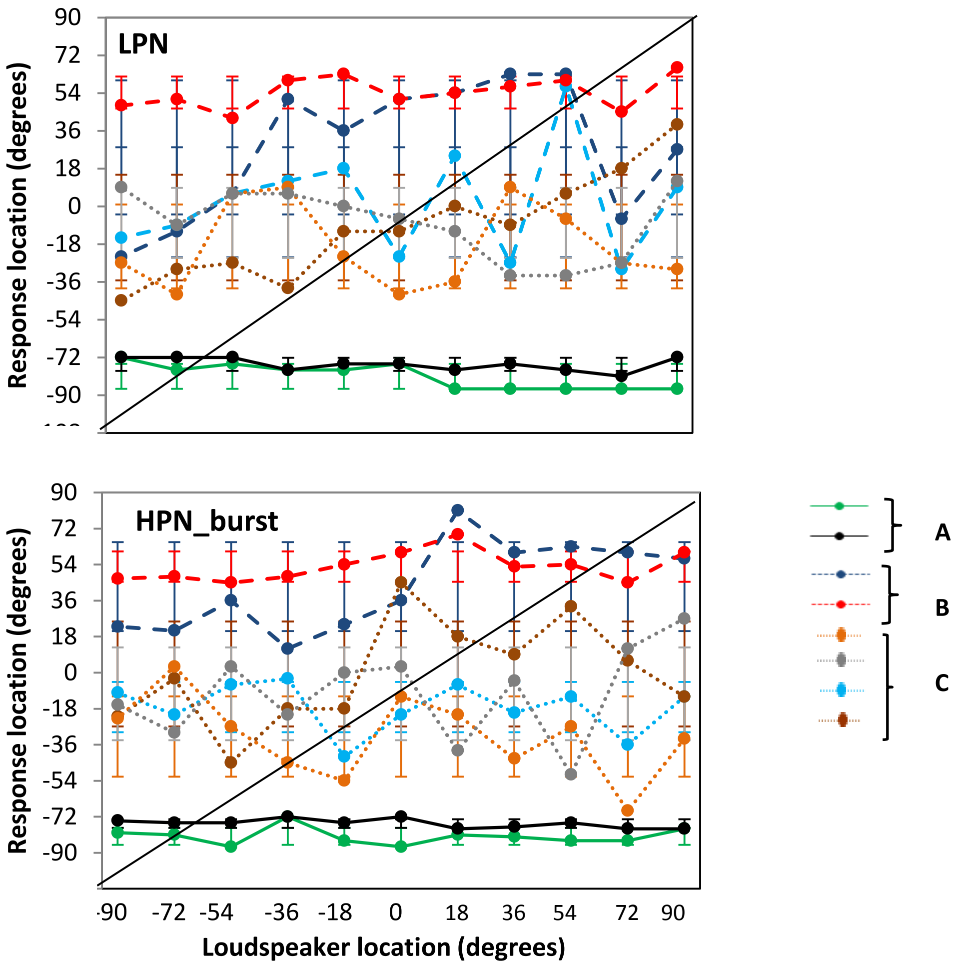


Figure 1: Sound localisation performance for unilateral cochlear implant subjects of category A, B and C while listening to different stimuli. Subjects were grouped according to their performance (see Section 6.3.1). Each data point represents the mean response given by a subject for each loudspeaker location. The error bar indicates the standard deviation across the 6 responses obtained at each loudspeaker location. The diagonal line represents the perfect localisation performance.

Appendix D. Results of localisation ability with synchronised bilateral CIs

Appendix D.1: Ethical approval for the synchronised bilateral CIs study

NHS
Health Research Authority
NRES Committee South Central - Oxford A
Bristol Research Ethics Committee Centre
Whitefriars
Level 3 Block B
Lewins Mead
Bristol
BS1 2NT

Telephone: 01173421331
Facsimile: 01173420445

25 September 2012

Mrs Noura Alothman
Institute of Sound and Vibration Research (ISVR), Building 13, Room 4076
University of Southampton
Southampton
SO17 1BJ

Dear Mrs Alothman

Study title:	**Binaural hearing in adults with Digisonic® SP Binaural cochlear implants**
REC reference:	**12/SC/0421**
IRAS Project Number:	**108112**
Protocol number:	**ISVR S&E approval# 2915**

Thank you for your letter of 13 September 2012, responding to the Committee's request for further information on the above research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Alternate Vice-Chair.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised, subject to the conditions specified below.

Ethical review of research sites

NHS sites

The favourable opinion applies to all NHS sites taking part in the study, subject to management permission being obtained from the NHS/HSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" below).

Non-NHS sites

Conditions of the favourable opinion

The favourable opinion is subject to the following conditions being met prior to the start of the study.

<u>Management permission or approval must be obtained from each host organisation prior to the start of the study at the site concerned.</u>

Management permission ("R&D approval") should be sought from all NHS organisations involved in the study in accordance with NHS research governance arrangements.

Guidance on applying for NHS permission for research is available in the Integrated Research Application System or at http://www.rdforum.nhs.uk.

Where a NHS organisation's role in the study is limited to identifying and referring potential participants to research sites ("participant identification centre"), guidance should be sought from the R&D office on the information it requires to give permission for this activity.

For non-NHS sites, site management permission should be obtained in accordance with the procedures of the relevant host organisation.

Sponsors are not required to notify the Committee of approvals from host organisations

It is the responsibility of the sponsor to ensure that all the conditions are complied with before the start of the study or its initiation at a particular site (as applicable).

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	*Version*	*Date*
Covering Letter		04 July 2012
Evidence of insurance or indemnity		29 June 2012
Investigator CV	Noura Alothman	
Investigator CV	Dr Daniel Rowan	
Investigator CV	Dr Helen Cullington	
Letter from Sponsor		29 June 2012
Letter of invitation to participant	2	13 September 2012
Other: Listening Scale	1.0	04 July 2012
Other: Response Slip	1.0	04 July 2012
Other: Reminder Letter	1	13 September 2012
Participant Consent Form: Consent Form	2	13 September 2012
Participant Information Sheet: Participant Information Sheet	2	13 September 2012
Protocol	1.0	04 July 2012
Questionnaire: SSQ Questionnaire		
REC application	108112	04 July 2012
Response to Request for Further Information		13 September 2012

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

After ethical review

Reporting requirements

The attached document *"After ethical review – guidance for researchers"* gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Adding new sites and investigators
- Notification of serious breaches of the protocol
- Progress and safety reports
- Notifying the end of the study

The NRES website also provides guidance on these topics, which is updated in the light of changes in reporting requirements or procedures.

Feedback

You are invited to give your view of the service that you have received from the National Research Ethics Service and the application procedure. If you wish to make your views known please use the feedback form available on the website.

Further information is available at National Research Ethics Service website > After Review

12/SC/0421	**Please quote this number on all correspondence**

With the Committee's best wishes for the success of this project

Yours sincerely

Pp Ms Alison Eden
Alternate Vice-Chair

Email: scsha.oxfordreca@nhs.net

Enclosures: "After ethical review – guidance for researchers" *[SL-AR2]*

Copy to: *Martina Prude, University of Southampton*
mad4@soton.ac.uk

Appendix D.2: Ethical approval from University Hospitals Birmingham Clinical Research Office for the synchronised bilateral CIs study

UNIVERSITY OF BIRMINGHAM **Birmingham Clinical Research Office** University Hospitals Birmingham NHS Foundation Trust

(Nov13)

Notice of No Objection

Project reference: **RRK 4537**

Noura Alothman
PhD Student
Room 4076
Tizard building (13)
Institute of Sound and Vibration Research University of Southampton
SO17 1BJ

Birmingham Clinical Research Office
Education Centre
1st Floor
Queen Elizabeth Hospital Birmingham
Mindelsohn Way
Edgbaston
Birmingham B15 2WB
Tel. 0121 371 4185
Fax 0121 371 4204

Trust Reference RRK4537

Main REC reference: 12/SC/0421

9 November 2012

Dear Ms Alothman,

Binaural hearing in adults with Digisonic® SP Binaural cochlear implants

Thank you for providing details of this study. I understand that the only involvement of UHB in this study is to identify potential participants and to provide them with information about the study. Anyone interested in taking part in the study will contact the Chief Investigator or their research team directly. Participants will not be consented at UHB nor will any study-related procedures be carried out here. On this basis I am happy to confirm there are no objections to the study and you may proceed with it.

If circumstances change, in particular if participants are consented here or any procedures are to be carried out here, then you will need to submit a fresh application for a full review of the study.

Please be sure to inform the R&D office at University Hospitals Birmingham of any amendments to the study.

Sponsorship
University of Southampton has agreed to act as sponsor for this study.

Indemnity arrangements.
You are not indemnified by University Hospital Birmingham against any claims arising out of this study unless you hold a substantive or honorary contract with the Trust. Liability will remain with your employer.

Annual Reports
We may ask you to provide an annual update of progress with this study.

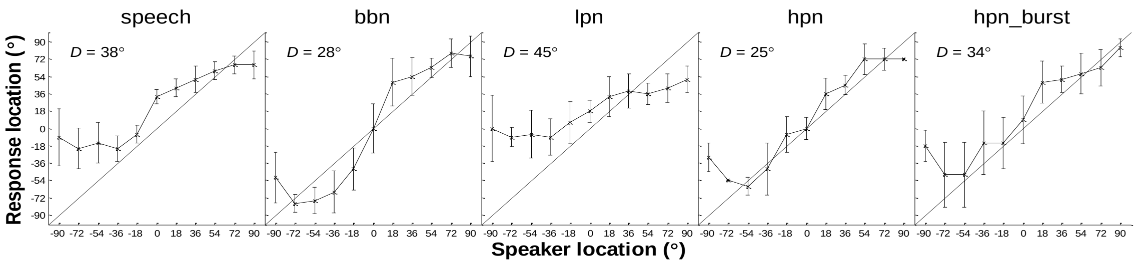
Yours sincerely,

CMcowell
09 November 2012

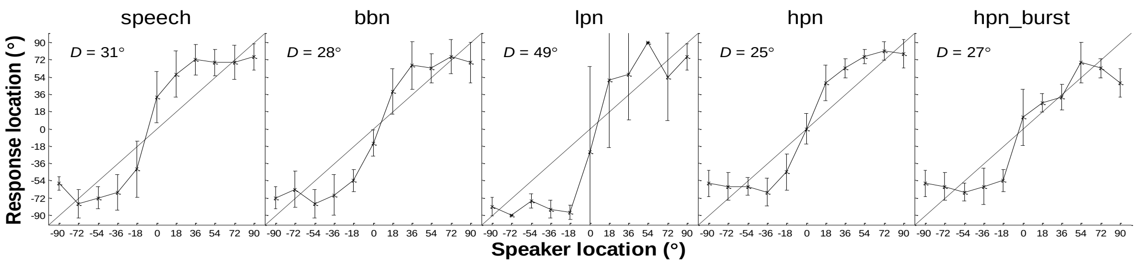
Birmingham Clinical Research Office
Co-directors: Professor Julian Bion & Professor Nick James
Manager: Dr Christopher Counsell
Room 17, Education Centre, Queen Elizabeth Hospital Birmingham, Edgbaston
Birmingham B15 2WB
Tel: 0121 371 4185 *Fax:*tbc *Email:* R&D@uhb.nhs.uk
Website: www.uhb.nhs.uk/research
Projects database: \\nt0351_bdc_0001\R & D\R&D database\distributed database 2002.mdb

Appendix D.3: Localisation data for each of the subjects implanted with the DSPB implants

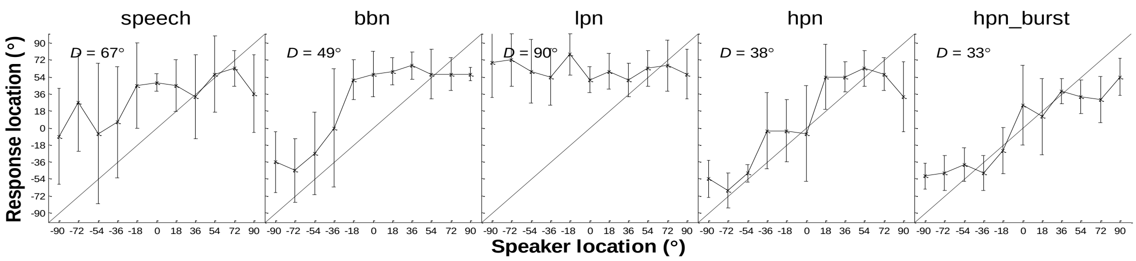
D1



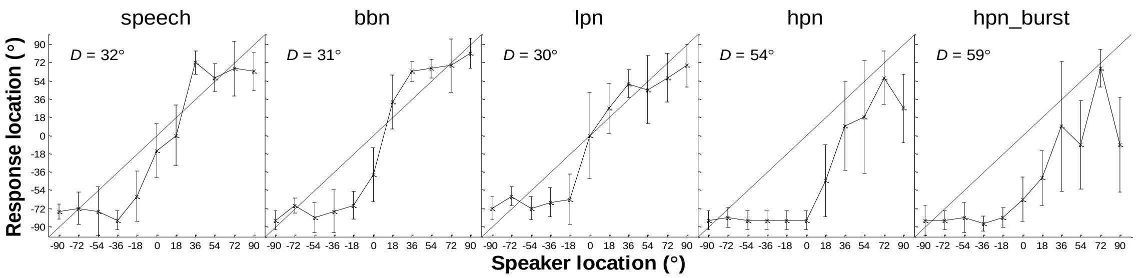
D2



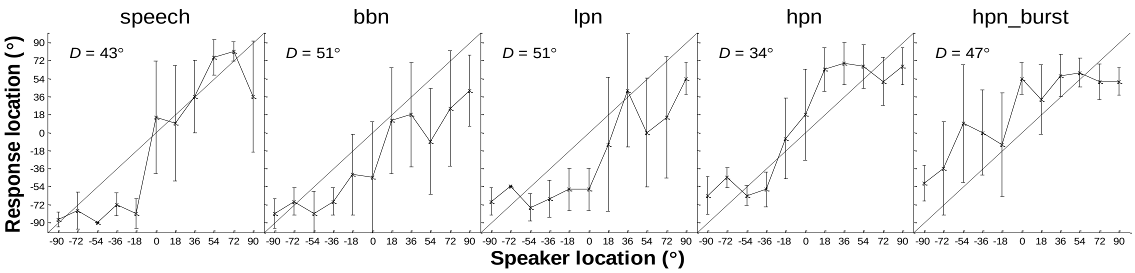
D3



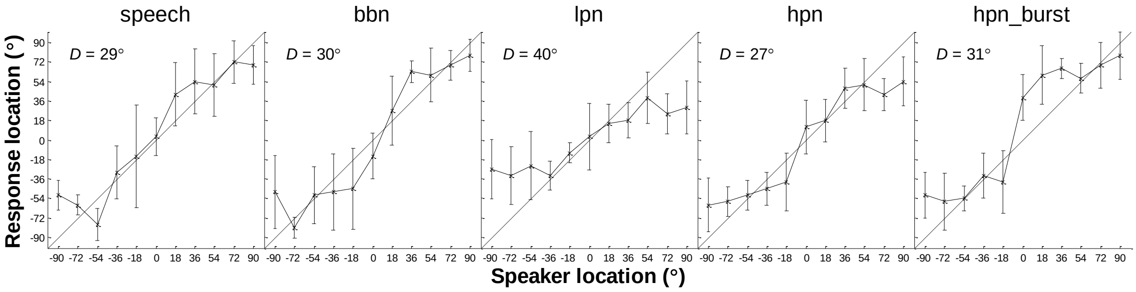
D4



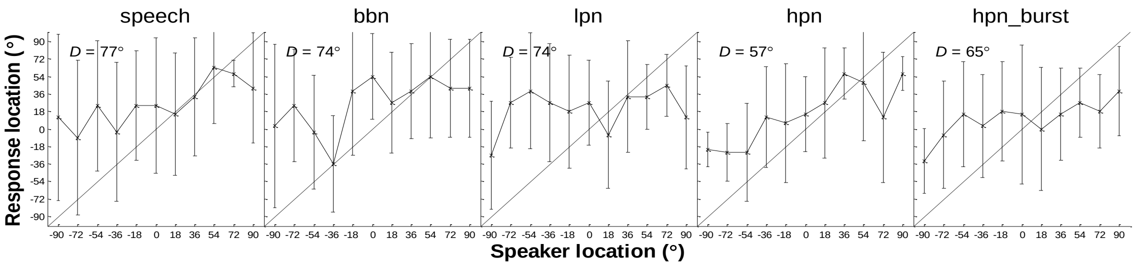
D5



D6



D7



D8

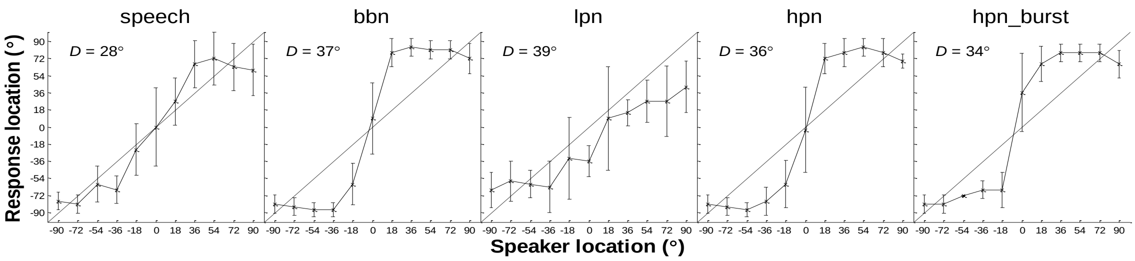


Figure 1: Sound localisation performance for each of the DSPB implant subjects. Each data point represents the mean response given by a subject for each loudspeaker location. The error bar indicates the standard deviation across the 6 responses obtained at each loudspeaker location. The diagonal line represents the perfect localisation performance. It should be noted that the polarities of the azimuths were mistakenly reversed in this figure.

Appendix D.4: Overall localisation error scores with each of the two replications

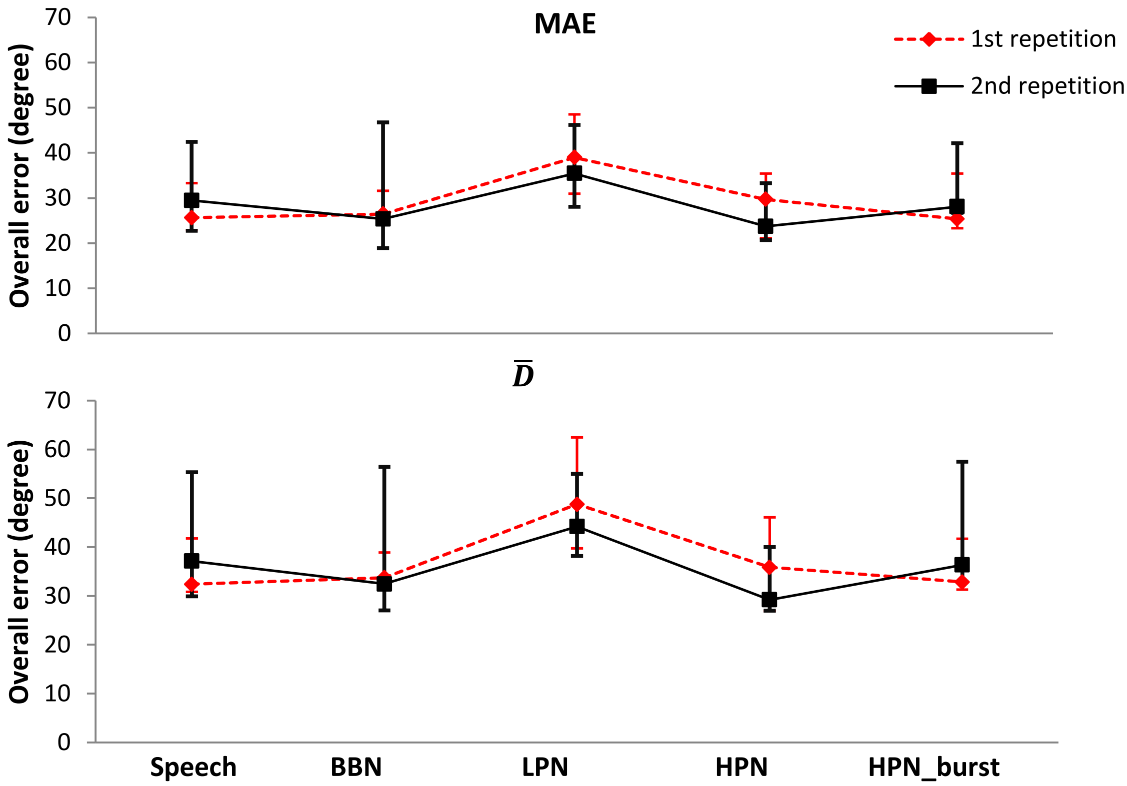


Figure 1: Median overall error with each of the two repetitions for DSPB implant subjects. Error bars represent the upper and lower quartiles.

Table 1: Test-retest statistics of the overall error scores (MAE and $\overline{D}$ error) between the two replications for each stimulus: one-way ANOVA (*F*) following a Bonferroni correction and the intraclass correlation coefficient (*r*)

Stimulus	**MAE**				**$\overline{D}$ error**			
	F	***P***	***r***	***P***	***F***	***P***	***r***	***P***
Speech	0.36	>0.05	0.91	0.002	0.26	>0.05	0.92	0.00
BBN	0.00	>0.05	0.75	0.04	0.02	>0.05	0.82	0.01
LPN	0.31	>0.05	0.92	0.002	0.26	>0.05	0.95	<0.0
HPN	0.00	>0.05	0.81	0.021	0.03	>0.05	0.80	0.03
HPN_burst	1.24	>0.05	0.96	<0.001	1.32	>0.05	0.93	0.00

Appendix E. Results of speech perception in noise with CIs

Appendix E.1: Listening effort benefits by individual CI subjects

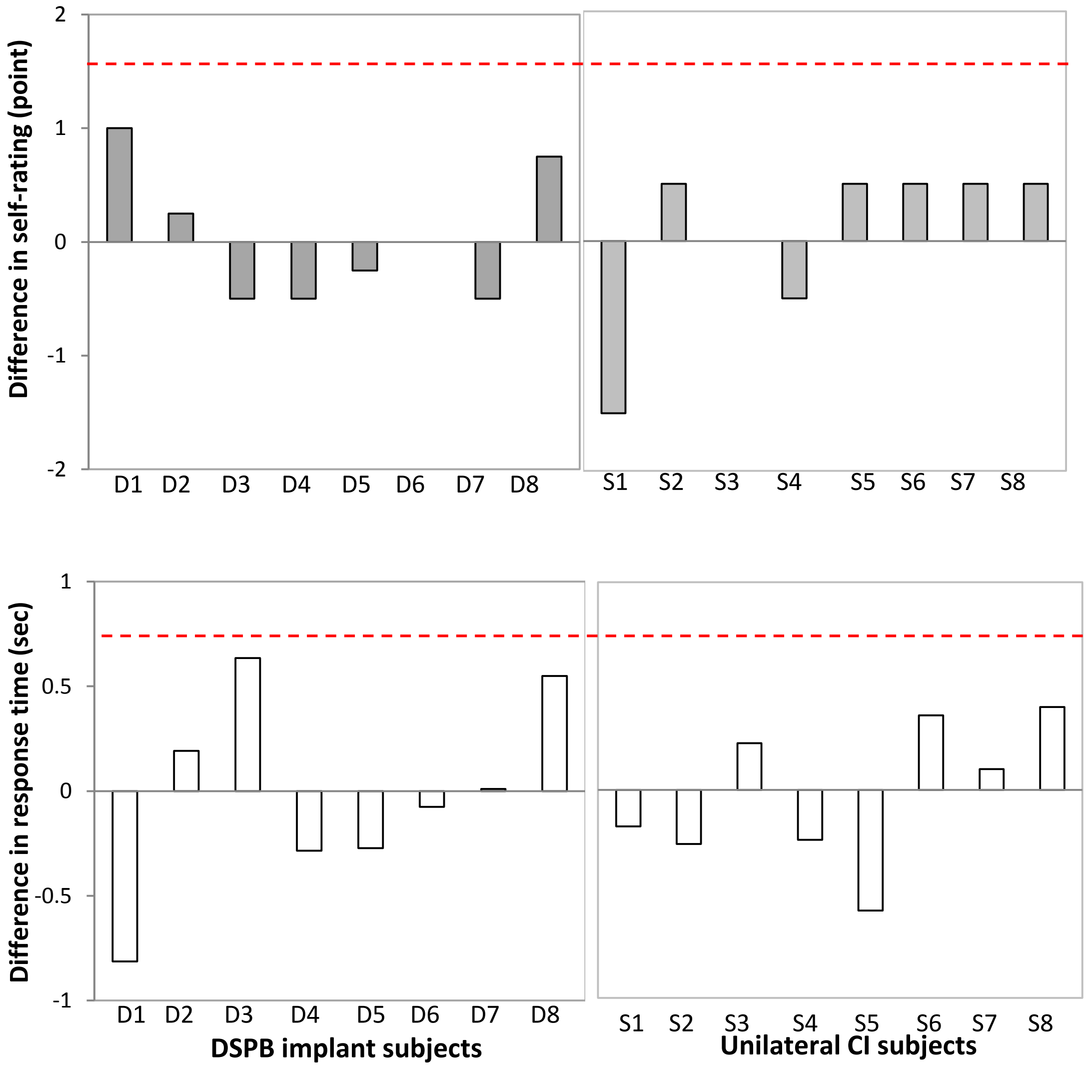


Figure 1: The differences in listening effort required to understand speech with noise at the side versus at the front on listening effort scale (upper panels) and response time (lower panels) for the DSPB implant group (left panels) and the unilateral CI group (right panels). The horizontal red dashed line indicates statistically significant benefit at the *P* < 0.05.

Appendix F. Results of self-reported measure

Appendix F.1: Results of correlation analyses between SSQ scores and laboratory test

Table 1: Results of correlation analyses between SSQ scores and laboratory test: localisation with speech, SRM and SRT for co-located speech and noise for **normal-hearing subjects**. The correlation coefficients (95% confidence intervals) are listed.

	Localisation	SRM	SRT
Overall SSQ	0.12 (-0.3-0.6)	0.27 (-0.2-0.7)	-0.12 (-0.6-0.3)
Speech SSQ	0.09 (-0.4-0.6)	0.25 (-0.2-0.7)	-0.24 (-0.7-0.2)
Spatial SSQ	0.14 (-0.3-0.6)	0.30 (-0.1-0.7)	0.07 (-0.4-0.5)
Quality SSQ	0.10 (-0.4-0.6)	0.21 (-0.2-0.7)	-0.20 (-0.6-0.3)

**P with Bonferroni correction* < 0.01

Table 2: Results of correlation analyses between SSQ scores and laboratory test: localisation with speech, SRM and SRT for co-located speech and noise for **DSPB implant subjects**. The correlation coefficients (*P* value) are listed.

		Loc	SRM	SRT
Speech	Speech in quiet	-0.42 (>0.1)	0.84 (0.009)	-0.14 (>0.1)
	Speech in noise	-0.07 (>0.1)	0.77 (0.024)	0.21 (>0.1)
	Speech in speech contexts	0.00 (>0.1)	0.65 (0.081)	0.00 (>0.1)
	Multiple speech-stream processing and switching	-0.03 (>0.1)	0.61 (>0.1)	-0.03 (>0.1)
Spatial	Localisation	-0.69 (0.018)	0.53 (>0.1)	-0.40 (>0.1)
	Distance and movement	-4.29 (>0.1)	0.55 (>0.1)	-0.42 (>0.1)
Qualities	Sound quality and naturalness	-0.07 (>0.1)	0.83 (0.010)	0.07 (>0.1)
	Identification of sound and objects	-0.35 (>0.1)	0.69 (>0.1)	-0.21 (>0.1)
	Segregation of sounds	-0.57 (0.04)	0.65 (>0.1)	-0.28 (>0.1)
	Listening effort	-0.29 (>0.1)	0.87 (0.004)	0.14 (>0.1)

Table 3: Results of correlation analyses between SSQ scores and laboratory test: localisation with speech, SRM and SRT for co-located speech and noise for **unilateral CI subjects**. The correlation coefficients (*P* value) are listed.

		Loc	**SRM**	**SRT**
Speech	Speech in quiet	-0.25 (>0.1)	0.28(>0.1)	0.13(>0.1)
	Speech in noise	-0.08(>0.1)	0.21(>0.1)	0.16(>0.1)
	Speech in speech contexts	-0.37(>0.1)	0.42(>0.1)	0.10(>0.1)
	Multiple speech-stream processing and switching	0.13(>0.1)	0.40(>0.1)	-0.03(>0.1)
Spatial	Localisation	-0.70 (0.052)	0.64 (0.026)	-0.36(>0.1)
	Distance and movement	-0.57(>0.1)	0.35(>0.1)	-0.06(>0.1)
Qualities	Sound quality and naturalness	-0.04 (>0.1)	0.42(>0.1)	0.17(>0.1)
	Identification of sound and objects	-0.62 (0.099)	0.57 (0.048)	0.18(>0.1)
	Segregation of sounds	-0.64 (0.085)	0.00 (>0.1)	0.05(>0.1)
	Listening effort	-0.09(>0.1)	0.500 (0.083)	0.02(>0.1)

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