University of Southampton

Faculty of Engineering and Physical Sciences

Institute of Sound and Vibration Research

Outcomes of unilateral, bimodal and bilateral cochlear implant users versus normal-hearing listeners on a real-life test battery

by

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Thesis for the degree of Doctor of Philosophy

September 2022

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Abstract

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Binaural hearing is important for spatial hearing in real-life listening situations, e.g., speech perception in noise, sound localisation, and tracking of moving sounds. Adults with bilateral severe and profound sensorineural hearing loss typically receive one cochlear implant (CI) due to cost constraints. To compensate for this, a hearing aid (HA) in the non-implanted ear is often recommended. HAs use a different processing strategy and thus sound different from CI which makes them challenging for some CI users to use. Integrated bimodal technology has been introduced with the view of allowing the two devices to work together on the same platform. Preliminary studies have suggested better bimodal benefits with integrated bimodal technology. However, further, and independent investigation is needed to substantiate these reported benefits. In addition, there is a need to compare outcomes with integrated bimodal technology versus bilateral CI in real-life listening situations to guide best practice and clinical decision making. The aim of this thesis is to investigate the outcomes of adult unilateral, integrated bimodal and bilateral CI users versus normal-hearing listeners on a real-life test battery.

To realise this aim, five studies were carried out. The first study assessed bimodal and bilateral CI service provision for adults worldwide using an online questionnaire that was sent to CI professionals in 75 countries (n=62). In the second study, a real-life test battery comprising of performance tests and subjective rating scales was developed. The measurement precision and reference data of the newly developed tests were assessed using a group of adults with normal hearing (n=45). The third study measured the outcomes and experiences of unilateral CI users when using the integrated bimodal technology (CI + Naida Link HA) versus the CI only using the real-life test battery (n=26). The fourth study compared the outcomes and experiences of bilateral CI users when they used one versus two implants on the real-life test battery (n=16). The fifth study compared the outcomes of integrated bimodal and bilateral CI users with those of normal-hearing participants.

Results from the international survey showed that binaural hearing for adult unilateral CI users is not well supported in terms of funding for a second implant or HA, and that there is no clear practice guidance for fitting and maintaining the contralateral HA in most world regions. However, CI professionals recognise the value of fitting contralateral HAs at CI services, with audiology departments and private HA dispensers playing an ongoing role in general maintenance and support. The survey also showed that CI professionals are unsure of the benefit of integrated bimodal technology. Results from the second study demonstrated that the new speech- in-noise tests developed showed good reliability and validity. In addition, the new speech-in-noise, localisation and modified tracking tests are feasible and easily administered using the AB-York

Crescent of Sound. The third and fourth studies indicated that using integrated bimodal technology and bilateral CI significantly improved performance compared with one CI for speech-in-noise perception, localisation, tracking of moving sounds and the SSQ questionnaire. The last study showed that the benefit provided by a second CI was significantly higher than that provided by the integrated bimodal technology in the spatial-listening tests (localisation and tracking) and the self-reported questionnaire (SSQ).

The study also showed that the performance of CI users, including integrated bimodal and bilateral cochlear implant users, is significantly poorer compared than normal-hearing listeners. This underscores the importance of using assistive listening technology and support for CI users.

Finally, the results suggest that using a test battery that includes tests more representative of real-life listening situations offers a better understanding of the performance of CI users.

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Dataset DOI: https://doi.org/10.5258/SOTON/D2400

Research Thesis: Declaration of Authorship

Print name: Manal Nasser Alfakhri

Title of thesis: Outcomes of unilateral, bimodal and bilateral cochlear implant users versus normal-hearing listeners on a real-life test battery

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. 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;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:-

- Alfakhri, M., Campbell, N. and Rowan, D. (2019). International survey of clinical practice and bimodal hearing aid use in adult cochlear implant recipients. Poster presented at British Cochlear Implant Group Meeting; 4th - 5th April, Solent Conference Centre, Southampton, United Kingdom
- Alfakhri, M., Campbell, N. and Rowan, D. (2019). Binaural hearing for adult cochlear implant users. Oral and poster presentation at the Institute of Sound and Vibration Research Human Science Group Away Day; 24th June, Southampton, United Kingdom
- Alfakhri, M., Campbell, N. and Rowan, D. (2019). The performance of normal hearing adults on real-life listening tests using the AB-York Crescent of Sound. Poster presented at 3rd British Society of Audiology e-Conference; 1st - 31st December

- Alfakhri, M., Campbell, N. and Rowan, D. (2020). Normal hearing listeners outcomes on a real-life speech in noise test using the AB-York Crescent of Sound. Oral presentation at Signal Processing Audio and Hearing Research Meeting; online, 11th August
- Campbell, N. and Alfakhri, M. (2021). Bilateral cochlear implant and bimodal fittings. Oral presentation at British Cochlear Implant Group Cochlear Implant Champions Training Event; Online, 11th May
- Alfakhri, M., Campbell, N., Lineton, B., Rowan, D., and Boyle, P. (2021). Comparison between bilateral implantation & bimodal fittings on a 'real life' test battery. Oral presentation at Signal Processing Audio and Hearing Research Meeting; online, 8th June
- Alfakhri, M., Campbell, N., Lineton, B., Rowan, D., and Boyle, P. (2021). Comparison between bilateral implantation & bimodal fittings on a 'real life' test battery; Preliminary results. Oral presentation at Advanced Bionics Journal Club Meeting; online, 24th June
- Alfakhri, M., Campbell, N., Lineton, B., Rowan, D., and Boyle, P. (2021). Outcomes of bimodal, unilateral and bilateral cochlear implant users versus normal hearing listeners on a 'real life' test battery. Oral presentation at University of Southampton Auditory Implant Services Meeting; online, 17th September
- Alfakhri, M., Campbell, N., Lineton, B., Rowan, D., and Boyle, P. (2022). Binaural Voice Stream technology for adult cochlear implant users. Oral presentation at Signal Processing Audio and Hearing Research Meeting; online, 12th April

Signature: ....Date: 30/09/2022

Acknowledgements

First and foremost, I would like to thank God for granting me countless blessings, knowledge, and strength to complete this PhD thesis.

I would like to express my sincere gratitude to my main supervisor, Prof. Nicci Campbell, for her continual supervision, invaluable guidance, and encouragement. Her immense knowledge and experience in the field of audiology have encouraged and inspired me in my academic research. I deeply appreciate her support throughout my study and her faith that I could complete my PhD. Without her guidance and persistent support, this PhD thesis would not have been possible. Furthermore, I extend my gratitude to my co-supervisors: Dr Ben Lineton for his expertise, support and feedback on my statistical analysis of data and review of thesis and Dr Daniel Rowan for his kind help with the study design, technical support in writing the MATLAB codes for the telephone test, and helpful discussions about psychoacoustics.

I would like to acknowledge the contribution of Dr Patrick Boyle for his technical support in writing the codes for new tests developed for the real-life test battery using the AB-York Crescent of Sound rig. I would like to extend my thanks to the USAIS team, in particular Doreen Sekibo, Becky Parsons, Edward Heard and Anna Read for helping to facilitate data collection; Devyanee Bele and Ellie Coulthard for helping to recruit participants; Dr Roberta Buhagiar for her generous help in programming the hearing aids and cochlear implant devices used in the experiments; and Anna Lyford and Samantha Johnson for their valuable feedback on the telephone test. Lastly, I am sincerely grateful to all the cochlear implant users who participated in these studies.

I express appreciation to King Saud University, Riyadh, Saudi Arabia and the Saudi Arabian Cultural Bureau, London in the UK for their generous financial support of this work and to the USAIS, at the University of Southampton for its additional financial support to cover the travel expenses for cochlear implant participants.

I would also like to thank my friends, Hind, Magi and Rania for their kind support and for all the moments we shared together during the PhD journey through good and bad days. I am lucky to have such amazing friends like you during this time.

Most of all, this PhD thesis is dedicated to my beloved family, particularly my parents Noura and Nasser. I am entirely grateful for their unconditional love and support and for all they have done for me. Their constant prayers for me and my progress during this entire journey have allowed me to successfully complete this thesis. I am also thankful to my husband Fahad for his understanding and support. Thanks to my brothers for their encouragement.

Lastly, to my little angel, Sarah, you are the most precious thing to me; thank you for just being there with me and for all your beautiful drawings on the desk and the walls of my home office!

Glossary

Critical difference in this thesis refers to clinically important difference which defined as the smallest difference in score in the domain of interest which patients perceive as beneficial and subsequently would lead to a change in the patient's management plan.

Just-noticeable difference (JND) refers to the minimum noticeable change in score, yet it does not indicate whether this change is meaningful or not.

Just-meaningful difference (JMD) is the minimum change in score necessary to motivate the individual with hearing loss to seek intervention.

Abbreviations

AB	Advanced Bionics
AGC	Automatic gain control
APDB	Adaptive Phonak Digital Bimodal
APHAB	Abbreviated Profile of Hearing Aid Benefit
BILD	Binaural intelligibility level difference
BKB	Bamford-Kowal-Bench
CI	Cochlear implant
dB	Decibel
dB SPL	Decibel sound pressure level
EAS	Acoustics stimulation system
EQ-5D	EuroQol EQ-5D
GHSI	Glasgow Health Status Inventory
HA	Hearing aid
HRQoL	Health-related quality of life
HUI3	Health Utilities Index Mark III
ICC	Intra-class correlation
ILD	Interaural level difference
ITD	Interaural time difference
IPD	Interaural phase difference
JMD	Just-meaningful difference
JND	Just-noticeable difference
LoA	Limits of agreement

LSO	Lateral superior olive
MAA	Minimum audible angle
MAMA	Minimum audible movement angle
MCID	Minimum clinically important difference
NCIQ	Nijmegen Cochlear Implantation Questionnaire
NH	Normal hearing
NHS	National Health Service
PTA	Pure-tone average
RMS	Root mean square
SD	Standard deviation
SDω	Within-subject standard deviation
SEM	Standard error of measurement
SLM	Sound level metre
SNR	Signal-to-noise ratio
SRM	Spatial release from masking
SRT	Speech-reception threshold
SSQ	Speech, spatial and qualities hearing scale
STARR	Adaptive Randomized Roving levels
TDT	Triple-digit test
TFS	Temporal fine structure
TTO	Time Trade-off
USAIS	University of Southampton Auditory Implant Service
VAS	Visual Analog Scale

Chapter 1 Overview of thesis

1.1 The rationale underpinning the PhD thesis

Hearing with both ears (binaural hearing) is important for spatial hearing in real-life listening environments, e.g., hearing speech when there is competing speech and/or background noise, sound localisation, and tracking of moving sounds. It is recommended that adult unilateral cochlear implant (CI) users be fitted with a second implant or with a hearing aid (HA) in the non-implanted ear.

Bilateral CI can restore some of the binaural hearing functions; however, bilateral CI is not available for adults in many countries due to cost constraints. To compensate for this, audiologists typically recommend fitting an HA in the non-implanted ear which may be helpful for some but not all CI users. Research in bimodal benefit shows mixed outcomes and user benefit reports (Ching et al., 2004, Dunn et al., 2005, Kong et al., 2005, Berrettini et al., 2010, Morera et al., 2012, Bouccara et al., 2016, Devocht et al., 2017, Devocht et al., 2020). Possible reasons include the fact that different modalities, i.e. CI (electrical stimulation) and HA (acoustic stimulation) sound different, which makes them challenging for some CI users to use (Veugen et al., 2016a). There may be loudness mismatch, different signal-processing schemes, and fitting them separately often by different professionals. Some unilateral CI users discard the use of the HA in the non-implanted ear due to difficulty integrating the two different sounds of the CI and the HA (Fitzpatrick *et al.*, 2009, Fitzpatrick and Leblanc, 2010). Integrated bimodal technology, namely the Naida Link hearing aid, has been developed with the view of allowing the two devices to work together on the same platform, overcoming the processing-strategy mismatch between the two devices. This technology permits CI users to use Binaural VoiceStream Technology to enhance binaural hearing by linking the CI and HA together wirelessly to stream full bandwidth audio signals from ear to ear simultaneously (Bionics, 2016b).

Prior to starting this thesis, to the best of the researcher's knowledge, there were only a few clinical studies (Bionics, 2016b, Bionics, 2016d, Bionics, 2017) that had assessed the benefits of integrated bimodal technology. Preliminary results reported potential benefit for speech understanding in noise and greater listening comfort with integrated bimodal technology compared to using CI alone or with any standard HA. Further and independent investigation was needed to substantiate these findings. Seven studies have been published within the time span of this thesis (Vroegop et al., 2018b, Cuda et al., 2019, Ernst et al., 2019, Vroegop et al., 2019, Holtmann et al., 2020, Warren et al., 2020, Auletta et al., 2021). All the studies assessed the benefit of the integrated bimodal technology in terms of speech perception only, except Holtmann et al. (2020) who assessed the benefit of this technology to improve localisation and self-reported benefits. The results from these studies showed that integrated bimodal technology can improve speech intelligibility in noise particularly compared to using CI only.

Although these results are in line with preliminary studies which showed the advantages of this technology, they have some limitations. They only assessed the benefit in improving speech perception in noise. There is still a need to assess the benefit of the integrated bimodal technology for other important auditory functions in real-life situations, such as localising the sound sources, tracking of moving sounds and using the telephone. In addition, there is a need to investigate self-reported benefits using subjective rating scales. Another limitation of these studies is that the target speech, in most studies, was presented from fixed loudspeaker placed at the front of the participants, whereas in real-life situations, the speech can randomly come from different locations. Thus, there still the need to assess the effectiveness of the integrated bimodal technology using more real-life representative test settings. There is also a need to compare the outcomes of adult CI users with integrated bimodal technology with those of bilateral CI users and adults with normal hearing.

As highlighted above, the performance of adult CI users is typically assessed with the standard speech-perception tests that use a single loudspeaker to present both speech and competing noise from the front. These tests do not reflect the different listening situations encountered in real life. Standard speech-perception tests might underestimate the value of bimodal hearing, bilateral CI, and recent technology (i.e. binaural beamformers) for adult CI users (van Hoesel, 2015, Dorman et al., 2020), or fail to show the differences between these technologies (Gifford et al., 2018, Gifford and Dorman, 2019). Using speech-perception tests only is not enough to provide information about other essential auditory functions in real life, such as identifying the source of sounds, music perception, using the telephone, and the perceived benefits from the CI user's perspective. There is a need for a test battery that incorporates both performance and subjective measurements that are more representative of real-life listening situations. Using such a test battery would offer a better understanding of the performance of adult CI users (including bimodal and bilateral CI users) in real-life listening situations, compared to those with normal hearing.

The main aim of this thesis is to investigate the outcomes of adult unilateral, bimodal and bilateral CI users versus normal-hearing listeners on a real-life test battery. To achieve this aim, five prospective studies were carried out:

1. An international survey of bimodal and bilateral CI-service provision for adults

2. Development of a real-life test battery, with analysis of measurement precision and collection of reference data on normal-hearing listeners
3. The performance of adult CI users with integrated bimodal technology on the real-life test battery
4. The performance of adult bilateral CI implant users on the real-life test battery
5. Comparison of integrated bimodal hearing and bilateral CI users versus normal-hearing listeners on the real-life test battery.

1.2 Thesis structure

The structure of this thesis is illustrated in Figure 1.1. The thesis starts with a review of the literature (as described in **Chapter 2**) that was conducted on psychoacoustic underpinnings of binaural hearing in the normal auditory system, consequences of hearing impairment on binaural hearing, an overview of the CI (how it works, candidacy, and the benefits), the benefits of bilateral implantation and bimodal hearing for unilateral CI adults, and the limitations of the current audiological tests.

Chapter 3 reports the first study which was a survey study using an online questionnaire that was sent to CI professionals worldwide (approximately 75 countries) to gauge bimodal hearing and bilateral CI service provision for adults. There were 62 respondents, representing 25 countries.

Chapter 4 reports the second study which involved two parts. The first part describes the development of a real-life test battery. The test battery involved performance measurements as the follows:

1. Three speech-in-noise tests, where each test simulates a common listening situation in real life
2. Spatial-listening tests: localisation and tracking moving sounds
3. Telephone tests: in quiet and noise.

Subjective rating scales were also included in the test battery to assess the benefits from the CI users' perspective. CI participants were asked to complete the speech, spatial and qualities of hearing scale (SSQ) (Gatehouse and Noble, 2004) questionnaire. The SSQ questionnaire was used to assess a range of hearing functions in everyday life across three subscales: speech, spatial and qualities of hearing. In addition, the SSQ specific questions relating to telephone use and music perception were analysed beyond the overall score of the SSQ and scores of three subscales in this study. The SSQ-specific questions relating to music perception were considered in the analysis to understand better the performance of bimodal and bilateral CI users on music perception. A music-perception test was originally considered for inclusion in the test battery but discarded for practical reasons, i.e. the length of the test battery for the participants. Adding the music-perception test would have lengthened the sessions by more than 90 minutes. In addition, a Telephone-Use questionnaire was developed and included in the test battery of the study to gauge the telephone use of the CI users in their real-life listening situations.

The second part of this chapter reports the measurement precision of the newly developed speech-in-noise tests included in the test battery. The test-retest reliability and concurrent validity of the new speech-in-noise tests were assessed on 45 adults with normal hearing. The study also provided a reference data for these new tests included in the test battery.

Chapter 5 reports the third study that measured the outcomes and experiences of adult unilateral CI users when using integrated bimodal technology versus CI only on the real-life test battery. The study also compared the outcomes of the integrated bimodal technology to the standard bimodal technology in a self-reported questionnaire (SSQ questionnaire). **Chapter 6** reports the fourth study that examined outcomes and experiences of adult bilateral CI users and the two implants versus one implant on the real-life test battery. Twenty-six CI users using the integrated bimodal technology and 16 bilateral CI users were recruited from University of Southampton Auditory Implant Service (USAIS). The last study which looked at a between-subject comparison for outcomes of adult CI users with integrated bimodal technology and bilateral CI users with outcomes of normal-hearing listeners on the real-life test battery is presented in **Chapter 7.**

Thesis ends with a summary of the findings of the studies included in this thesis and a general discussion about the implications of these findings. Recommendations for future research and clinical practice are offered.

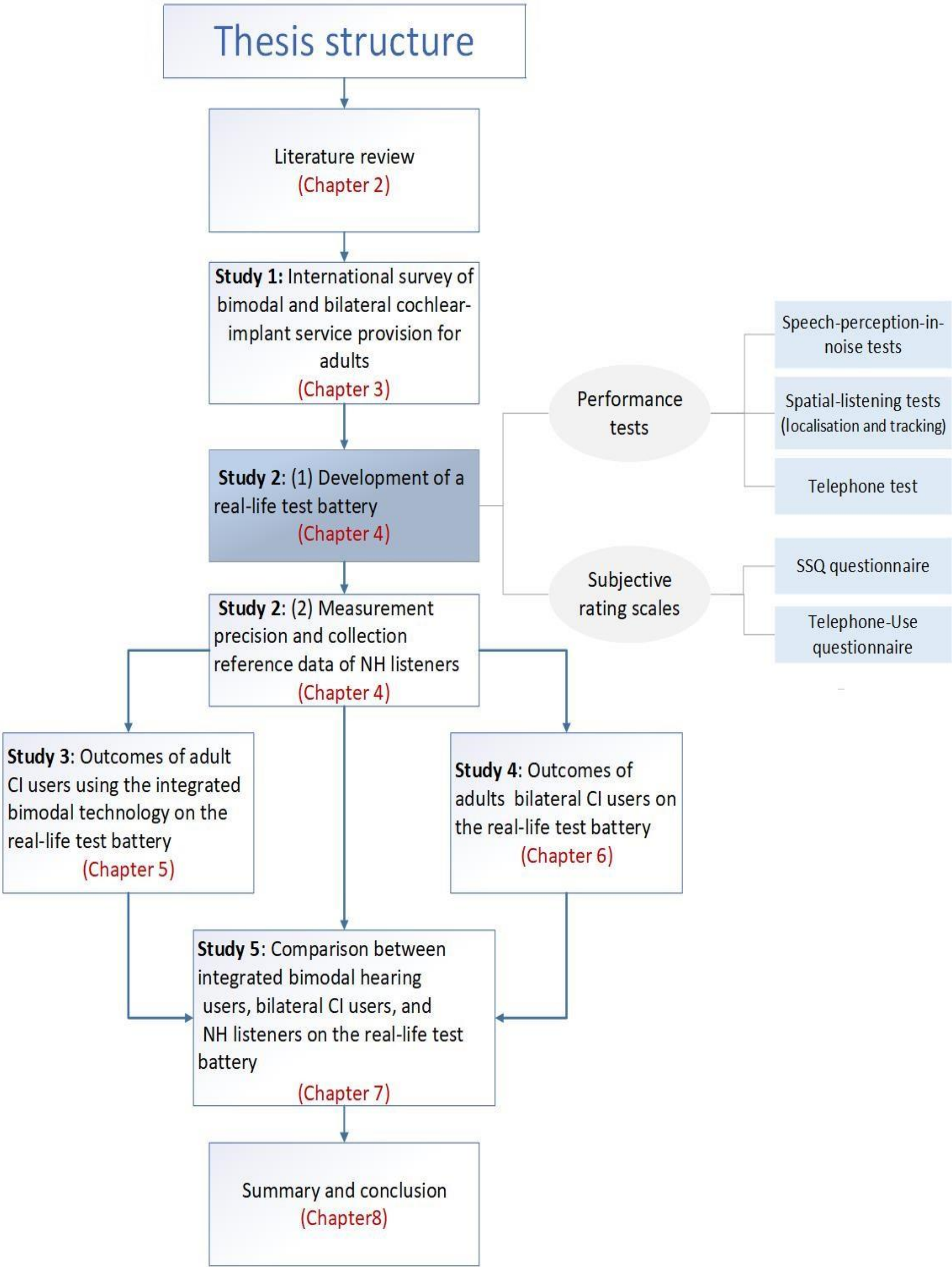

Figure 1.1: Schematic illustration of the structure of thesis: outcomes of adult bimodal, unilateral, and bilateral CI users versus NH listeners on a real-life test battery.

1.3 Contributions to knowledge

It is anticipated that the results of this PhD thesis will offer several contributions:

1. An insight into current bimodal and bilateral CI service provision for adults around the world
2. A better understanding of the performance of adult unilateral CI users fitted with integrated bimodal technology on real-life listening situations
3. A better understanding of the performance of adult bilateral CI users on real-life listening situations
4. A better understanding of the differences between adult unilateral CI, integrated bimodal, and bilateral CI users on real-life listening situations in relation to NH listeners
5. Greater awareness of the importance of developing audiological tests, procedures and equipment to extend beyond current audiology practice, i.e. audiometry and only basic measures of speech perception in noise. This is needed to better assess 'hearing with two ears' and spatial hearing in more real-life listening environments, e.g. hearing roving speech when there is competing speech or background noise, sound localisation, and tracking of moving sounds
6. An opportunity to inform clinical practice and potentially help shape national policy and funding for adult CI users.

Chapter 2 Literature review

Chapter 2 provides the context for the thesis. Options to optimise binaural hearing for adults with a unilateral cochlear implant are discussed and differences between bimodal hearing and bilateral cochlear implant use and outcomes are discussed against the background of real-life listening demands. The chapter begins with a review of binaural hearing in the normal auditory system, which includes the time and level differences in the two ears based on the origin of the sound, the sensitivity of normal-hearing adults to interaural differences, benefits of normal hearing, and consequences of hearing impairment on binaural hearing. Then, an overview of how a cochlear implant works, cochlear implant candidacy, and the benefits of a unilateral cochlear implant for adults are provided. The benefits of bilateral implantation and bimodal hearing for unilateral cochlear implant adults reported in the literature are then reviewed. The chapter concludes with a discussion of the limitations of the current audiological tests and the need for tests that are more representative of real-life listening situations. Figure 2.1 illustrates the chapter structure.

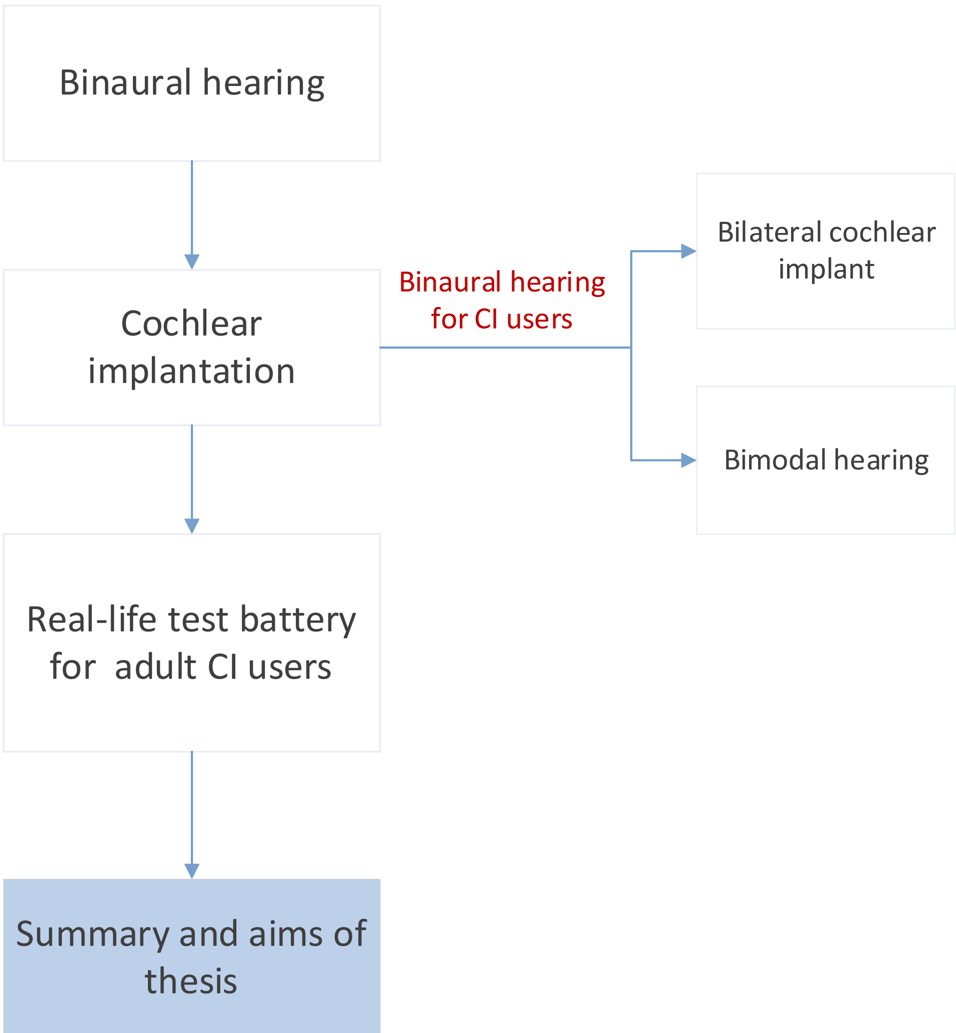

Figure 2.1: Flow chart illustrating the structure of Chapter 2.

2.1 Binaural hearing

Binaural hearing refers to "the mode of functioning of the auditory system of humans or animals in the context of tasks where the system benefits from having two ears" (Braasch, 2005, p.75). Tasks related to binaural hearing include hearing speech in noisy backgrounds and localising sound sources. The sound that arrives at one ear usually differs from the other ear; therefore comparing the signal that arrives at the two ears is useful in segregation and localising sounds. The difference between sound at the two ears is typically referred to as the ‘difference in arrival time and level’ across the ears. For example, when a sound source is located somewhere on the left side of a listener (as illustrated in Figure 2.2), the sound will arrive in the right ear just after it arrives in the left ear. In addition, as the sound travels further to the right ear, it arrives with lower intensity. The difference in the arrival time of sounds across the two ears is the **interaural time difference (ITD)**, whereas the difference in the level of sounds at the two ears is the **interaural level difference (ILD)**. Figure 2.2 illustrates the two binaural cues (ITD and ILD), which can only be determined through binaural hearing. Both cues are dependent on the angle of the sound source. When the angle of a sound is displaced relative to the centre of a listener's head on a horizontal plane, it refers to the azimuth of the sound source (Moore, 2007a). Throughout this thesis, the convention of positive and negative azimuths detonates sounds to the listeners' right and left respectively, on the horizontal plane. Further discussion of the interaural differences is provided in Sections 2.1.1 and 2.1.2

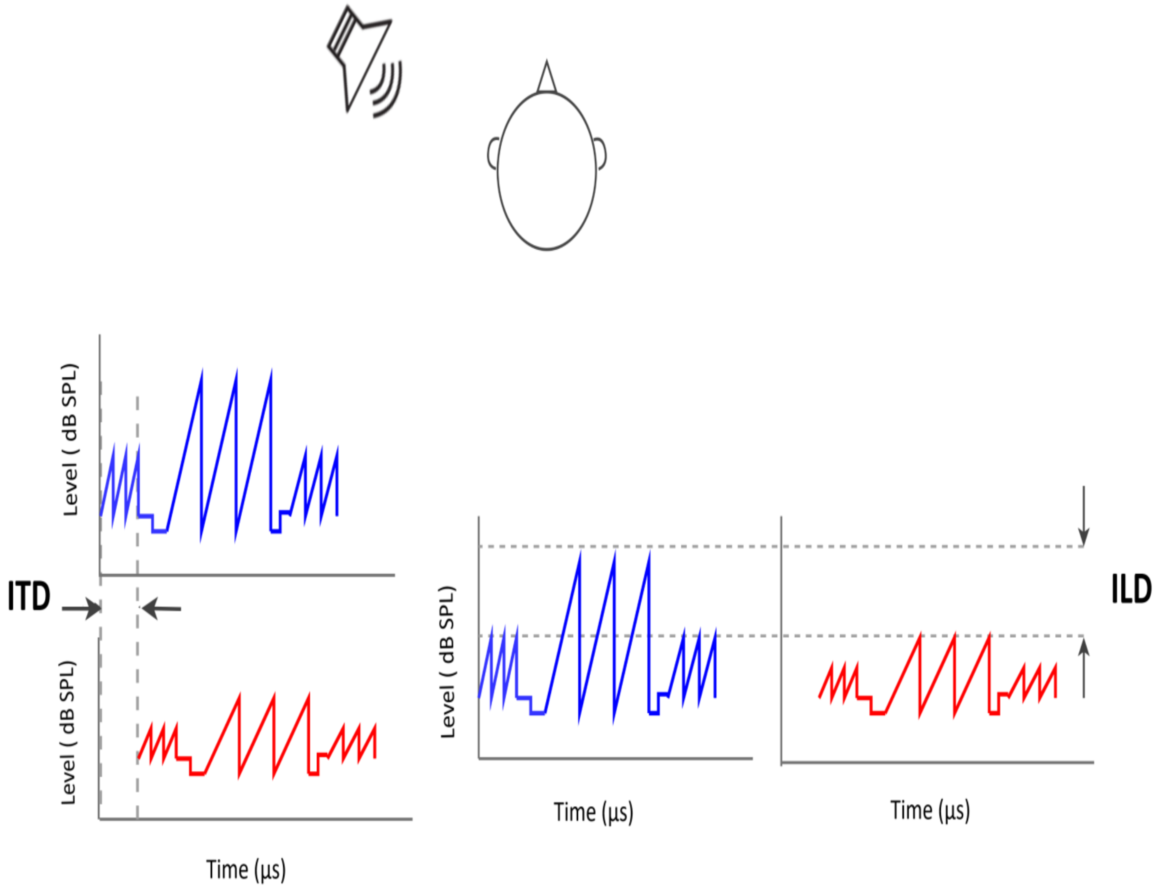

Figure 2.2: Schematic illustration of the binaural cues for a sound source placed on the left side: interaural time difference (ITD) and the interaural level difference (ILD). The sound arrives at the left ear (blue waveform) earlier (with a higher level) than the right ear (red waveform).

2.1.1 Interaural time differences (ITDs)

The ITDs appear in different stimulus components (i.e. an amplitude-modulated sound), such as onset ITD, temporal fine structure ITD, and envelope ITD. The onset ITD reflects the arrival time of the sound at the ear and corresponds to an increase in the firing rate of the spiral ganglion in the auditory nerve, which provides a base for ITD sensitivity. The temporal fine structure and envelope ITDs are referred to as ongoing ITDs (throughout the stimulus). Temporal fine structure (TFS) is defined as the rapid oscillations with which the stimulus crosses zero and has dominant rates from 600 to 10,000 Hz, while the envelope refers to the relatively slow fluctuations in the overall amplitude within the frequency band of 2 to 50 Hz (Rosen, 1992). Figure 2.3 illustrates the envelope and TFS for an amplitude-modulated stimulus. For periodic sounds (i.e. pure tones and amplitude-modulated tones), the ongoing ITDs correspond to interaural phase difference (IPD) which is systematically related to the phase-locking of the auditory nerve. For stimulus durations greater than 150 ms, listeners are more sensitive to ongoing fine structure ITDs than the onset ITDs (Tobias and Schubert, 1959).

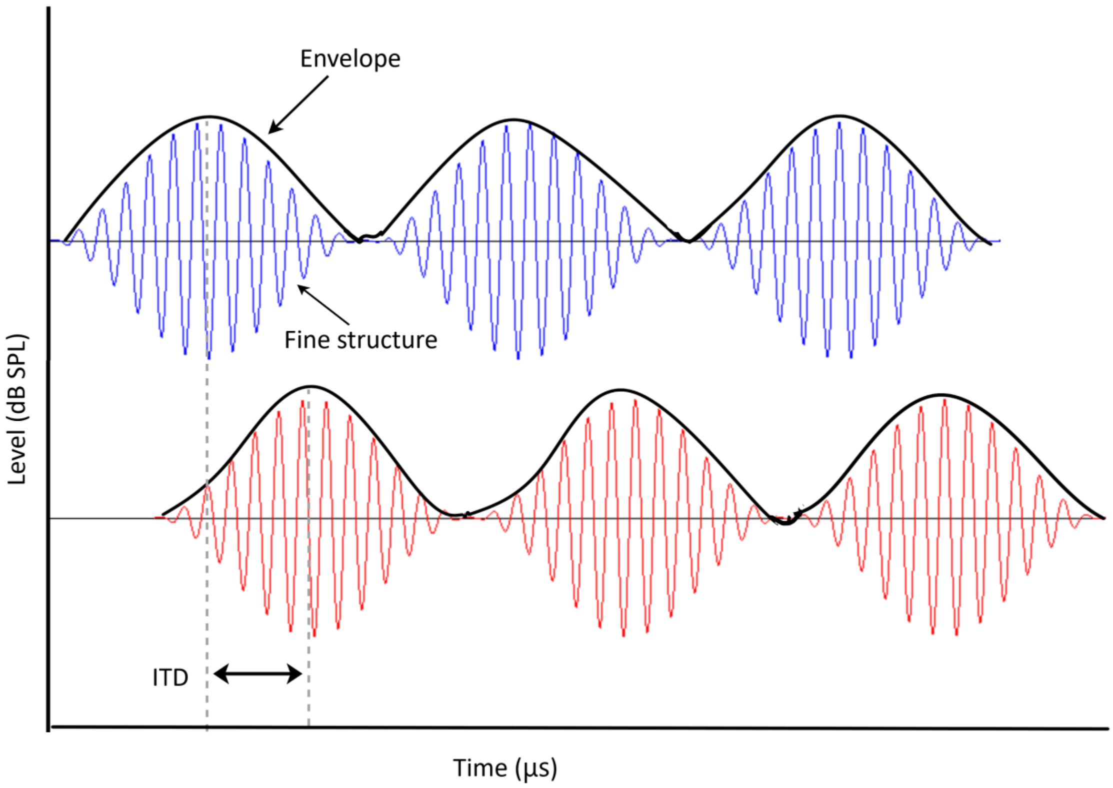

Figure 2.3: Waveform of an amplitude-modulated stimulus recorded at each ear showing the interaural time difference (ITD) obtained from the envelope.

ITDs range from zero microseconds (µs) for a sound source placed at an azimuth of 0° (straight ahead) or 180° (behind) to reaching a maximum of about 650-700 µs at for a sound at an azimuth of ± 90° (Akeroyd, 2006, Francart *et al*., 2009, Moore, 2012). Normal-hearing (NH) listeners can detect a change in ITDs of about 10 µs for a low-frequency tone (Yost, 1974). However, ITDs are undetectable for frequencies above 1500 Hz because the period is smaller than the available ITDs (Francart *et al*., 2011b). This effect is because of phase ambiguity in the acoustic signal for tonal stimuli. However, the ITDs carried by the envelopes could be detectable for high-frequency sounds such as amplitude-modulated tones, tone complexes, and bands of noise that are absent from high-frequency pure tones (Macpherson and Middlebrooks, 2002). The auditory neurons can encode the envelopes of these sounds (Avan *et al.*, 2015). Figure 2.3 illustrates an envelope ITD for an amplitude-modulated stimulus presented somewhere on the left-hand side of a listener. Bernstein and Trahiotis (2002) demonstrated that ITD processing for transposed high-frequency stimuli, which are synthesised to provide the high-frequency channels with information similar to that available in low-frequency channels, was sometimes equal to the ITD processing for low-frequency tones.

ITDs processing for high-frequency sounds can also be affected by low-frequency sounds (Akeroyd, 2006). It has been shown that the ITD sensitivity for a narrowband noise at 4000Hz was substantially decreased when another band of noise at 500 Hz was presented simultaneously (McFadden and Pasanen, 1976). However, this effect would not be applied to different types of stimuli. For instance, Bernstein and Trahiotis (2004) showed that transposed stimuli are immune to the interference of low-frequency sounds.

The ITD processing can mainly be explained based on the classical model of Jeffress (Jeffress, 1948). The model consists of an array of neurons at the primary site of binaural interaction (superior olivary complex SOC) that act as coincidence detectors (or equivalently as cross-correlators). This array fires maximally when action potentials arrive simultaneously from the two ears. The array is innervated by a series of delay-lines axons of variable path length from the two ears (McAlpine, 2005). For a sound coming from one side (i.e. right), actional potentials generated by the right ear are delayed in time (by some neural inhabitation or by making them travel further in the neural path) thus both sets from action potentials can catch up and arrive at the neuron simultaneously. The neuron phase locks the position of the sound source. Therefore, each neuron in the array encodes for a different ITD; thus, a neural place code for sound location is created. Fitzpatrick *et al.* (2000) pointed out that the ITD's sensitivity in the Jeffress model was based only on phase-locked inputs to low-frequency sounds. This model does not consider ITD sensitivity to high-frequency stimuli. However, as discussed earlier, recent studies showed that the auditory neurons can encode the envelopes of high-frequency sounds.

2.1.2 Interaural level differences (ILDs)

The head in a sound field forms a sound barrier between the two ears and produces an acoustic shadow to any sound source. The ear in the shadowed range will have less intensity than the other ear, creating a level difference between the two ears. Therefore, ILDs result from the head-shadow effect. As shown in Figure 2.2, the shadowed ear is the right ear with less intensity than the left ear. The amount of head shadow, and thus the ILDs, largely depends upon four factors: frequency of sound, sound azimuth, the distance between the listener and sound, and the listeners.

ILDs are strongly dependent on frequency; higher-frequency sounds have larger ILDs. Higher-frequency sounds have a shorter wavelength; therefore the head will easily block it. In contrast, low-frequency sounds have a longer wavelength which assists the sound to diffract around the head. The maximum ILDs reported in the literature were 3, 10, 17, and 21 dB at the frequencies of 500 Hz, 1000 Hz, 5000 Hz, and 10 kHz respectively (Akeroyd, 2006). The azimuth and the distance of the sound source are also affecting the ILDs. The further the sound source from the midline, the greater the ILD tends to be. Maximum ILDs can be obtained when the sound source is at lateral azimuths which are roughly opposite one ear (±60°, ±90°, ± 105°and ± 135°). As the sound source is closer to the listener, the greater ILD tends to be. It has been shown that as the distance reduced from 1 to .012 metres, the ILDs reached 20-30 dB even for low-frequency sound (500 Hz) that was in the proximal region (Brungart and Rabinowitz, 1999). Lastly, the shadowing depth is substantially dependent on the head's size (how much the head blocks the sound). In addition, deviations might occur from the interfering effects of reflected sounds from the torso or the shoulders, particularly for high-frequency sounds above 2000Hz.

The physiology mechanism of ILD sensitivity depends on the neurons of the lateral superior olive (LSO). The LSO neurons are usually excited by ipsilateral inputs and inhibited by the opposite side. As a result, the activity of LSO can provide a natural structure to extract the ILDs (Steven Colburn *et al.*, 2006). If a sound is more intense at one ear, the excitatory input would be stronger than the inhibitory input, resulting in greater neuron firing in that ear. However, if the sound intensity is similar at both ears, the inhibition of the LSO increases, reducing neuron firing.

2.1.3 The sensitivity of binaural cues

It is important to measure the sensitivity of NH listeners to interaural differences (ITDs and ILDs) when quantifying binaural abilities. The sensitivity to interaural differences can be achieved by measuring the smallest ITD or ILD that listeners can discriminate from a reference value of zero, referred to as the just-noticeable difference (JND). ITDs and ILDs can be easily created and measured over headphones by delaying (for ITDs) or attenuating (for ILDs) the signal at one ear relative to the other ear.

The smallest JND in the ITDs for pure ones is just 10 µs or less (i.e. (Klumpp and Eady, 1956, Domnitz, 1973). The JND in the ITDs increases as the frequency of pure tone increases, and it cannot be measured above about 1500 Hz. This effect, as discussed earlier, is perhaps because of the ambiguity of IPD, which occurs when half the period of a pure tone is equal to or higher than the maximum ITDs provided to the human head (700 µs). The ITDs' JND for other stimuli that include low frequencies (clicks, noise bands, and tone burst) is about 15 µs (Steven Colburn *et al.*, 2006). For noise bands of 2400 Hz and above and high-frequency tones whose amplitude is modulated at a lower frequency, the ITDs' JND can be detectable; however it is somewhat greater than the ITDs' JND for low-frequency stimuli (Klumpp and Eady, 1956, Steven Colburn *et al.*, 2006). In contrast to JND for the ITDs, the JND for changes in ILDs is approximately independent of frequency between 200 Hz and 1000 Hz and is roughly 0.5 to 1 dB (Mills, 1960).

The range of normal binaural abilities, or the normal range for the ITDs and ILDs' JND, varies widely among the population of NH listeners. For instance, Bernstein *et al*. (1998) reported a broad range of JNDs that differ by hundreds of microseconds for ITDs and several dB for ILDs.

2.1.4 The benefits of binaural cues

The sounds in everyday life produce both ITDs and ILDs, but they can only be determined through binaural hearing. The importance of binaural hearing on sound localisation (in the horizontal plane) and speech perception in noise is well established. These two auditory functions are important for everyday communication. It has been shown that the performance with binaural hearing is significantly better than with monaural hearing (listening with one ear) in speech understanding and sound localisation tasks (Butler, 1986, Feuerstein, 1992). Furthermore, binaural hearing is advantageous in tracking moving sounds (Middlebrooks and Green, 1991). It has been shown that the perception of motion was better in binaural hearing conditions than in monaural conditions (Strybel and Neale, 1994, Phillips and Hall, 2001). The following sections discuss ITD and ILD contributions in speech perception in noise, sound localisation and perception of moving sounds.

2.1.4.1 Speech perception in noise

The benefit of binaural hearing to improve speech understanding in complex listening environments (i.e. in the presence of background noise) is well established. The ITDs and ILDs provide the listener with spatial information about the sound sources, which can help the listener to discriminate between speech and noise (Dieudonné and Francart, 2019). The benefit of binaural hearing for speech understanding in noise can be assessed by measuring the speech-reception threshold (SRT) in different spatial set-ups (Dieudonné and Francart, 2019). The SRT refers to the minimum signal-to-noise ratio (SNR) at which the listener can accurately identify a certain proportion of the target speech (such as 50% or 71%). Lower SRT values indicate a better ability to tolerate more noise (better performance). Speech improvement in the presence of background noise with binaural hearing can be attributed mainly to three effects: (1) binaural summation, (2) binaural squelch and (3) head-shadow effect.

Binaural summation: also known as **binaural redundancy**, refers to the benefit of listening with two ears when identical speech and noise are presented from the same location, compared to listening with one ear. In other words, the sounds are perceived to be louder when the sounds are presented to the two ears instead of one ear. The binaural summation can give a 1-3 dB advantage for speech improvement when listening with both ears rather than monaural listening (Bronkhorst and Plomp, 1988, Hawley *et al*., 2004, Ching *et al*., 2007, van Loon *et al*., 2014). This effect can be interpreted as cancelling internal noise (a noise that occurs in the auditory system) due to sounds arriving in the two ears (Dieudonné and Francart, 2019). Binaural redundancy is typically measured by presenting speech alone or both speech and noise (collocated) from a signal loudspeaker placed in front of the listener (Sammeth *et al*., 2011), as shown in Figure 2.4 (A). The acronym (S0°N0°) is usually used in research to indicate that speech and noise are presented from a loudspeaker placed in front of the listener where the 'S' stands for speech, 'N' for noise and '0' indicates 0° azimuth.

Binaural squelch*:* this refers to the ability of the central auditory system to compare interaural differences (ITDs and ILDs) between speech and noise stimuli that are spatially separated and then to selectively attend to speech (Kokkinakis and Pak, 2014). It has been demonstrated that binaural squelch mainly depends on the interaural differences (particularly the ITDs) for low-frequency sounds (Levitt and Rabiner, 1967, Bronkhorst and Plomp, 1988). The improvement in speech perception occurs by adding the ear with a poor signal-to-noise ratio (SNR), which provides the listener with interaural differences (ITDs and ILDs) that help extract and concentrate on the speech. The mechanism of the central auditory system in using the interaural differences to improve speech perception can be explained by the Equalization-Cancellation model (Durlach, 1963). The model suggested that the auditory system equalises the ITDs and ILDs (using various transformations) at each ear, then subtracts the input at one ear from the other. However, binaural processing improves speech perception only when the noise is more intense than the speech; if the speech is more intense, it is processed monaurally. In addition, if the ITD of the noise differs from that of the speech, the optimal equalisation will compensate for the noise's ITD because it is more intense, and then the cancellation stage will cancel the noise. Since this model is based on equalising the ITD for a single noise masker, it might be expected that the model would be ineffective for multiple noise maskers in different locations with different ITDs. However, it was found that the binaural processing models, including the Equalization-Cancellation model, are more robust in complex listening situations (Culling *et al.*, 2004).

Furthermore, larger binaural squelch effects are found with multiple noise maskers (Hawley *et al.*, 2004). Binaural squelch is usually measured by presenting the speech from a frontal loudspeaker (0° azimuth) and noise from a side loudspeaker placed at 90° right or left azimuth, as shown in Figure 2.4 (B). The squelch effect is calculated as the difference between the monaural listening condition with the ear opposite the noise source and the binaural listening condition when the ear directed to the noise is added. The improvement in speech perception by binaural squelch effect for adult NH listeners can be ranged from 1 to 9 dB depending on the speech material and the type and number of maskers (Bronkhorst and Plomp, 1988, Bronkhorst and Plomp, 1992, Culling *et al.*, 2004, Hawley *et al.*, 2004). For instance, the lowest binaural squelch effect was obtained with monosyllabic words (1.9-3.7 dB) compared with sentences (4.5-7.5 dB). Additionally, Hawley *et al*. (2004) showed a larger binaural squelch effect that ranges from approximately 6 to 8 dB when using multiple (two or more) speech and reversed speech maskers compared to using one or more noise maskers (1-4 dB).

Head-shadow effect*:* this is a physical effect where the head acts as an “acoustic barrier", resulting in a level difference (ILD) between the two ears. Thus, the ear furthest from the noise has a better SNR than the other ear as the head attenuates the noise. With binaural hearing, the improvement in speech perception occurs as the head-shadow effect shelters the ear at the speech source from the noise source at the other side. However, the effect size will be reduced as the speech and noise get closer, or if the sounds have low frequencies. As discussed in Section 2.1.2, as the frequency of sounds increases, the ILD increases; therefore, better SNRs would be at high frequencies. The head-shadow effect can provide a 3 dB advantage on average to 15 dB (Bronkhorst and Plomp, 1988, van Loon *et al.*, 2014, Avan *et al.*, 2015). In contrast to binaural squelch, more than one noise masker, particularly located at the opposite side, would reduce the head-shadow effect and hence the binaural benefit compared to the case of a single masker (Bronkhorst and Plomp, 1988). The head-shadow effect is typically measured by presenting speech from a loudspeaker placed at 0° azimuth and noise from a side loudspeaker placed at 90° right or left, as shown in Figure 2.4 (C). The head-shadow effect is measured by comparing the monaural listening condition with the ear at the noise source and binaural listening condition. The acronym (S0°N± 90°) is usually used in research to refer to the noise presented from the right or left of the listener.

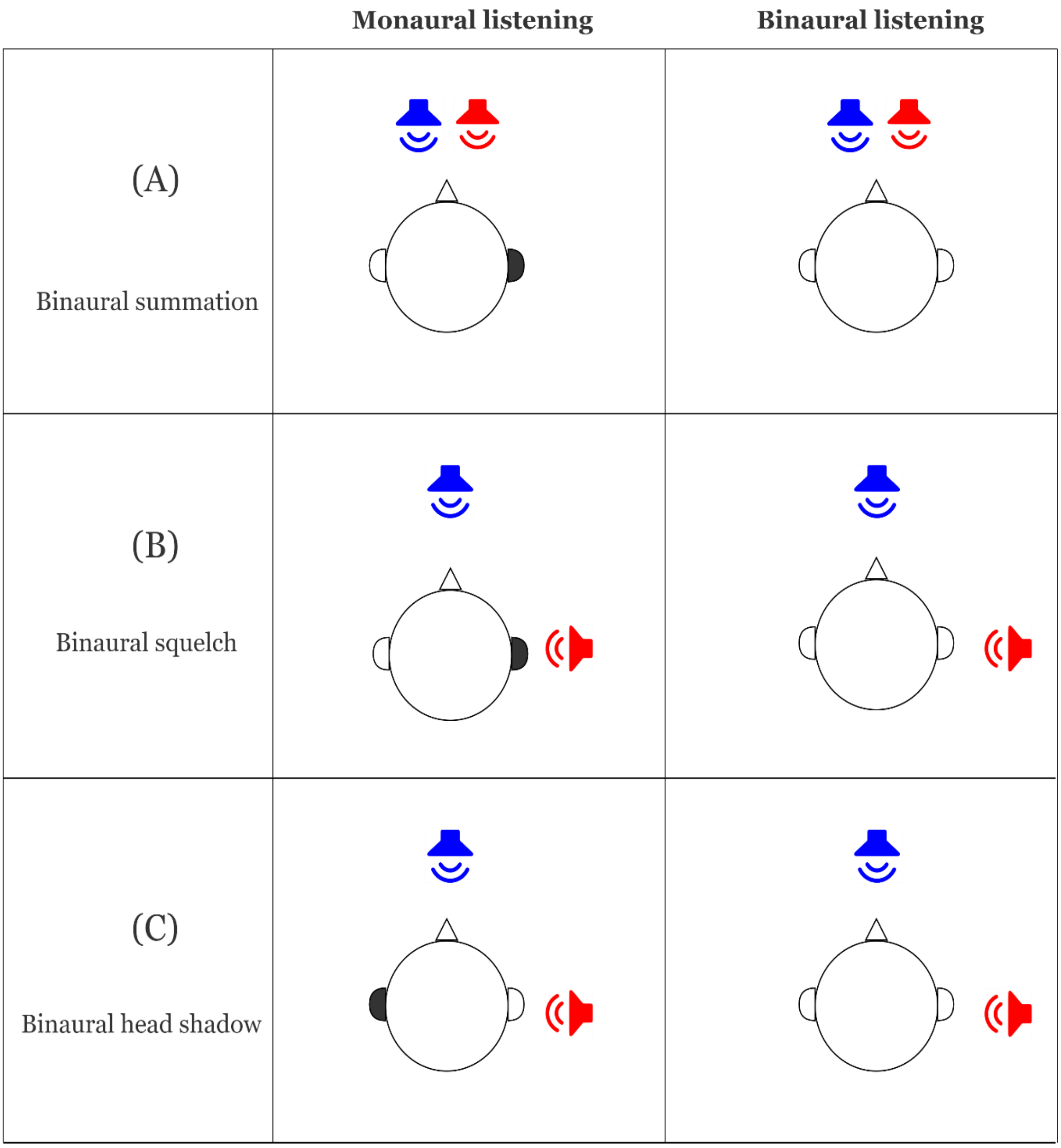

Figure 2.4: Schematic illustration of the loudspeakers configurations that are commonly used to measure the three binaural phenomena attributed to speech perception in noise: (A) binaural summation, (B) binaural squelch and (C) head-shadow effect. The blue loudspeaker indicates a speech source, and the red loudspeaker indicates a noise source. The shaded ear in the monaural listening condition indicates a non-listening ear.

The previous paragraphs discussed the three binaural mechanisms or effects involved in improving speech perception in noise with binaural hearing and the contribution of ITDs and ILDs to each binaural effect. The role of ITDs and ILDs in binaural redundancy and head-shadow effects are more straightforward than in binaural squelch. Binaural redundancy can be defined without interaural differences, whereas binaural head shadow depends only on ILDs (Dieudonné and Francart, 2019). In contrast, binaural squelch is more complex as it is primarily determined by exploiting ITDs and ILDs to extract the speech from the noise masker. Binaural squelch arises from the differences in low-frequency ITDs for speech and noise (Zeng *et al*., 2011). The gain in speech intelligibility at the level of 50% due to the introduction of ITDs in speech and noise is known as binaural intelligibility level difference (BILD) (Bronkhorst and Plomp, 1988). A difficulty might be associated with measuring the BILD because the effect of ITDs might be confounded with the ILDs. Bronkhorst and Plomp (1988) measured the separate effects of the ITDs and ILDs on the BILD for normal-hearing listeners. The noise masker (a noise that had a spectrum equal to the long-term average spectrum of speech) has been vocoded into two further signals: one containing only ITDs and the other only containing ILDs. The BILD ranged from 3.9 to 5.1 dB when the ITDs-only noise signal was used and ranged from 3.5 to 7.8 dB with ILDs only. Surprisingly, the BILD was reduced to 2.1-3.4 dB when the noise signal had both ITDs and ILDs, indicating a degrading effect of ILDs on the ITDs. Similar findings were demonstrated by Dieudonné and Francart (2019), who showed that introducing ILDs always degrades binaural squelch. They used four simulated head-related transfer functions corresponding to four different spatial conditions: no cues (noise at 0°), only ILDs, only ITDs, and all cues. The squelch effect in all cue conditions was smaller than in the only-ITDs condition. In addition, they showed that introducing the ITDs always increases binaural benefit as the squelch effect in all cue conditions was larger than that in the only-ILDs condition. Moreover, Dieudonné and Francart (2019) also demonstrated that their findings were the same across different types of noise.

Another advantage of binaural hearing relating to improving speech understanding in noise is the spatial release from masking (SRM). The SRM is defined as improving speech understanding due to the spatial separation of speech and noise while *listening binaurally*. The SRTs are typically lower (better) when the noise is presented at the side (as in Figure 2.5, panel B) compared to when it is at the front (as in Figure 2.5, panel A) while the target speech is at the front. The SRM is calculated by taking the difference between the SRT for the condition with noise at the front and the SRT for the condition with noise at the side (i.e. at 90°). Different mechanisms have been involved in the SRM: (1) better ear effect, which results from head-shadow effect (the SNR increases in one ear and decreases in the other ear), (2) binaural squelch, which results from utilising ITD and ILD differences of the target speech and the noise masker (Litovsky, 2012), and (3) spatial release from informational masking (informational masking occurs when the features of both the speech and masker can be heard but the listener has difficulty in discriminating between them particularly when the masker is speech or speech-like) (Moore, 2021). Dieudonné and Francart (2019) considered that the interpretation of the SRM quantitatively is hard due to the complexity of the different mechanisms involved. In other words, it would be difficult to interpret a measurement of reduced SRM as it would not be possible to know which mechanism is affected. The SRM values can be as large as 12 dB depending on the types and number of maskers and the degree of separation between the target speech and the noise masker (Hawley *et al.*, 2004, Litovsky, 2012, Dieudonné and Francart, 2019). For instance, the SRM tends to be larger when the speech and masker are similar (i.e. similar voices or content) compared when the speech and masker are different.

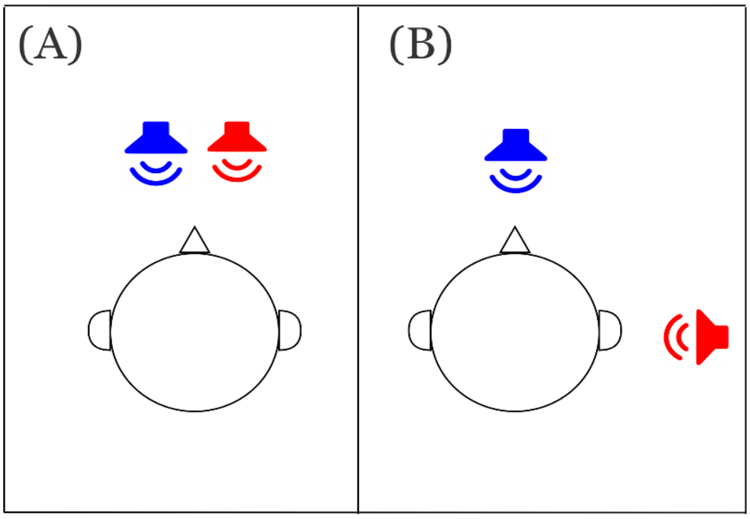

Figure 2.5: The two binaural listening conditions used to measure spatial release from masking (SRM). The left-hand panel (A) shows that speech (indicated as a blue loudspeaker), and noise (indicated as a red loudspeaker) are presented from the front of the listener. The right-hand panel (M) shows that speech (indicated as a blue loudspeaker) is presented from the front, and noise (indicated as a red loudspeaker) is presented from the right-hand side of the listener at 90°. The SRM is calculated as the SRT in condition A minus the SRT in condition B, where positive SRM values indicate a speech improvement in condition B.

2.1.4.2 Sound localisation

The role of ITDs and ILDs for sound localisation was explored in 1907 by Lord Rayleigh, who proposed an influential theory known as the Duplex theory (Rayleigh, 1907). Based on measurements using pure-tone stimuli, the theory proposed that only ITDs are used to localise low-frequency tones, and only ILDs are used to localise high-frequency sounds (above 500 Hz). Given that (as discussed earlier) the ILDs are negligible for low-frequency tones because their wavelength is much larger than the diameter of the head and the ITDs are undetectable for frequencies above 1500 Hz because of phase ambiguity, the Duplex theory seems to be satisfactory only to explain the localisation of pure-tone stimuli in the horizontal plane. However, most sounds encountered in everyday listening environments are complex sounds. As discussed in Section 2.1.1, previous studies showed that listeners are sensitive to ITDs carried by the envelopes in high-frequency complex sounds (Bernstein and Trahiotis, 2002, Macpherson and Middlebrooks, 2002). Therefore, the Duplex theory seems to be not strictly accurate to describe localisation for complex sounds. Wightman and Kistler (1992) and Macpherson and Middlebrooks (2002) investigated binaural cues to localise complex stimuli (broadband, low-pass, and high-pass noise burst) using virtual auditory-space techniques, which allow independent manipulation of ITD and ILD cues. These studies indicated that ITDs are the dominant cue for localisation of the broadband stimuli containing low-frequency components. The ILDs are the dominant cue for those containing only high-frequency components. For wideband stimuli, both ITD and ILD cues provided considerable weight; however the ITDs dominated most listeners. In more challenging situations, such as localisation in the presence of a background noise, neither cue always dominates: the listeners can use either cue that would provide most accurate estimation of the location of the sound source (Lorenzi *et al.*, 1999b, Akeroyd, 2006).

The ability of sound localisation can be assessed with different methods. One method measures the minimum audible angle (MAA) for a left-right discrimination task. The MAA refers to the smallest detectable change in the azimuth position. The lowest MAA can be measured at 1° for pure-tone stimuli (at 500 and 1500 Hz) when the reference location is straight ahead at 0° azimuth (Mills, 1958). This finding is in line with studies of the sensitivity of ITDs (Section 2.1.3) which showed that the smallest detectable change in ITDs is approximately 10 µs when the reference ITD is at the midline (at 0°). Such a change in the ITD would be obtained by moving the source of a sound through an angle of 1° relative to the listener (Moore, 2007a). Another method to assess the ability to localise sounds is measuring the accuracy in identifying the location of a source of sound when presented using different loudspeakers around the listener (Lovett *et al.*, 2010). Accuracy can be calculated as the percentage of correct responses, or the root mean square (RMS) error (the deviation in degrees between the actual locations of a sound source and locations identified). The RMS error would vary according to the testing environment, stimuli type and number of loudspeakers. For instance, Yost *et al*. (2013) reported a mean RMS error of 6° for 45 listeners with normal hearing when tested with 13 loudspeakers arranged in the front hemifield with 15° separation using loss pass, high pass, and broadband stimuli, whereas Hartmann (1983) reported a mean RMS error of 2.3° and 3.2° for seven listeners with normal hearing when tested with 11 loudspeakers with 18° separation using broadband noise in absorbing and reflecting rooms respectively.

2.1.4.3 Perception of source motion

The role of binaural cues for sound localisation, discussed in the previous section, is related to stationary sound sources. The binaural cues, particularly the ITDs, also contributed to the perception of moving sound sources. Warnecke and Litovsky (2019) investigated the role of TFS and envelope ITD cues on moving-sound perception. The authors used chimaera-style speech and noise stimuli to simulate stationary and moving sounds in virtual auditory space. The results showed that removing low-frequency TFS cues reduced the ability to discriminate between stationary and moving sounds for NH listeners. In addition, the study showed that the envelope cues strongly impact the perception of moving sound. When the stimuli had speech in the envelopes, the listeners' ability to distinguish between stationary and moving sounds was degraded and biased towards considering a sound as stationary, whereas the stimuli that had noise in their envelopes were biased towards the listeners considering a sound as moving. The impact of envelope cues on response bias is greater when the angular distances are smaller and reduce as angular distance increases, and motion perception becomes easier (Warnecke *et al.*, 2020).

However, ITD cue contribution is systematically dependent on the form of motion (i.e. linear, rotational, looming) and the velocity of the motion (Carlile and Leung, 2016). For example, intensity and ITDs are the dominant cues for linear motion (in front of the listener) at a moderate velocity of 10 m/s according to Rosenblum et al. (1987), (Lutfi and Wang, 1999). For rotational motion, the ITD cues were dominant in auditory motion perception, particularly for harmonic complex stimuli with low fundamental frequencies (Féron *et al.*, 2010). This would presumably be due to the greater availability of ITD information in such a type of stimuli with low fundamental frequency (Féron *et al.*, 2010, Carlile and Leung, 2016). In contrast, the ITDs have negligible effect in the perception of looming (the source is moving toward the listener) and receding (the source is moving away from the listener) motions. Increasing and decreasing the intensity are the most dominant cues in the perception of looming and receding motion, respectively (Seifritz *et al.*, 2002, Carlile and Leung, 2016).

Motion perception can be assessed by asking the listener to discriminate between a stationary and a moving sound or between motion directions (tracking the direction) (Middlebrooks and Green, 1991). The threshold can be measured by the minimum audible movement angle (MAMA), defined as the minimum change in location that a sound source needs to be moved to be detectable from a stationary sound source. Similar to the MAA for stationary sound sources, the smallest MAMAs are for stimuli at the midline in the horizontal plane (0° azimuth) and increase by increasing the azimuth (Grantham, 1986, Middlebrooks and Green, 1991). However, the MAMAs are two to three times larger than the MAAs for stationary stimuli when measured under comparable conditions in the horizontal plane (Grantham, 1986, Carlile and Leung, 2016). For instance, the MAMA for rotating stimulus (500-Hz pure tone) near 0° azimuth was 8.3° (Perrott and Musicant, 1977), whereas the MAA was 1° for stationary pure tone stimuli (at 500 and 1500 Hz) when the reference location is straight ahead at 0° azimuth (Mills, 1958). Furthermore, the MAMA is strongly dependent on the velocity. Perrott and Musicant (1977) showed that the MAMA increases from 8.3° to 21.2° as the velocity increases from 90° per sec to 360° per sec respectively.

2.1.5 Hearing impairment and binaural hearing

Peripheral hearing loss (conductive and sensorineural hearing loss) can distort or delay processing binaural information such as neural firing and phase-locking. Such distortions or delays could degrade the transformation of binaural information into spatial cues and the ability to assign spatial locations to perceived sources of the different sounds (Gallun, 2021). For example, it has been found that hearing loss, specifically cochlear hearing loss, has adverse effects on binaural processing, particularly the ability to perceive ITDs in TFS (Moore, 2021).

A substantial body of research was carried out on the binaural hearing abilities of listeners with hearing loss, including studies (Häusler et al., 1983, Bronkhorst and Plomp, 1989, Bronkhorst and Plomp, 1992, Koehnke et al., 1995, Lorenzi et al., 1999a). A general outcome of these studies indicates that the performance of hearing-impaired listeners, on average, is worse than NH listeners, with considerable variability among the hearing-impaired listeners in binaural tasks, such as (MAA and JND in ITDs and ILDs), speech perception in noise, and localisation. For instance, Häusler *et al.* (1983) measured the localisation and the interaural differences for 49 hearing-impaired and 39 NH listeners. The median MAA of hearing-impaired listeners was 4°, with one-quarter of listeners having an MAA of 9° or more. On the other hand, the average range of MAA of the NH listeners was 1- 4°. Additionally, their results showed that the JNDs for the ITDs and ILDs of the hearing-impaired listeners were impaired, regardless of the type of hearing loss, with the most severe binaural impairment found in those with severe unilateral hearing losses. Similarly, Bronkhorst and Plomp (1989) and Bronkhorst and Plomp (1992) reported a smaller SRM for hearing-impaired listeners than NH listeners. When the masker azimuth is moved from 0° to other azimuths for hearing-impaired listeners, the binaural gain was 2.6-5.1 dB less than for NH listeners (the gain ranged from 1.5-8 dB for NH and from 1-6.5 dB for hearing-impaired listeners). Moreover, the results showed that the gain due to ILDs for those with symmetrical hearing loss varied from 0 dB to normal values of 7 dB or more, whereas the gain due to ITDs was nearly similar to NH listeners. However, the gain due to ITDs was reduced for asymmetrical hearing loss. Therefore, the findings from these studies indicated that binaural hearing would be more adversely affected for listeners with asymmetrical hearing loss than those with symmetrical loss.

Although there is clear evidence of the adverse effect of hearing loss on binaural hearing, the degree of binaural impairment could not be predicated based on the degree or the type of hearing loss (Steven Colburn *et al*., 2006). For example, individuals with severe hearing loss showed small ITD JNDs, while others with moderate hearing loss had relatively high ITD JNDs (Häusler *et al.*, 1983). Furthermore, there was substantial heterogeneity in the binaural performance of the hearing-impaired listeners reported in the literature (Gallun, 2021).

Providing the appropriate intervention for listeners with hearing impairment can help restore some of the binaural functions of normal hearing. For instance, the benefit of bilateral hearing aid (HA) fittings for hearing-impaired listeners with symmetrical hearing loss are well established (Chan *et al.*, 2008, Dillon, 2012). Research showed that bilateral HA users have better binaural summation, binaural squelch, and head-shadow effects for speech understanding in noise (Bronkhorst and Plomp, 1989) and superior localisation performance compared to those who have unilateral fittings (Byrne *et al*., 1992). Furthermore, providing bilateral fittings can reduce the risk of auditory deprivation. Auditory deprivation refers to the reduction in speech perception scores in the unaided ear (Parks *et al.*, 2004). Silman *et al*. (1984) conducted a longitudinal study to compare pure-tone thresholds and speech-perception scores between 44 listeners fitted with bilateral HAs and a group of 23 individuals fitted with an HA in one ear over a period of four to five years. There was no difference for pure-tone thresholds for both ears of both groups. However, the results revealed a decrement in speech-perception scores in the unaided ear relative to the aided ear of the same participants or ears of those who had bilateral HAs, indicating an auditory deprivation effect for those monaurally fitted with an HA. Similarly, Silverman *et al.* (2006) found a reduction in word recognition scores in the unaided ear for a group of adults with asymmetric hearing loss over a duration of two years, whereas a reduction in the aided ear was not observed. Together these findings show the importance of providing binaural hearing for listeners with bilateral hearing loss to avoid further auditory deprivation. In addition, providing binaural hearing for bilateral hearing loss is important to retain the brain ability to use inputs from each ear effectively (Sammeth *et al*., 2011).

For listeners with bilateral severe to profound hearing loss, a single cochlear implant (CI) is often standard treatment. Adults typically receive one CI in most countries due to cost constraints. Therefore, restoring binaural hearing functions for adults with unilateral CI is challenging. An overview and discussion about the CI and possible treatment options to try restoring binaural hearing functions for adults with unilateral CI are provided in Sections (2.2 – 2.4).

2.1.6 Interim summary

Binaural hearing is important for improving the ability to understand speech in the presence of background noise, localise sounds, and track moving sounds. NH listeners are remarkably sensitive to even a 1° change in sound-source locations. The mechanism of binaural hearing can mainly be understood by considering the processing of interaural differences in time and the level of sounds at two ears. The normal auditory system can detect a change as small as in ITD of 10 µs or less and in ILD of 0.5 to 1 dB with binaural listening. The models and theoretical approaches of binaural cues for NH listeners were reviewed. It has also been shown that hearing loss and asymmetrical hearing can distort or delay the processing of binaural information. Providing appropriate intervention for restoring some of the binaural hearing functions is an important consideration within the field of audiology.

2.2 Cochlear implantation

2.2.1 Background

A cochlear implant (CI) is an electronic device for the functional replacement of the inner ear that can trigger auditory sensation through direct electrical stimulation of the auditory nerve (Lenarz, 2017). It is an intervention method devised to help individuals with bilateral severe and profound sensorineural hearing loss to provide hearing sensation. The CI consists of (1) internal and (2) external components. The internal components are a receiver-stimulator coil and electrode array surgically implanted into the inner ear. The receiver-stimulator coil is located under the skin into the mastoid bone behind the ear. The electrode array is placed in scala tympani in the cochlea, taking advantage of the cochlea's highly developed tonotopicity; the progression from high frequencies at the base of the cochlea to low frequencies at the apex (Ramsden, 2002). The modern electrode system is multichannel, which includes up to 22 electrodes. The external part sits behind the ear and comprises microphone, sound processor, and transmitter. Figure 2.6 illustrates a schematic diagram for the components of the CI. The microphone picks up sounds in the environment and sends them to the sound processor. Then, the sound processor is used to process the sounds by transforming the acoustic information into electrical stimulation codes. These codes and the power needed to activate the electrodes are transmitted to the internal part via a radio-frequency link which consists of a transmitter coil. The receiver-stimulator then decodes the radio-frequency signal using a demodulator to extract the electrical pulses, and each electrode in the electrode array collects the impulses from the receiver and sends them to the auditory nerve by simulating the spiral ganglion and the nerve fibres.

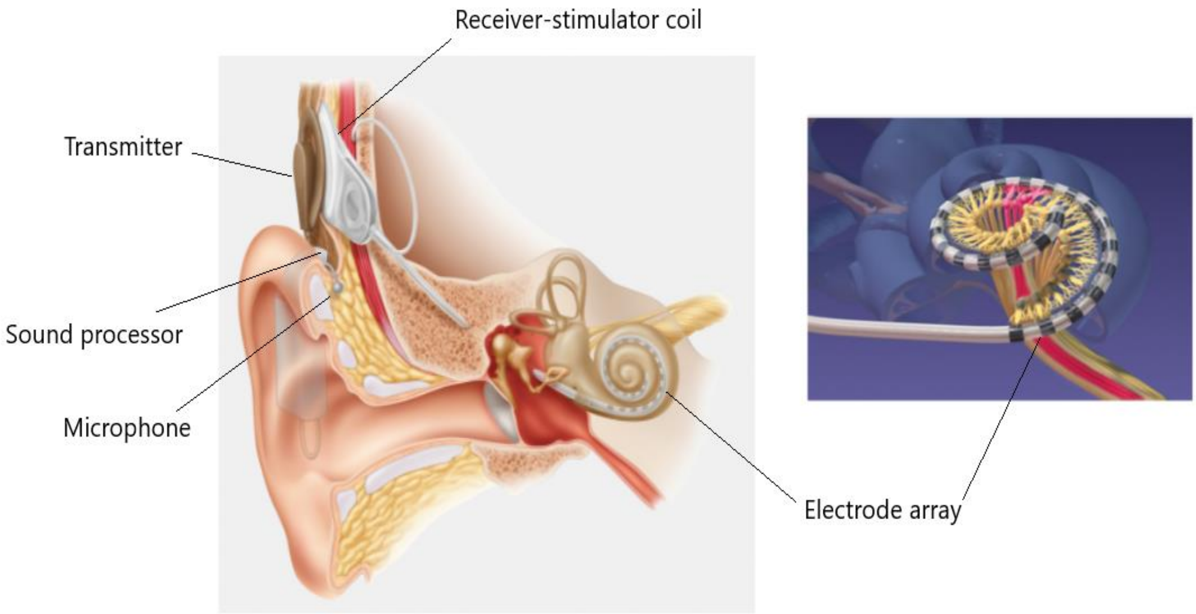

Figure 2.6: A schematic diagram of a cochlear implant showing the device's external and internal parts. Image adapted with permission from Lenarz (2017).

There are several processing strategies that can be utilised in the CI. Most of the current devices use one or a combination of the standard processing strategies: continuous interleaved sampling (CIS), main peak interleaved (MPIS), number of maxima, advances of encoding strategy, and high resolution (HiRes). The detailed description of these processing strategies is beyond the scope of this thesis; however the main aim of these strategies is to mimic the tonotopic organisation of the cochlea and the filtering function of the normal auditory system (Cosetti and Waltzman, 2011, Macherey and Carlyon, 2014). The CI sound processor converts an acoustic signal into electrical stimulation by subdividing the input signal spectrum into different frequency bands with a bandpass filter (ranging from 12 to 22). The signal's envelope is then extracted from the output of each band and used to modulate electrical pulses that stimulate the auditory nerves at different sites along the cochlea. Stimulation of electrodes placed at the basal part of the cochlea results in the perception of high frequencies while stimulation towards the apex of the cochlear would enhance low-frequency perception.

However, sounds with the CI may not be correctly perceived as the ability to extract information from sounds limited in the frequency, temporal, and amplitude domains. These limitations result from device and sensory limitations. The first limitation is that the spatial specificity of each electrode for a specific frequency range is limited. It has been shown that there are considerable overlaps between the electric fields of adjacent electrodes that reduce the number of stimulation areas to between four and eight instead of the physical availability of up to 22 electrodes (Cosetti and Waltzman, 2011). Therefore, the representation of the frequency content of the sounds is distorted due to poor spatial selectivity in the CI. In addition, the distortion of frequency content is also related to the position of the electrode array in the cochlea. Most of the electrode arrays are typically placed in the first (or the first one and a half) turn to prevent inner-ear tissue damage of the cochlea; thus the CI may not stimulate the nerve fibres in the apex, which is responsible for low-frequencies coding. To compensate for this, low frequencies are conveyed by electrodes that stimulate other parts of the cochlea, which typically respond to high-frequency sounds, resulting in a mismatch for the sound information and the stimulating part of the cochlea. The second limitation is that most processing strategies have a limited ability to convey the TFS of the acoustic sounds. The carrier signal used to convey the information of sounds to the nerve fibres is a train of biphasic pulses, which has a short duration of approximately 50 µs. This carrier signal permits the acoustic sounds to be sampled at a very high rate. However, It has been found that CI users cannot differentiate between stimuli that differ in their temporal modulations when they are fast (Macherey and Carlyon, 2014). Stimulation at high rates in the CI seems to have a deleterious effect on the TFS of the acoustic sounds. The third limitation in the CI is the narrow dynamic range (the differences in level between the comfortable sound and just audible sound) which is around 10-20 dB compared to the dynamic range in normal hearing (roughly 120 dB). In addition, there is considerable variability in the perceived current steps among CI users ranging from small numbers (seven steps) to similar numbers as in NH listeners (45 steps) (Macherey and Carlyon, 2014). Nevertheless, a CI provides a hearing sensation for those with severe to profound hearing loss and the brain shows flexibility to adapting to new signals.

2.2.2 CI candidacy

The criteria for CI candidacy vary across and also within countries (Vickers *et al*., 2016). This includes pure-tone audiometry thresholds, speech perception performance, duration of deafness, age, and benefit from HAs (Gifford, 2011). For instance, the guidelines in Belgium are that adults with pure-tone thresholds average worse than 85 dB HL at 500 Hz, 1 and 2 kHz in the better ear, and a CVC phoneme score of less than 31% at 70 dB SPL are candidates for CI (Raine and Vickers, 2017). In the UK, the guidelines for adults are pure-tone thresholds equal to or greater than 80 dB

HL at two or more frequencies between 500Hz-4000Hz without acoustic hearing aids, and an aided phoneme score worse than 50% on the Arthur Boothroyd word test presented at 70 dBA (NICE, 2019). CI candidacy guidelines for adults within the USA are more variable and dependent on aspects such as funding, e.g. private insurance or Medicare and Medicaid coverage, and specific CI company guidance (Medicare and Services, 2004, Gifford, 2011).

In countries where national (state) funding is the only funding source, and CI professionals are accountable to external bodies (i.e. in the UK and Belgium), the criteria for CI candidacy are stricter with less flexibility (Vickers *et al.*, 2016, Raine and Vickers, 2017). For example, the UK has used strict audiometric thresholds (equal to or greater than 90 dB HL at 2 and 4 kHz) and a BKB sentence score of less than 50% for adult candidacy criteria for many years until 2019, when the guidance was updated with more relaxed criteria (equal to or greater than 80 dB HL at two or more frequencies between 500Hz-4000Hz, and a phoneme score worse than 50% on the Arthur Boothroyd word test presented at 70 dBA). In addition, adults are eligible for one CI (unilateral CI) in UK. Offering two implants (bilateral CI) is only available via self-funding or in special circumstances such as in the UK, where bilateral CIs can be offered for adults who are blind or who have additional disabilities that increase their dependence on auditory stimuli as a primary sensory mechanism for spatial awareness. In contrast, the candidacy criteria are less restrictive and more flexible in countries where the CI is provided by other sources other than national funding, such as private insurance, local funding, and self-funding, as in the USA, India, and South Africa (Vickers *et al.*, 2016, Raine and Vickers, 2017).

In short, the CI candidacy guidelines in many countries where national funding is the main funding source tend to be less flexible and provide a unilateral CI for adults with bilateral severe to profound hearing loss. In other countries, although a second implant may be more accessible, the uptake is also limited and subject to private insurance coverage and personal funds.

2.2.3 Unilateral CI outcomes in adults and binaural hearing

It is well established that a unilateral CI is a cost-effective intervention for adults with bilateral severe and profound hearing loss (UK Cochlear Implant Study Group, 2004, Bond *et al.*, 2009, Cutler *et al.*, 2021). In addition, the outcomes with unilateral CI have significantly improved due to the development in CI technology over the last 25 years and expanding candidacy criteria of CI in terms of less strict candidacy criteria (Sammeth *et al.*, 2011). A recent scoping review (Boisvert *et al.*, 2020) appraised and integrated the recent evidence of the outcomes of unilateral CI in adults. The review included 102 studies that had a sample size of more than 10 participants. It showed that 75% of adult unilateral CI users obtained equal to or more than 42% and 60% on word and sentence perception in quiet respectively. The authors estimated that approximately 82% of adults with post-lingual hearing loss and 53% of adults with prelingual hearing loss were expected to have a speech perception improvement of 15% in the CI implanted ear. Furthermore, it has been shown that a unilateral CI improves quality of life, including improved mental health social functions (Damen *et al.*, 2007, Arnoldner *et al*., 2014, Hilly *et al*., 2016), improved general wellbeing (Vermeire *et al.*, 2005, Sanchez-Cuadrado *et al.*, 2013), and improved health-related quality of life (Lenarz, 2017). However, it should be noted that there is significant variability in outcomes and the ability to understand speech among the CI users (Green *et al*., 2007, Boisvert *et al*., 2020).

Unilateral CI has been found to be a highly effective intervention; however unilateral CI users do not have access to binaural cues (ITDs and ILDs). Given the advantages of binaural cues (Section 2.1.4), limited access to ITDs and ILDs affects the CI user's ability to localise sounds and understand speech, particularly in less favourable listening environments such as where there is environmental noise. Speech perception in noise for unilateral adult CI users continues to be challenging (Fetterman and Domico, 2002, Firszt *et al*., 2004, Dunn *et al*., 2010). Localisation performance with unilateral CI remains close to chance level (Buhagiar *et al.*, 2004). These two auditory functions are important for effective everyday communication. In addition, it has been found that the asymmetry of hearing resulting from monaural fitting (single HA or CI) reduces the naturalness of sound quality and increases listening effort (Noble and Gatehouse, 2004). Binaural processing is thus more disrupted with asymmetrical input than when the input is symmetrical for listeners with bilateral hearing loss (Firszt *et al*., 2008).

It is important to consider ways to improve binaural or symmetry hearing in unilateral CI users. Bilateral CI seems to be a possible intervention to restore binaural hearing functions. However, bilateral CI is not available for adults in several countries due to cost constraints, such as in the UK, Netherlands, and Belgium (Raine *et al.*, 2010, Crathorne *et al.*, 2012, Smulders *et al*., 2016b, NICE, 2019). To compensate for this, audiologists typically recommend an (hearing aid) HA for the non-implanted ear, known as *bimodal hearing*. Binaural hearing (either with a bilateral CI or bimodal) has been shown to be advantageous for adults with unilateral CI (Ciorba *et al*. (2021) and was significantly better than adults with unilateral CI in a speech-intelligibility task.

In summary, improvements to binaural hearing for adults with unilateral CI can be provided through fitting the contralateral ear with a second implant or with an HA. The benefits of bilateral CI and bimodal hearing for adult CI users are discussed in Sections 2.3 and 2.4.

2.3 Bilateral CI

Interest in bilateral implantation has increased in recent years. Bilateral CIs ensure that the ear with the best performance outcome is implanted. In addition, bilateral CIs can potentially improve binaural hearing by allowing bilateral input into the auditory system in both ears.

2.3.1 Binaural cues with bilateral CI

Using bilateral CI could help to improve some binaural hearing functions; however it does not mean that it can necessarily restore full functional binaural hearing like that of a person with normal hearing in both ears. This is because binaural hearing primarily depends on the precise integration of the interaural cues (ITDs and ILDs). However, the ITD and ILD cues may not be accurately represented with bilateral CI for several limitations.

The first limitation is related to the CI signal processing. Low-frequency fine-timing (TFS) ITD cues are discarded in current clinical CI devices. As described in Section 2.2.1, the incoming signal is separated into several frequency bands using a bank of bandpass filters functioning where the number of filters is equal to the number of available electrodes. Then, further processing is applied to the output of each band to extract the envelope of the signal in that band. However, the maximum rate at which the envelope can fluctuate is limited by the bandwidth of the band, which is often not more than a few hundred Hz wide. Envelope information from each band is used to determine the electrical stimulation for the corresponding electrode at a fixed stimulation rate which is not related to the acoustic signal properties (van Hoesel, 2011). Thus, the TFS information contained in the electrical pulse rate is discarded, and any ITD-based benefit would be obtained from low-rate envelope cues. Moreover, since two processors with bilateral CI function independently, each sound processor responds to signals above the noise at independent times (Litovsky *et al.*, 2012), resulting in disrupted timing cues. Therefore, the ITDs are poorly perceived by bilateral CI users. Although the ITDs may be present in the envelope cues, the ITD thresholds for bilateral CI users can vary dramatically (van Hoesel, 2004). The ITD thresholds for pulse trains of about 100 pps can range from 100 to 350 μs with much higher or immeasurable for higher pulse rates exceeding 400-800 pps (Francart *et al*., 2009, Laback *et al*., 2015). Laback *et al*. (2015) pooled reported ITD thresholds in the literature for pulse training from 14 studies (a total of 100 bilateral CI users). They compared them to the ITD thresholds of NH listeners for pure-tone stimuli from five studies (a total of 22 NH listeners). The ITD thresholds for CI users varied dramatically from the lowest thresholds being close to the thresholds of NH listeners and the worst thresholds exceeding the natural range of ITDs in normal hearing (800 μs).

Furthermore, the median ITD threshold for CI users (roughly 144 µs) was greater than for NH listeners (11.5 µs).

In contrast, the ILD cues seem to be perceived accurately with bilateral CIs as the amplitude of the electrical pulses represents the amplitude envelope of the signal (Lovett *et al.*, 2010). Several studies showed good ILD sensitivity for bilateral CI users (van Hoesel and Tyler, 2003, Laback *et al*., 2004, van Hoesel, 2004, Grantham *et al*., 2008, Litovsky *et al*., 2012). For example, the sensitivity to ILD cues for some bilateral CI participants in the van Hoesel and Tyler (2003) study was better than 1 dB. In another study, the ILD thresholds ranged from 1.9 to 3.8 dB (Grantham *et al*., 2008). In a more recent study, Ausili *et al*. (2020) measured the ILD sensitivity for 25 bilateral CI users. The results showed bilateral CI users were sensitive to ILD cues as all the participants had ILD sensitivity of approximately 11.2 dB. Furthermore, several studies demonstrated that the ILD cues seem to account for much of the performance of bilateral CI users in the localisation tests (Laback *et al*., 2004, van Hoesel, 2004, Grantham *et al*., 2007, van Hoesel *et al*., 2008, Aronoff *et al.*, 2010). For instance, Aronoff *et al*. (2010) used head-related transfer functions to assess ITD and ILD contributions to bilateral CI users' ability on localisation tasks. The participants were tested on three conditions: (1) both ITD and ILD cues present, (2) only-ITD cues present and (3) only ILD cues present. The mean performance in both cues and only-ILD cue conditions was identical, whereas the performance was significantly poorer in the only-ITD cue condition. This finding indicates the strong reliance on ILD cues with bilateral CI.

However, the ILDs are variable across bilateral CI users. This could be related to different possible reasons such as duration of deafness, duration of time between implants, and duration of binaural input (Litovsky *et al.*, 2012). It was also shown that ILD sensitivity is affected by the CI dynamic range processing. Dynamic range is often reduced through the compression of the typical front-end automatic gain control (AGC) which affects the representation of ILDs particularly when the input levels on both sides exceed the dynamic range (Vaerenberg *et al*., 2014a, Spencer *et al*., 2019). For instance, Grantham *et al.* (2008) showed that the ILD sensitivity was poorer (mean thresholds 3.8 dB) when the AGC was activated compared to when the AGC was switched off (mean thresholds 1.9 dB). Furthermore, independent operation of the two processors (two AGCs) can substantially reduce the ILDs, especially when the compression of one sound processor is activated while not in the other processor (Tyler *et al*., 2003, Seeber and Fastl, 2008, Dorman *et al.*, 2015, Potts *et al*., 2019). This can be seen when the sound source is at one side of the listener; because the head acts as an acoustic barrier; each sound processor will receive a signal with different levels. This will cause the AGC in each processor to work differently.

A second limitation that affects binaural advantages with bilateral CI is binaural asymmetry, resulting from a mismatch in electrode arrays' position and insertion depth or the difference in the implantation time between the two ears (Ausili *et al.*, 2020). This is likely to produce inaccurate matching of the inputs in the two ears because the current sound processors are likely to deliver stimuli bearing different frequency ranges to electrodes place-matched in the two ears (van Hoesel, 2004, Litovsky *et al*., 2012). The mismatch processing can distort ITD and ILD cues (Tyler *et al*., 2003, van Hoesel, 2004). For example, Long (2000) tested the effect of the place-matching of the electrodes on the interaural sensitivity for one participant, and the results showed that place variations to the order of 2 mm could change the interaural sensitivity. Additionally, ITD and ILD sensitivity was found to increase as the electrode mismatch increased above 3 mm (Goupell *et al*., 2013).

The third limitation is related to pathology in the auditory system of CI users. As the CI users have severe to profound hearing loss, peripheral and central neural degeneration due to lack of stimulation is most likely to occur. For instance, a degradation of neural ganglion cells is known to occur after a prolonged period of auditory deprivation (Kan and Litovsky, 2015). Furthermore, listeners with hearing loss might develop abnormal binaural brain maps or have different patterns of hearing loss in each ear (Tyler *et al*., 2003).

In summary, binaural advantages with bilateral CI are limited to some degree by three main limitations. Firstly, CI signal processing and the independence of the two sound processors have been shown to affect the accuracy with which ITDs and ILDs are presented. Secondly, mismatch place and the insertion depth of electrode arrays between the two ears and finally, auditory-system pathology and having survival hair cells and nerve fibres.

2.3.2 Bilateral CI benefits

There are many studies that have looked at the benefits of bilateral implantation compared to a unilateral CI but they differ in terms of methodology, such as outcome measures, test materials and test settings. A summary of these studies is provided in Appendix A, B, and C.

It is noted that the most frequently reported benefits of bilateral implantation are improved speech recognition in noise and sound localisation. The body of literature on these bilateral implantation benefits is discussed in the Sections 2.3.2.1 to 2.3.2.4

2.3.2.1 Speech perception in noise

Speech understanding in the presence of noise is perhaps the most frequently reported performance-outcome measure used to contrast unilateral CI versus bilateral CIs. A summary of speech-in-noise outcomes from bilateral CI studies can be found in Appendix A.

When speech and noise are presented from the front (S0°N0°), the average bilateral CI benefit equates to no significant difference or slightly better improvement than unilateral CI (Gantz *et al*., 2002, Tyler *et al*., 2002a, van Hoesel and Tyler, 2003, Schleich *et al.*, 2004, Ramsden *et al*., 2005, Litovsky *et al*., 2006a, Buss *et al*., 2008, Laske *et al*., 2009, Litovsky *et al*., 2009, Koch *et al*., 2010, van Zon *et al*., 2017). For instance, Buss *et al*. reported a slight improvement of up to 5.7% from binaural summation, and van Zon *et al*. showed no difference in the performance between bilateral and unilateral CI users when the speech and noise were presented from the front. Only a few studies showed a significant improvement for bilateral CI users. A recent study (de Graaff *et al.*, 2021) used direct audio input to present a digits-in-noise test for ten bilateral CI users, demonstrating better SRTs with the two CIs than with one CI. The authors suggested that improved performance in bilateral CI conditions were probably related to the binaural summation effect.

When the noise was spatially separated from the speech signal, many studies showed a significant improvement with bilateral CI compared to unilateral CI resulting from the head-shadow effect, when the ear with good SNR is added (Gantz *et al*., 2002, Mueller *et al.*, 2002, Tyler *et al*., 2002a, van Hoesel and Tyler, 2003, Laszig *et al*., 2004, Schleich *et al*., 2004, Senn *et al*., 2005, Litovsky *et al*., 2006a, Tyler *et al*., 2007, Buss *et al*., 2008, Litovsky *et al.*, 2009, Koch *et al*., 2010, Rana *et al.*, 2017). A substantially large improvement of 32% to 38% in speech scores was reported by Mueller *et al*., Senn *et al*. and Buss *et al.*, and improvement of 4 to 7.5 dB in SNR was reported by Schleich *et al*., Litovsky *et al*. and Rana *et al*. However, a small improvement of 10-13% in speech scores was observed in a few studies (Mueller *et al.*, 2002, Buss *et al*., 2008) with bilateral CI compared to unilateral CI with noise on the opposite side of the CI (squelch effect). Similarly, Litovsky *et al*. (2009) and Kokkinakis and Pak (2014) reported a small improvement that ranged from 0.9 to 2 dB in SNR with bilateral CI over unilateral CI with noise at the opposite side of the CI. These findings indicate that bilateral CI users may only benefit from a limited advantage of binaural squelch. Given that binaural squelch arises from the differences in low-frequency ITDs for speech and noise (Zeng *et al.*, 2011), the limited binaural squelch advantage for bilateral CI users may be related to the poor sensitivity to ITD cues with current clinical CI devices (as discussed in Section 2.2.1). Kraaijenga *et al*. (2016) argued that bilateral CI users can develop a measurable benefit from binaural squelch after a period of 2-3 years post-implantation as a result of central adaptation due to brain plasticity. They measured the squelch effect for 19 simultaneous bilateral CI users yearly for 3 years. After the first year, the binaural squelch was measurable for 13 out of 19 participants but was not significant. By the end of the second year, a significant binaural squelch effect (1.9 dB) was found in the participants' best performing ear. The squelch effect amounted to 1.3 to 1.7 in both ears after 3 years. In contrast, an evident binaural squelch effect did not develop for 16 sequential bilateral CI users with a 2-year inter-implant interval after a median follow-up of 4 years (Kraaijenga *et al.*, 2018). The authors examined whether a difference in the performance between the first and the second CI or implanting the better or the worst ear first was related to the absence of squelch effect for the sequential CI users. They did not find any correlation between these two factors and the results. The findings from these studies (Kraaijenga *et al.*, 2016, Kraaijenga *et al*., 2018) suggest the benefit of having simultaneous binaural access in the central adaptation of the brain and continuing the binaural processing.

All the studies discussed above assessed speech-perception abilities for CI users by using a single noise source to measure the three potential binaural advantages (head-shadow effect, binaural squelch and summation) individually. Ricketts *et al*. (2006) used a slightly more real-life listening configuration to assess the speech-perception abilities of 16 bilateral CI users. The speech signal was presented from a speaker placed in front of the listeners where uncorrelated competing noise samples were played simultaneously through five loudspeakers placed at 30°, 105°, 180°, 255° and 330° azimuths relative to the position of the head. They used both fixed and adaptive SNR methods. The results revealed a significant bilateral advantage of 3.3 dB using the adaptive SNR method, and a significant improvement of 9% was also obtained using a fixed method (+10 dB SNR). The authors suggested that the bilateral advantage obtained by using this specific test arrangement was primarily attributable to the combined effects of binaural squelch and summation. The impact of the head-shadow effect seemed to be limited in this listening situation as both ears would have similar SNRs. Mosnier *et al.* (2009) used a similar method of diffuse noise presented simultaneously from five loudspeakers. They found a bilateral advantage of 5-10% with bilateral CIs compared to unilateral performance in difficult listening conditions (poor SNR +5 dB).

It is challenging to interpret the findings of these studies due to the large variability in the participants' demographics, testing protocol and methodological design. Despite these differences, a few general conclusions can be drawn. The findings suggest that bilateral CI users stand to gain more benefits of speech understanding in the presence of noise than using one implant, particularly when the speech and noise are spatially separated. In addition, the most widely reported and largest binaural advantage is the head-shadow effect.

2.3.2.2 Localisation and tracking of moving sounds

Several studies assessed localisation ability for sounds presented in the frontal horizontal plane for bilateral adults CI users. A summary of these studies is provided in Appendix B.

It can be seen that there is strong evidence that sound localisation ability in adult CI users is significantly improved with two implants compared to one CI alone (Gantz *et al*., 2002, van Hoesel and Tyler, 2003, Laszig *et al*., 2004, Nopp *et al*., 2004, Verschuur *et al*., 2005, Grantham *et al*., 2007, Neuman *et al*., 2007, Tyler *et al*., 2007, Dunn *et al*., 2008, Litovsky *et al*., 2009, Koch *et al.*, 2010, Dunn *et al*., 2012, van Zon *et al.*, 2017). In these studies, participants were tested using various numbers of loudspeakers (2-17) placed in a frontal plane, various sound levels (54-80 dB SPL), and different types of stimuli (noise burst, broadband noise, tones, speech samples). The average improvement with bilateral CIs ranges from 13° to 43° reduction in localisation errors compared to a unilateral CI. For instance, Verschuur *et al*. (2005) compared the sound localisation accuracy of 20 adult bilateral CI users using an 11-loudspeaker array with five different types of stimuli. They found that the mean localisation error with bilateral CIs was reduced by 43° compared with a unilateral implant (the mean error was 24° and 67° for bilateral and unilateral conditions respectively). However, the localisation ability of bilateral CI users is still poorer than those of hearing-aid users (10°) or NH listeners (2-3°) when tested with the same methodology (Verschuur *et al.*, 2005).

In a more recent randomised controlled trial conducted by Smulders *et al*. (2016a), the localisation performance between 19 bilateral CI users and 19 unilateral users was compared using the Dutch AB-York Crescent of Sound. A phrase was presented from one of nine loudspeakers, and the results were calculated as a percentage of correct responses with 60°, 30°, and 15° angle separation between loudspeakers. Participants with bilateral CIs performed significantly better than those with unilateral CI in all possible test conditions (the percentage differences between the two groups were 43%, 41%, and 27% when sounds were presented from 60°, 30°, and 15° respectively). Additionally, van Zon *et al.* (2017) conducted a follow-up after two years of implantation for the participants enrolled in the Smulders *et al*. study to evaluate the learning effect over time. The results showed no significant difference between the first- and second-year follow-up, indicating the benefits of bilateral CIs remain stable over time. The localisation advantage of bilateral CIs is possible because bilateral CI users have much better sensitivity to differences in levels between the ears ILDs than to differences in ITD (Peters *et al*., 2010).

All the studies discussed above were done in quiet. Mosnier *et al.* (2009) assessed the localisation performance of 27 bilateral CI users in a complex, noisy environment. The participants were asked to determine the location of speech signals presented in a random sequence from one of five loudspeakers in the presence of a cocktail-party background noise coming from five loudspeakers. The results indicated that speech localisation in noise was better with bilateral CI than unilateral CI. However, there were large individual differences as there was a lack of improvement in localisation abilities in noise in 12 of the 27 participants included in that study. The reason for this variability might be related to the method that they used as it seems that identifying the source of sound in the presence of background noise was challenging for CI users.

The benefit of bilateral CI over unilateral CI on tracking moving sound was also investigated. As discussed in Section 2.1.4, perception of moving sound is one of the benefits of binaural hearing. Although little research has assessed the performance of adult bilateral CI users, the results indicated the superiority of bilateral CI over unilateral CI on tracking moving sound tasks. For instance, Goman (2014) used a semi-circular array of nine loudspeakers to present a sequence of acoustic stimuli. The stimuli were presented into four trajectories of movement as: (1) left-front-right, (2) right-front-left, (3) left-front-left, (4) and right-front-right. The mean performance was significantly better when using two CIs (80.21%) compared to when using one CI (31.25%).

In summary, bilateral CI improves the performance of adult unilateral CI users on localisation and tracking of moving sound.

2.3.2.3 Self-reported benefits

Self-reported benefits for bilateral CI users were assessed with different measures (as reported in Appendix C).

The speech, spatial and qualities hearing scale (SSQ) has been used in many studies (Summerfield *et al.*, 2006, Noble *et al.*, 2008, Laske *et al*., 2009, Smulders *et al*., 2016a, van Zon *et al*., 2017, Lee, 2018). These studies showed better self-ratings for two CIs than one CI. Noble *et al*. (2008) compared self-reported ratings on the ten subsections of the SSQ between 36 bilateral CI users and 105 unilateral users. The bilateral group showed significantly higher ability ratings than the unilateral group in the spatial-hearing domain and on most aspects of other qualities of hearing (segregation, naturalness, and listening effort). There was no significant difference in the speech subsections. This finding was consistent with the measured speech perception and localisation performance. Noble *et al*. (2008) stated that unilateral CI could provide significant benefit across most hearing functions included in the SSQ, whereas bilateral CIs would offer further benefit across those functions. Laske *et al*. (2009) found better mean and median on all three sections with bilateral CI but differences were just below statistical significance. However, in two more recent studies conducted by Smulders *et al.* (2016) and Lee (2018), the bilateral CI group showed significantly higher ratings in all three sections than those with a unilateral CI. Furthermore, the bilateral CI group, in a randomised controlled trial conducted by van Zon *et al.* (2017), showed significantly better results in spatial hearing and speech subsections, particularly in understanding in silence, background noise, resonating environments, and on the telephone than the unilateral CI group after two years' follow-up. In addition, the bilateral CI group showed higher scores on the qualities-of-hearing subscale but not significant. The results of the above studies suggested that bilateral CI users showed higher self-reported ratings on at least one of the subsections of the SSQ than those with a unilateral CI.

Self-reported benefits have also been assessed with other measures such as the Abbreviated Profile of Hearing Aid Benefit (APHAB) (Litovsky *et al*., 2006a, Wackym *et al*., 2007), Nijmegen Cochlear Implantation Questionnaire (NCIQ) (Smulders *et al*., 2016a, van Zon *et al.*, 2017), Glasgow Health Status Inventory (GHSI) (Summerfield *et al.*, 2006), EuroQol EQ-5D (EQ-5D) (Summerfield *et al.*, 2006, van Zon *et al*., 2017), the Health Utilities Index Mark III (HUI3) (Summerfield *et al*., 2006, van Zon *et al.*, 2017), Time Trade-off (TTO) (Smulders *et al*., 2016a, van Zon *et al*., 2017), and Visual Analog Scale (VAS) (Summerfield *et al.*, 2006, Smulders *et al*., 2016a). The bilateral CI group reported better hearing capabilities than the unilateral CI group on the NCIQ questionnaire, however not significantly so (Smulders *et al.*, 2016a, van Zon *et al*., 2017). The findings suggested that the second implant might not have a positive effect on the individual's self-esteem, activity levels or social communication. Although the NCIQ includes items on hearing in both easy and difficult environments, it does not focus on spatial hearing like the SSQ scale. This might explain why the participants in those studies had significantly better results in the SSQ but not in the NCIQ.

Summerfield *et al*. (2006) used four different quality-of-life measures (GHSI, HUI3, VAS, and EQ-5D) to measure the bilateral CI benefits after three and nine months' post-bilateral activation. A significant improvement was only found in GHSI with bilateral CI compared to the unilateral condition. In addition, they measured the annoyance of tinnitus using a questionnaire. The mean annoyance due to tinnitus significantly increased with having the two CIs particularly after 3 months' post-bilateral activation. The researchers suggested that the absence of a positive effect on the three quality-of-life measures (HUI3, VAS, and EQ-5D) from improved hearing with using two implants might result from the negative effect of worsening tinnitus on quality of life after receiving the 2nd implant. To test their hypothesis, Summerfield *et al*. (2006) carried out a statistical analysis to investigate the relationship between the annoyance due to tinnitus and the change in the quality of life. They found that the significant increase in the overall quality of life was significantly correlated with a reduction in annoyance due to tinnitus. Therefore, they concluded that the change in annoyance due to tinnitus is a significant contributor to the change in quality of life.

Smulders *et al*. (2016a) and van Zon *et al*. (2017) also used quality-of-life measures to assess the difference between bilateral CI and unilateral CI groups (between-subject comparison) 1- and 2-year post-implantation respectively. Smulders *et al*. (2016a) found significantly better scores for the bilateral CI group compared to the unilateral CI group on TTO and VAS hearing one-year post-implantation. Interestingly, van Zon *et al*. (2017) found no significant difference between the two groups at two years' post-follow-up on the same outcome measures (VAS and TTO). In addition, they did not find significant differences between the two groups on other quality-of-life measures used in their study (EQ-5D and HU13). van Zon *et al*. (2017) concluded that the CI, either unilateral or bilateral, would improve the quality of life compared to preoperative situations. They also suggested that the difference between the unilateral and bilateral CI on quality-of-life measures would be investigated properly by using within-subject design. However, Summerfield *et al*. (2006) used a within-subject design and showed, as discussed earlier, that there was no difference between the unilateral and bilateral CI condition on the same quality-of-life measures used in van Zon *et al*. (2017) (HUI3, VAS, and EQ-5D). Moreover, using a within-subject design would not reflect the real difference between unilateral and bilateral CI because the unilateral CI condition of bilateral CI users is not representative for the actual unilateral CI users in real-life listening conditions.

In short, a second implant may result in self-reported benefits, particularly on speech and spatial hearing but these benefits are not necessarily reflected in the quality of life measures.

2.3.2.4 Benefit versus cost-effectiveness of bilateral CI in adults

Bilateral CIs have been shown to be an effective hearing rehabilitation for children (Litovsky et al., 2006c), and there is a trend of providing bilateral CIs simultaneously for children (Peters *et al*., 2010). Adults, however, typically only receive one CI. Although many studies have shown that bilateral CI can provide benefits in terms of speech perception, localising sound source and self-reported benefit (Nopp *et al.*, 2004, Schleich *et al*., 2004, Verschuur *et al*., 2005, Litovsky *et al*., 2006a, Litovsky *et al*., 2009, Cullington and Zeng, 2011, Schafer *et al.*, 2011, van Schoonhoven *et al*., 2013), there is considerable variability in benefit reported across studies.

The policy and candidacy guidelines in many countries is for unilateral CI rather than bilateral CI for adults because of the cost constraints (Smulders *et al*., 2016b). Summerfield *et al*. (2002) estimated the cost-utility of bilateral CI versus unilateral CI for a 30-year period using a scenario-based approach applied to 79 NH listeners who answered the TTO questionnaire. They found a greater improvement in quality of life per unit of cost with a unilateral CI when compared to the improvement in quality of life achieved by the second CI. In a randomised control trial, Summerfield *et al.* (2006) used the HUI3 and the EQ5D questionnaires to assess cost-utility for 24 unilateral adult users who received a second implant after 12 months. There was no significant difference in utility scores between the unilateral and bilateral CI, and the mean gain from the bilateral CI was similar to those found with bilateral CI in their previous study (Summerfield *et al.*, 2002). Similarly, the assessment of health-utility benefit for bilateral CIs reveals that most of the benefit is derived from the first implant, whereas the second implant only provides an additional 11% benefit of health utility (Chen *et al*., 2014, Grewal *et al*., 2015).

However, Smulders *et al*. (2016b) argued that measurement of the cost utility largely depends on the quality-of-life questionnaire used. They measured the cost utility of bilateral CI compared to unilateral CI for 38 adults eligible for CI using the multicentre randomised controlled trial in the Netherlands. The cost utility was assessed using five quality-of-life and quality-of-hearing questionnaires, namely the HUI3, TTO, VAS on hearing, VAS on general health, and EQ-5D. They calculated the quality-adjusted life years by multiplying utility scores with periods of 2, 5, 20, 25 years and the actual life expectancy of CI users. The measurements showed that bilateral CI becomes cost-effective after periods of 5 to 10 years of bilateral CI use, based on the HUI3, VAS on hearing, and TTO. Yet the measurements based on EQ-5D and VAS on general health status indicated a second implant would not be cost-effective.

In the UK, NICE (2009) and NICE (2019) reviewed the evidence and cost-effectiveness of CI for adults. Although it found some positive trends towards bilateral CI benefits, it could not find significant evidence; as a result, it recommends a unilateral CI for adults. Two further systematic reviews assessed the effectiveness and cost-effectiveness of bilateral CIs in adults (Crathorne *et al.*, 2012, van Schoonhoven *et al.*, 2013*)*. Their findings are similar to the NICE review, reporting that bilateral CIs are clinically effective, particularly in localisation tasks and self-reported measures but are unlikely to be cost-effective. In a more recent study, Theriou *et al*. (2019) assessed the cost-effectiveness of available treatment options, i.e. unilateral CI, bilateral CI, and bimodal stimulation for adults with bilateral severe to profound hearing loss from a nationally funded healthcare perspective in the UK and the USA. The cost-utility was estimated using the self-reported health-related quality-of-life questionnaire (HUI3) for 91 adult unilateral CI users. The analysis indicated that although bilateral CI produces more health benefits than other treatment options, bilateral CI is highly unlikely to be the most effective treatment option for adults with bilateral severe to profound hearing loss due to the excessive costs needed when providing the two CIs.

However, one important limitation of studies looking at the effectiveness of bilateral CI (Nopp *et al.*, 2004, Schleich *et al*., 2004, Litovsky *et al*., 2006a, Litovsky *et al*., 2009, Cullington and Zeng, 2011, Schafer *et al.*, 2011, van Schoonhoven *et al*., 2013) centres around the measures that have been used. Measures used in standard audiology practice and for research often include only measures of speech in noise, both presented by a loudspeaker directly in front of the person. Measures that represent real-life listening situations, such as roving speech in noise, localisation, tracking of moving sound and telephone use in both quiet and noise are needed to better capture functional gain in a more ecologically valid way.

In summary, there is evidence that bilateral CI can offer benefit over unilateral CI for adults, but the reported outcomes are variable. Most studies to date show that despite benefits, bilateral CI is not necessarily cost-effective. A limitation of current practice and many research studies is that the measures used are not as effective as they need to be and offer a poor reflection of real-life listening environments.

2.4 Bimodal hearing

Using an HA in the non-implanted ear, known as bimodal hearing, is an intervention option for those with unilateral CI. Bimodal hearing is recommended for unilateral CI users with residual hearing in the non-implanted ear (Offeciers *et al.*, 2005).

2.4.1 Binaural cues with bimodal hearing

Binaural advantages with bimodal hearing are limited because the ITD and ILD cues might not be perceived accurately for the same factors that affect the users with bilateral CI (as discussed in Section 2.3.1). First, TFS cues are not preserved in the signal that picked up the CI sound processor. Second, binaural asymmetry results from a mismatch between the CI and HA place of stimulation where the same signal stimulates different places in the cochlea for electric (CI) and acoustic (HA) stimulation (Francart and McDermott, 2013). For acoustic stimulation, the place in the cochlea that will be stimulated is based on the frequency content of the signal, whereas the CI stimulation, delivered by electrodes placed in the cochlea, is based on a frequency-to-electrode allocation applied in the sound processors during the mapping. Third, the effect of the hearing loss on the auditory system and neural survival across the two ears is an important factor that greatly affect the representation of binaural cues.

There are also limitations specific to bimodal hearing that restrict the binaural advantage. The different signal processing of the two modalities (HA and CI) systematically affects the representation of ITDs and ILDs in terms of signal processing, signal travel path, frequency range and the neural activation approaches between the two ears (van Hoesel, 2012). The two devices have different processing delays subject to the sampling rate and the algorithm implemented in each device. When the signal is picked up by the microphone of the CI sound process, it is subjected to a device-dependent processing delay ranging from 5 to 20 msec. (Stone and Moore, 1999). Additional short processing delay is also applied when the implanted chip decodes the signal; then the electrical signal stimulates the auditory nerve. Similarly, the signal that picked up the HA microphone is also subjected to a device-dependent processing delay and a frequency-dependent travelling wave delay (Stone and Moore, 1999). The processing delay of the HA is generally smaller than the processing delay of the CI sound processor, with differences of up to tens of milliseconds. The processed signal produced by the HA receiver then passes through the middle and inner ear and finally stimulates the nerve fibres in the auditory nerve. Figure 2.7 illustrates the processing path for the CI and HA in bimodal hearing. Since the two devices have different processing delays, the neural stimulation at one ear with a shorter delay occurs first, leading to temporal asynchrony between the two ears. Temporal asynchrony to the order of more than 10 msec. can adversely affect the ITDs sensitivity (Francart and McDermott, 2013).

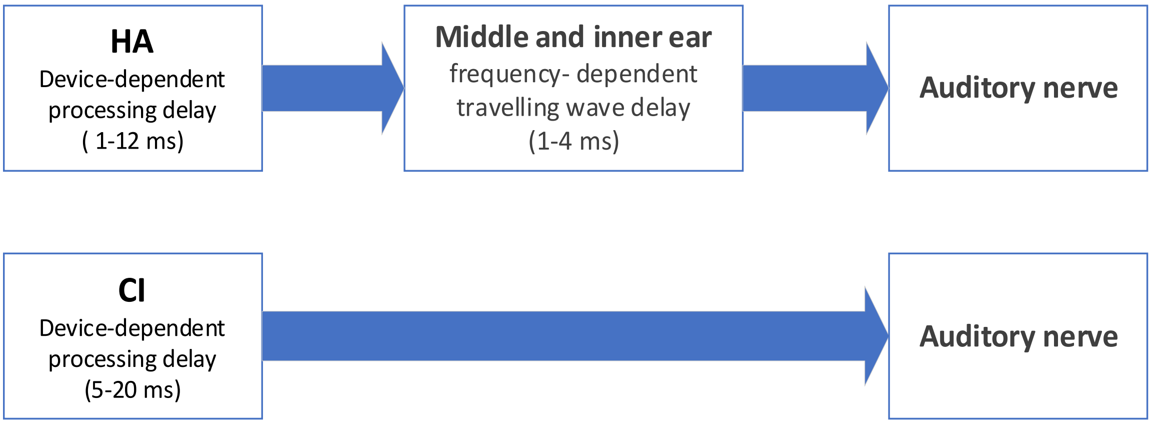

Figure 2.7: Block diagram illustrating the signal processing pathway and delay with bimodal hearing. Image adapted from Francart and McDermott (2013).

The loudness growth for electric and acoustic hearing is also different (McDermott and Varsavsky, 2009). The loudness growth through the CI is monotonic with a narrower dynamic range. The interaural differences in loudness growth can distort interaural loudness relations, affecting the perception of ITDs and ILDs, given that good binaural cue perception, particularly ITDs, require proper loudness balance between the two ears (Francart *et al.*, 2011a, Francart and McDermott, 2013).

Another potential problem limiting binaural cue perception with bimodal hearing is the differences in prepossessing options (such as AGC, noise reduction, feedback suppression) between the two devices. The independent operation of AGC circuits of the two devices has dramatically reduced the ILD cues (Keidser *et al.*, 2006, Francart *et al.*, 2011a). CI sound processors typically comprise a single-channel dual-loop AGC system that incorporates both slow and fast-syllabic time constants circuits, whereas the AGC circuit of HAs comprises multichannel fast-acting compression (Veugen *et al*., 2016a). Further discussion about the differences in AGCs between the HA and CI can be found in Section 2.4.3.2

ITD and ILD sensitivity have been demonstrated in bimodal listeners in laboratory settings using well-controlled stimuli (i.e. pulse trains) such as in (Francart *et al*., 2008, Francart *et al*., 2009, Francart *et al*., 2011b). Francart *et al.* (2009) measured the ITD sensitivity for eight bimodal listeners using 100 Hz pulse trains paired with 100 Hz acoustic click trains. Only four participants showed ITD sensitivity that ranged from 91 to 341 µs. All four participants had unaided hearing thresholds better than 100 dB HL at 1 and 2 kHz in the non-implanted ear, while the average of unaided thresholds was higher than 100 dB HL at 1 and 2 kHz for the other participants who could not consistently perceive differences in ITDs. This finding indicated the effect of residual hearing in binaural-cue perception, given that the ITDs can only be detected for frequencies below 1000 Hz. In addition, the lowest (best) sensitivity was found by applying an absolute delay of 1.5 ms for the electrical signal to achieve synchronous stimulation. In another study, Francart *et al*. (2008) measured the ILDs sensitivity for ten bimodal listeners using a simultaneous presentation of a pulse train on the CI side and a sinusoid signal on the HA side. The mean ILD sensitivity was 1.7 dB when the tonotopically matched electrical and acoustic stimulation was applied.

ITD and ILD cues are poorly perceived with current clinical bimodal devices (Ching *et al*., 2007, van Hoesel, 2012). Francart *et al*. (2011b) suggested that binaural cues, particularly the ITD cues, could be perceived with bimodal clinical devices if some modifications are applied to CI sound processors and HAs to balance loudness, synchronise timing, balance loudness growth, and match the place of stimulation. They showed that some bimodal listeners were sensitive to ITDs when using stimuli more similar to those produced by bimodal clinical devices.

In summary, ITD and ILD cue perception is limited with bimodal hearing due to the technical and processing limitations of the current devices.

2.4.2 Bimodal benefits

Bimodal hearing is a non-invasive method that does not require surgery and is cost-effective (Offeciers *et al*., 2005). One potential benefit of bimodal hearing is that low-frequency sounds will be enhanced by acoustic stimulation from the HA in the non-implanted ear, and higher-frequency sounds will be enhanced by electrical stimulation from the CI (Gantz and Turner, 2003). As a result, perception of relatively lower phoneme groups can be achieved. Additionally, bimodal hearing can provide greater spectral resolution and TFS cues through the acoustic stimulation of the non-implanted ear in the low-mid frequency region (Gifford *et al*., 2015).

Many studies demonstrated the benefits of the combination of acoustic amplification from the HA and electrical stimulation from CI (see Appendix D and E). There are, however, methodological differences in terms of (1) patient selection regarding demographic characteristics, especially the amount of residual hearing in the non-implanted ear, (2) outcome measures and test materials and (3) test settings and configurations. The most frequently reported benefits of bimodal stimulation are improved speech recognition in noise, sound localisation, music enjoyment and functional hearing (Ching *et al*., 2006, Veugen *et al.*, 2016a, Devocht *et al*., 2017, Olson and Shinn, 2008). The body of literature on these bimodal hearing benefits is discussed in Sections 2.4.2.1 to 2.4.2.5. It should be noted that these sections discussed the benefits of standard bimodal-hearing technology. The advances in the bimodal technology are discussed in Section 2.4.4.

2.4.2.1 Speech perception in noise

The bimodal benefit for speech perception in noise has been extensively researched; a summary of studies can be found Appendix D.

Mixed findings can be seen among the studies. Some studies reported a significant benefit with bimodal hearing, such as in (Armstrong *et al.*, 1997, Ching *et al.*, 2004, Flynn and Schmidtke, 2004, Iwaki *et al.*, 2004, Kong *et al*., 2005, Ching *et al.*, 2006, Gifford *et al.*, 2007, Dorman *et al.*, 2008, Berrettini *et al.*, 2010, Morera *et al*., 2012, Jang *et al*., 2014, Devocht *et al.*, 2017). The amount of improvement varies due to differences in test set-ups and procedures. The speech and noise were presented from the same loudspeaker in front of the participant (diotic listening) in some studies (Armstrong *et al*., 1997, Kong *et al*., 2005, Pyschny *et al.*, 2011, Hua *et al*., 2017) or spatially separated (dichotic listening) in other studies (Ching *et al.*, 2004, Jang *et al*., 2014, Bouccara *et al*., 2016). Additionally, some studies used fixed procedures while others used adaptive procedures. For instance, Dorman *et al.* (2008) used a fixed procedure with a dichotic listening set-up. The results showed 8% to 30% improvement on speech-perception measures in noise with bimodal hearing. Morera *et al*. (2012) used an adaptive procedure for diotic listening and then spatially separated test set-ups. They reported a significant improvement of 3 to 5.3 dB with bimodal hearing compared to the CI-alone condition. The greatest improvement was when the speech was presented from the front of the listener and the noise on the CI side. Similar findings obtained by Devocht *et al*. (2017) showed an improvement by 5.9 dB with bimodal hearing when the noise was presented to the CI side and speech from the front.

Veugen *et al*. (2016a) explained that improving speech in noise with bimodal hearing is related to several underlying mechanisms. Complementarity of information obtained from an HA allows access to acoustic low-frequency information not found in CI. This is thought to improve the segregation and perception of different voices (Ching *et al*., 2006, Berrettini *et al.*, 2010). Another mechanism is redundancy, where listening with both ears could help to compensate for the noisiness in each auditory and cognitive pathway. In addition, 'better ear glimpsing' is believed to improve speech perception as the better ear can detect the target speech during spectral and temporal gaps of the masker. The head-shadow effect is another underlying mechanism, particularly when the noise is presented from the HA or CI side.

On the other hand, some studies showed non-significant benefits with bimodal hearing (Tyler *et al*., 2002b, Morera *et al.*, 2005, Mok *et al.*, 2006, Pyschny *et al.*, 2011), while other studies showed a decrement in the performance with bimodal hearing compared to CI alone such as in (Dunn *et al*., 2005, Bouccara *et al.*, 2016). The mixed findings in the literature might relate to differences in the methodological designs used and variables that could affect the performance with bimodal hearing. Further discussion about the factors and variables was provided in Section 2.4.3.

2.4.2.2 Localisation and tracking of moving sounds

Many studies evaluated the sound source-localisation ability of adult bimodal users (Tyler *et al*., 2002b, Ching *et al.*, 2004, Flynn and Schmidtke, 2004, Seeber *et al*., 2004, Dunn *et al*., 2005, Ching *et al*., 2006, Potts *et al*., 2009, Morera *et al*., 2012, Goman, 2014, Jang *et al.*, 2014). A summary of these studies, including test settings and findings, is in Appendix E.

The performance of localisation ability was measured mainly as the root mean square (RMS) error degree with bimodal hearing rather than with CI alone. A lower RMS error indicates better localisation ability.

The mean bimodal RMS errors reported in the literature ranged from 32° to 42.7° (Ching *et al.*, 2004, Dunn *et al*., 2005, Potts *et al.*, 2009) whereas the RMS errors with CI alone ranged from 40° to 60° (Ching *et al.*, 2007) which indicated that the localisation ability for unilateral CI users might be improved by using an HA in the contralateral ear. However, considerable variation in the performance is notable among the participants of these studies. For instance, Tyler *et al*. (2002b) showed that localisation ability was improved for two out of three participants using an HA in the contralateral ear for speech noise presented from two loudspeakers located at 45° to the right and 45° to the left (the performance reported as a percentage correct score rather than an RMS error).

Similarly, Ching *et al.* (2004), Potts *et al.* (2009) and Morera *et al*. (2012) found a significant improvement for localisation ability with the addition of an HA in the contralateral ear for the majority of the participants. However, Dunn *et al.* (2005) found that the performance varied widely among the participants with the RMS error ranging from 27.6^{o} up to 48.7^{o}. Although two out of the 12 participants were able to localise fairly well in bimodal conditions, the majority of participants were unable to show a significant improvement in their ability to localise the sound source. Similar findings were reported by Seeber *et al.* (2004) and Jang *et al.* (2014), where most of the participants did not show a significant improvement in localisation ability when they used an HA in the contralateral ear.

In another study, Goman (2014) assessed the localisation ability for 12 bimodal users in three different settings with three different loudspeaker separation settings (i.e. three loudspeakers with 60° separation, five loudspeakers with 30° separation and five loudspeakers with 15° separation). There was no significant improvement in the localisation performance using an HA in the non-implanted ear in testing settings of 60° and 30° separation. However, a significant benefit was found when localising sounds that were separated by 15°. This is an interesting finding as localising sounds with a very small angle separation is the most challenging task. The reason is not clear, although the author suggested that the number of trials in the less challenging localisation tasks were too few to show the difference in the performance between listening conditions.

A considerable variation in the findings can be seen, and the improvement of sound localisation with bimodal hearing is inconclusive. These studies included different measurement methods and demographic characteristics (e.g. amount of usable residual hearing in the non-implanted ear). In addition, different processing systems and interference between the CI and HA might affect the users' ability to use ITD cues. Potts *et al.* (2009) suggested that abnormal and asymmetric cues with bimodal hearing may limit localisation ability.

The benefit of bimodal hearing to improve the ability of adult CI users to track moving sounds has received little attention to date. Goman (2014) used a semi-circular array of nine loudspeakers to assess the ability to track moving sounds for 12 adult bimodal users. The results showed the performance was improved in the bimodal listening condition compared to the unilateral CI condition; however the improvement was not significant. Further research is needed to explore the tracking ability of bimodal-hearing users with a larger sample size.

Overall, using an HA in the contralateral ear for unilateral CI users might help in improving the ability to localise and track moving sound.

2.4.2.3 Music perception

Although CI greatly improves speech perception, many CI users find listening to music challenging and less enjoyable. CI users tend to rate the quality of musical sounds lower than the ratings given by individuals with normal levels of hearing (McDermott, 2004). CI users tend to describe music sounds as unclear, unpleasant, or unnatural with poor overall quality of music (Dincer D'Alessandro *et al.*, 2021).

This is because there is limited spectral and pitch information conveyed by CI. Most current CI-processing strategies discard TFS information, and only the envelope information is used to process the signal (Cullington and Zeng, 2011). Furthermore, poor spectral resolution in CI limits harmonics' resolution, which is important for pitch perception, timbre perception, and the distinction of musical instruments (Galvin *et al.*, 2007).

HA users who are CI candidates performed better with HAs on pitch tests than with CI (Looi *et al*., 2008). This is because an HA can provide better spectral resolution for the low frequencies. Unilateral CI users reported improved sound quality and music perception when using an HA in the contralateral ear (Armstrong *et al.*, 1997, Tyler *et a*l., 2002b, Ching *et al.*, 2004, Hamzavi *et al*., 2004).

Music perception for bimodal-hearing users was assessed using different tasks, such as melody perception (Kong *et al.*, 2005, Dorman *et al*., 2008, El Fata *et al*., 2009), pitch perception (Crew *et al.*, 2015, Dincer D'Alessandro *et al.*, 2018, D'Alessandro *et al.*, 2021), timbre perception (Kong *et al.*, 2012, D'Onofrio and Gifford, 2021), and musical emotion perception (D'Onofrio *et al.*, 2020). Kong et al. (2005) assessed melody recognition for five adult users with HA alone, CI alone and CI+HA. They used three sets of 12 familiar melodies with rhythmic information removed for each melody using notes of the same duration; therefore, only the pitch cue was available for melody recognition. The performance varied remarkably among the participants. Kong *et al*. (2005) suggested that different device versions (newer and older devices) used by participants could be the reason for the remarkable difference in performance. Dorman *et al*. (2008) reported different findings, when he evaluated melody recognition in a larger group of bimodal users (N=15). The performance with bimodal devices (71.2%) was significantly better than with CI alone (52%). However, there was no significant difference in performance between HA alone and CI+ HA conditions. Similar findings were reported by El Fata et al. (2009). There was a significant improvement in the melody recognition using the HA in the contralateral ear for 8 out of 14 adult CI users with low-frequency residual hearing better than 85 dB HL. There was no significant benefit for the remaining participants from using bimodal devices over CI alone.

Crew et al. (2015) measured the pitch perception for eight bimodal listeners using a melodic contour-identification task. The mean performance was 77% correct in listening, using the HA only and 42.2% correct in the listening condition of using the CI only. The performance in the bimodal listening condition was slightly poorer (but not significantly) than the listening condition of using the HA only, suggesting the limited contribution of CI in pitch perception. Recent studies (Dincer D'Alessandro et al., 2018, D'Alessandro et al., 2021) assessed pitch perception in bimodal listeners using two tests (harmonic intonation and disharmonic intonation). The performance in the bimodal listening condition was significantly better than the CI-only condition.

Kong et al. (2012) and D'Onofrio and Gifford (2021) showed that using an HA in the non-implanted ear improved the timbre perception compared to using the CI only. Moreover, bimodal listeners reported more typical musical emotion judgements compared to the CI only as the ratings in the bimodal listening condition were not statistically significantly different from the NH ratings (D'Onofrio *et al.*, 2020). Similarly, the ratings on a music-quality questionnaire (including clarity, pleasantness, naturalness and overall quality of sound were significantly better with the bimodal listening condition than the CI only (D'Alessandro *et al*., 2021).

Taken together these findings indicate that access to the fundamental frequency and TFS cues at low frequencies via an HA in the non-implanted ear for CI users can improve the key structural elements of music: melody, pitch and timbre.

2.4.2.4 Self-reported benefits

The benefits of bimodal hearing discussed in the previous sections are mainly quantified in laboratory settings and might not reflect the benefit in real-life situations. Several studies have been carried out to assess hearing functions in everyday life by using self-report questionnaires. Some studies have used non-standardised questionnaires especially designed for their experiments (Armstrong *et al*., 1997, Tyler *et al.*, 2002b, Ching *et al.*, 2004, Flynn and Schmidtke, 2004, Berrettini *et al*., 2010, Devocht *et al.*, 2017). The reported benefits from bimodal users using non-standardised questionnaires are summarised in Table 2.1. The most reported benefits for using bimodal hearing devices appear to be dominated by improved communication in noise and the 'naturalness' of music.

Table 2.1: Summary of the reported benefit by bimodal hearing users.

Study	Sample size	Reported benefits
Tyler et al. (2002b)	3	• Comfortable hearing in both ears • More directional sound • HA picks up additional information and gives 'clarified' hearing
Ching et al. (2004)	21	• Better sound balance • Greater confidence in everyday life • More music enjoyment • Easier listening in a noisy environment
Flynn and Schmidtke (2004)	8	• Improved conversation in noise • Improved localisation • Improved sound quality for speech • Improved sound quality for music
Berrettini et al. (2010)	10	• Improved conversation in noise • Improved localisation • More natural sound • Improved sound quality for music
Devocht et al. (2017)	15	• Reduction in the listening effort • Sounds are more voluminous, less tiny and more pleasant

Other studies used standardised questionnaires to assess bimodal benefits such as SSQ *(*Noble *et al.*, 2008, Noble *et al.,* 2009, Potts *et al.*, 2009, Farinetti *et al.*, 2015, Devocht *et al.*, 2020), the NCIQ (Farinetti *et al.*, 2015), APHAB (Morera *et al.*, 2012), the Hearing Handicap Inventory for the Elderly (HHIE) (Noble *et al.*, 2009), the Hearing Handicap Questionnaire (HHQ) (Noble *et al.,* 2009), and the Amsterdam Questionnaire for Unilateral or Bilateral Fittings (AVETA) (Devocht *et al.*, 2020). The results from these studies were mixed and inconclusive because they used different instruments and designs. In addition, a few studies only administered the questionnaire in the bimodal hearing condition that did not measure the significance of improvement compared to CI alone. For instance, Noble *et al*. (2008) used SSQ to assess the benefit of using an HA in the contralateral ear for unilateral CI users. They administered a questionnaire when the participants used CI alone and CI+HA. They found no significant difference in any of the 10 subscales of SSQ between the two listening conditions. In another study, Morera *et al*. (2012) used the APHAB to assess the hearing functions for everyday life of bimodal hearing. They administered the questionnaire three times, once after each listening condition: CI alone, HA alone, and CI + HA. There was no significant difference between CI alone and the bimodal hearing conditions for any questionnaire categories. The questionnaire results contradicted the findings for speech in noise in the same study and the findings for the subjective preference of sound quality reported by the participants, where bimodal hearing outweighed CI alone.

In contrast, Devocht *et al*. (2020) found significantly higher ratings overall and for the three subscales of the SSQ questionnaire in the bimodal listening condition compared to using the CI only for 26 bimodal users. In addition, the bimodal listening condition was rated significantly higher in all categories of the AVETA questionnaire than the CI-only condition except in the discomfort-of-loud-sounds scale.

Overall, bimodal hearing can provide benefits for auditory functions in real life in terms of ease of communication and improving the sound quality of speech and music. The mixed findings might be related to different methods, designs, and demographic characteristics encountered in these studies.

2.4.2.5 Benefit versus cost-effectiveness of bimodal hearing

Although mixed findings of bimodal benefit can be seen in the literature, bimodal hearing has been shown to provide some benefits, particularly in understanding speech in noise and improving music perception for many CI users. A systematic review by Olson and Shinn (2008) assessed the evidence of bimodal-hearing benefit for adult CI users by reviewing 11 studies. They demonstrated that the greatest trend of the bimodal-hearing benefit tends to improve speech, especially in noise and functional ability based on self-assessments, whereas improving localisation ability was varied among participants and studies. In addition, they concluded that reported bimodal-hearing benefit is not represented by high-quality evidence due to the constraints in terms of design and sample size. However, a review of the available evidence is needed since many studies have been published since the Olson and Shinn (2008) review. Another reason for inconsistency in bimodal benefits is the presence of some factors, such as the degree of residual hearing in the non-implanted ear. These factors were discussed in Section 2.4.3.

Only one study so far has assessed the cost-effectiveness of bimodal hearing compared to unilateral and bilateral CI for adults with bilateral severe to profound hearing loss (Theriou *et al*., 2019). The cost-utility analysis was carried out based on a public healthcare system perspective and used data from the UK and the USA. Utility weights were estimated using 91 adult unilateral CI users who completed the HUI3 questionnaire. The analysis results indicated that bimodal hearing was the most effective intervention option compared to unilateral and bilateral CI with 72% and 67% decision certainty in the UK and the US respectively. Bimodal hearing was found to produce greater health benefits than the unilateral CI, and those benefits outweighed the burden of the increased costs related to maintaining the HAs. In contrast, the analysis showed that bilateral CI generated more health benefits than unilateral CI and bimodal stimulation; however the excessive costs of bilateral CI limit their cost-effectiveness compared to unilateral CI and bimodal hearing.

Overall, bimodal hearing might be a potential option to improve binaural hearing for adult CI users. Schafer *et al.* (2011) proposed that bimodal hearing be used as standard practice for unilateral adult CI users before proceeding to bilateral CI, only if there is no benefit from HA use.

2.4.3 Factors affecting bimodal-hearing outcomes

Many factors and variables might be related to the mixed findings in the literature for bimodal-hearing benefits. For instance, demographic variables included age, gender, age of hearing loss, duration of HA use and age at CI surgery. Although Potts *et al.* (2009) did not find any significant effects of these variables on the bimodal benefits, they argued that the effects of demographic variables could not be excluded due to the limited number of participants in the study. Another factor that might influence the bimodal benefits is the aided thresholds in the non-implanted ear. Jang et al. (2014) found a significant correlation between the bimodal benefits (speech perception and localisation) and the aided threshold in the non-implanted ear (average of 500, 1000, 2000, and 4000 Hz). The authors suggested that better-aided thresholds in the non-implanted ear might provide a greater loudness in that ear; therefore more balanced loudness between CI and HA might be achieved. However, their findings should be treated with caution as there are several confounding variables associated with aided thresholds such as the HA-fitting formula and parameters (i.e. compression, frequency response) which might complicate the interpretation. A recent systematic review by Vroegop et al. (2018a) underlined the lack of evidence for the effect of certain parameters in HA fitting on the bimodal benefits and the need for thorough investigation.

In addition, the correlation between the bimodal benefits and unaided hearing thresholds (severity of hearing loss) in the non-implanted ear as well as device processing has been examined extensively. The effect of these two factors on the bimodal benefits is discussed in Sections 2.4.3.1 and 2.4.3.2.

2.4.3.1 The severity of hearing loss in the non-implanted ear

As the inclusion criteria for CI candidacy have expanded over recent years, more people with better levels of residual hearing have been implanted with CI (Gifford *et al.*, 2010). Many studies have investigated the role of residual hearing, particularly at low frequencies, for bimodal benefit. Ching *et al.* (2004), Ching *et al.* (2006), Ching *et al.* (2007), Gifford *et al.* (2007), Potts *et al.* (2009), Davidson *et al*. (2015), Veugen *et al.* (2016b), D'Onofrio *et al.* (2020), and D'Onofrio and Gifford (2021) found no correlation between bimodal speech performance and the degree-of-hearing threshold in the non-implanted ear, even with better residual hearing at low frequencies. In the Gifford *et al*. (2007) study, participants had good residual hearing, particularly at the low frequencies. The hearing thresholds at 250 and 500 Hz were ≤ 60 dB HL and the threshold at 2000Hz and above was ≥ 80 dB HL (the mean thresholds for the contralateral ear at 250, 500,750 and 1000Hz were 38, 53, 69, and 81 dB HL respectively). There was no significant correlation between the amount of residual hearing in the contralateral ear (250 Hz, 500 Hz, mean of 250 and 500 Hz, mean of 250, 500, and 1000 Hz, difference between 250 and 1000 Hz, and difference between 500 and 1000 Hz) and bimodal performance. Similarly, Veugen *et al*. (2016b) showed no significant correlation between the unaided hearing thresholds at low and high frequencies and the bimodal benefit for speech perception in noise. Bimodal benefits for timbre perception and musical-emotion perception were also found to not be significantly correlated with low-frequency unaided thresholds in the non-implanted ear (D'Onofrio *et al.*, 2020, D'Onofrio and Gifford, 2021).

In contrast, other studies such as those by Armstrong *et al*. (1997), Tyler *et al*. (2002b) and *Illg et al.* (2014) reported better results for bimodal users who had better hearing thresholds for the low-frequency region. Illg and colleagues (2014) investigated the benefit of residual hearing in the non-implanted ear in a large group of CI users with different degrees of residual hearing. They analysed the data of 141 bimodal-hearing users retrospectively. All the participants underwent monosyllabic speech understanding, sentences in quiet, sentences in noise, and sentences with a competing talker when wearing the CI alone and when wearing both the CI and HA. They found a significant correlation with the hearing threshold level of 125 Hz and 250 Hz for sentences in noise (r= -0.32, -0.232). However, for the hearing level of 500 Hz and above, the correlation was not significant for bimodal benefit in speech understanding in noise. Their findings suggest that hearing loss in the non-implanted ear should not exceed 80 dB HL in low frequencies for significant benefits from bimodal hearing. With this large sample size, the importance of a residual-hearing level in the low frequencies can be seen for bimodal benefits. The finding of Illg *et al.* (2014) is in line with Zhang *et al.* (2010), who showed that the residual hearing in the frequency region below 250 Hz accounts for the majority of the bimodal benefits. They presented different acoustic stimuli to the non-implanted ear (low-pass-filtered at 125, 250, 500, or 750 Hz or unfiltered wideband). The improvement was observed when the acoustic stimuli were limited to the 125-Hz-low-pass signal. Sheffield and Gifford (2014) replicated the method used in Zhang et al. (2010) with a steeper filter roll-off to assess the minimum low-pass bandwidth required to obtain bimodal benefit for speech perception in quiet and in noise. They found that the cut-off for bimodal benefit was as low as 125 to 250 Hz based on the presence of noise masker and the gender of the speaker. However, they found a systematic increase in bimodal benefit with increasing acoustic low-pass bandwidth in the non-implanted ear (i.e. < 250 and 250-500 Hz), which contradicts the findings of Zhang *et al.* (2010). A recent study (Hoppe et al., 2018) found a significant correlation between the unaided hearing thresholds in all frequency ranges and bimodal benefits for speech perception in quiet and noise.

Taken together, there is no consensus on relationship between unaided hearing thresholds in the non-implanted ear and bimodal benefits. This might be related to differences in aetiology of hearing loss, difference in the amount of residual hearing among the participants in these studies, different HAs used by the participants and different fitting strategies. In addition, differences in the methods used to measure bimodal benefits could be another possible reason for the inconsistent results. Furthermore, the amount of usable residual-hearing levels, especially at low frequencies that needed to have significant bimodal benefits remains questionable. It is important to identify the level of usable residual hearing in the contralateral ear needed to receive the significant benefit of bimodal hearing. This would help to determine the potential candidates of the bimodal users.

Despite bimodal benefits, Fitzpatrick *et al.* (2009) found a small but significant relationship between the severity of hearing loss in the non-implanted ear and the likelihood of using a contralateral HA. Similarly, Devocht *et al.* (2015) found a significant relationship between the amount of residual hearing loss in the non-implanted ear and HA retention, especially at the hearing threshold at 250 Hz. In addition, CI participants who use an HA in Yamaguchi's (2013) study have a 107-dB hearing level, whereas those who do not use an HA have a 117-dB hearing level. The probability of bimodal HA retention increased with having better residual-hearing thresholds in the contralateral ear.

2.4.3.2 Device processing

One possible reason for individual differences in bimodal-hearing benefit is related to the technology of the two devices (CI and HA) in terms of loudness mismatch, different signal-processing schemes, and fitting them separately. Standard HAs are not designed specifically to work together with a CI, which can result in temporal synchronisation difficulties (as discussed in Section 2.4.1) and mismatch in stimulation place between the two cochleae (Francart and McDermott, 2013). Ching *et al.* (2007) recommended a procedure to achieve loudness balance between both devices in bimodal users for soft and loud sounds by adjusting the overall frequency response of the HA. However, Veugen *et al.* (2016b) argued that overall loudness matching might result in loudness mismatch because an over-amplification of the low frequencies by the HA may result in the presence of low-frequency residual hearing. They suggested that using frequency-dependent loudness balancing between devices might improve bimodal benefit compared to broadband balancing. They assessed the effect of loudness balancing in three separate frequency bands: low frequencies up to 500 Hz, the middle frequency band (500 Hz-1 kHz) and frequencies above 1 kHz. They compared this frequency-dependent procedure with broadband loudness-balancing for speech perception in quiet and noise. The results showed no difference between the two procedures of loudness matching between HA and CI devices.

Another important component in HA and CI is automatic gain control (AGC). The main function of AGC is to adapt the wide dynamic range of sounds to the narrow dynamic range of hearing-impaired listeners (Spirrov *et al.*, 2020). AGC circuits were developed to optimise the audibility of soft sounds and avoid the distortion and discomfort associated with peak clipping by adjusting the gain dynamically depending on the average of input levels over a certain period (Boyle *et al*., 2009, Dillon, 2012). In most devices, linear amplification is applied to a certain level then the signal level is compressed. The level where the system starts to compress the signal is known as the compression threshold (or knee point). The speed of AGC to react to a sudden change of sound level is determined by the attack time and release time (Moore, 2007b, Dillon, 2012). AGC systems in hearing devices are classified into two typical types based on compression speed: slow and fast-syllabic compressions. Slow compression is characterised by a slow attack time of more than 100 milliseconds and a release time of more than 400 milliseconds with a high compression ratio. The gain changes slowly to adapt to the overall level of speech and other sounds with changes in signal level (Moore, 2008, Boyle *et al.*, 2009, Dillon, 2012, Veugen *et al.,* 2016a). Fast-syllabic compression has an attack time of less than 10 milliseconds and a release time of 10-50 milliseconds with a lower knee point and compression ratio than the slow compression system. The gain changes over time to reduce intensity differences between speech sounds (Moore, 2008, Boyle *et al.*, 2009, Dillon, 2012, Veugen *et al.*, 2016a). Both systems can be combined in the same device to form a 'dual front-end AGC system' that incorporates a fast AGC loop to decrease sudden changes in sound level and a slow AGC loop to control the overall sound level (Moore, 2008).

The CI sound processors and the standard HAs used in studies investigating bimodal-hearing benefits have different AGC designs and operations. The mismatch in AGC characteristics between the two devices appears to be an influential factor responsible for the variation in bimodal benefits found in the literature and for the decreasing rate of HA retention by CI users (Mok *et al*., 2006, Fitzpatrick and Leblanc, 2010, Veugen *et al*., 2016a). The AGC parameters in the CI are rarely changed, whereas the AGC parameters in the HA vary according to the fitting formula used and possible fine-tuning done (Vaerenberg *et al*., 2014b, Spirrov *et al*., 2020). Moore (2007b) stated that the AGC in both devices could react to changes in input level in different ways, resulting in unstable binaural cues. The ILD cues may be disrupted, which would cause conflicting binaural information because of the differences in signal processing in both devices, especially for signals with dynamically changing levels such as speech sounds (Veugen, 2017). For instance, speech sounds at a stable conversational level would normally trigger the fast-syllabic compressor in the HA, but they do not trigger the fast loop of the CI processor. Thus, it will cause unmatched binaural input that could lead to conflicting ILD cues and increase listening effort, especially for soft to moderate speech sounds. In addition, it was shown that fast-syllabic compression may deteriorate the envelope of speech and perceptual segregation by applying a common component of modulation which compresses the target and background noise together (Stone and Moore, 2007). In contrast, slow compression is not affected by this problem which mostly perseveres with temporal fluctuations in the target signal. Therefore, if the AGCs in both devices are equivalent, that might enhance bimodal hearing, particularly in single-talker noise. In addition, Veugen *et al*. (2016) suggested that using 'real-time synchronisation' of the compression in both devices would help to preserve ILD cues across the dynamic range by ensuring equal gain at both devices at all times. Therefore, more benefits could be obtained for bimodal-hearing listeners particularly as they have limited or no access to ITD cues (as ITD cues are highly distorted by CI processing). Figure 2.8 illustrates the effects of using different AGC systems in both devices for stimuli presented from the front of the listener (diotic listening). It should be noted that even if the two devices have the same processing strategy, the ILDs may be disrupted if the two AGCs receive different inputs presented in a dichotic listening configuration.

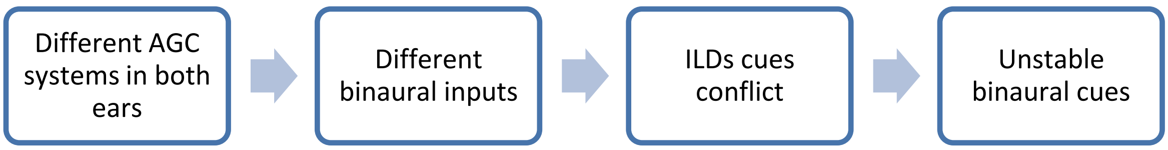

Figure 2.8: The effect of using different AGC systems in the CI and HA on the stability of binaural cues.

Veugen *et al.* (2016a) assessed the effect of using a similar design of AGC in the CI sound processor and HA to increase bimodal benefit. The study included bimodal users who only used the Advanced Bionics Harmony processor and the Phonak Naida IX UP HA. The Harmony CI processor has a single-channel dual-loop AGC system that incorporates both slow (240 and 1500 msec. attack and release time) and fast-syllabic (3 and 80 msec. attack and release time) time-constant circuits with a compression ratio of 12:1 (for further details, see Boyle *et al.* (2009)). The Naida HA has standard multichannel fast-acting compression that operates independently in 20 different frequency bands with a 1-millisecond attack time and 50-milliseconds release time. To match the AGC circuits between both devices, Veugen *et al*. (2016a) altered the AGC circuit of the HA only. They kept the CI AGC circuits without any alteration because the CI is the main source of the auditory information of bimodal users. The HA was programmed to have slow- (240 and 1500 msec.) and fast-syllabic (3 and 80 msec.) time constants, then compression channels were coupled to mimic the signal channel broadband compression in the CI processor. The compression knee point was fixed at 63 dB SPL then a slow AGC loop was activated in the CI and AGC-matched HA (or the fast-syllabic compression in the standard HA). The fast-syllabic compressor of the dual-loop in the CI was active above 71 dB SPL (for further details, see Veugen *et al*. (2016a)).

The bimodal performance for 15 adult CI users was compared when they used the CI only, AGC-matched HA, and the HA with standard AGC for speech perception in quiet and in single-talker noise. Veugen *et al.* (2016a) used a three-visit crossover design where the participants were divided into two groups and were not told which type of AGC was programmed in the HA. Speech in noise was assessed in four test configurations: S0°N0°, S0°N$_{HA}$, S0°N$_{CI}$ and S0°N±90°. In addition, they used the SSQ questionnaire to assess the difference between the two AGCs and through a bimodal listening questionnaire. The bimodal listening questionnaire contains seven basic questions relating to everyday listening situations. At the end of the study, participants were asked about subjective preference. There was no improvement for bimodal hearing (with both AGC) for speech in quiet over the CI-only condition. In noise, a bimodal benefit ranged on average from 0.7 to 2.5 dB (over the four test configurations) when using the standard HA (standard AGC) compared to using the CI only. However, the significant bimodal benefit of a total 3 dB was only found for the AGC-matched HA compared to the CI only for the speech tests (S0°N$_{HA}$ and S0°N$_{CI}$) with signal-talker noise. Compared to the standard HA, the HA with matched AGC provided a significant benefit of 1.9 dB when the noise was presented from the HA side (S0°N$_{HA}$). The matched-AGC HA also increased the bimodal benefit by 0.6 dB when the noise was presented from the CI side (S0°N$_{CI}$) and by 0.8 when the noise was simultaneously presented at both sides (S0°N±90°); however, these improvements were not significant. The SSQ did not show significant differences between AGCs for the main three subscales or subsections.

Nevertheless, there was a small significant improvement in the bimodal listening questionnaire for the AGC-matched HA compared to the standard HA only for the questions related to understanding one person in quiet and in noise, for the quality of sounds. In addition, 9 of the 15 (60%) participants preferred to use the AGC-matched HA after the study, which raised a question about the sensitivity of SSQ to capture the subjective preference.

These results suggested that the AGC-matched HA can result in a bimodal benefit when the noise and speech are spatially separated in single-talker noise, particularly when the noise is presented on the HA side. Veugen *et al.* (2016a) claimed that the improvement obtained by the HA with matched AGC might result from reducing interaural mismatch in loudness between the two devices, which reduced conflicting binaural information and increased listening comfort. Additionally, matching the AGC between the CI and HA might improve binaural processing due to the overlapping frequency range of input between the two devices and the loudness matching between the two ears. They supported their view with the additional bimodal benefit found when the noise was presented from the HA side, which is the least favourable SNR.

However, Spirrov *et al.* (2020) argued that for the bimodal benefit found by using the matched AGC HA in the Veugen *et al*. (2016a) study, it was not clear whether it was the loudness-matched compressors or the application's slow time constants in the HA which improved the SNR at the HA. To disentangle the influence of loudness matching and time constants, they suggested that the monaural CI-only condition should be tested with both fast and slow time constants, unlike Veugen *et al*., who only tested the CI-only condition with slow time constants (as it was the dominant loop). If there is an improvement with the slow AGC compared to the fast AGC in the monaural CI-only condition, then the effect seen in the bimodal condition would be related to the time constants and not to loudness matching (by matching the knee points). Spirrov *et al.* (2020) used a Nucleus 6 processor from Cochlear and an Enzo 3D HA from GN hearing in their experiment. The parameters of the AGCs for the CI sound processors and the HA are shown in Table 2.2. In the CI sound processor, the knee point of loop 2 (fast-syllabic) is lower than loop 1 (slow) in the CI AGC; thus, the behaviour of the CI AGC was mainly determined by the fast-syllabic loop.

Table 2.2: Characteristics of AGCs for the CI sound processors and the HA used in the study by Spirrov *et al*. (2020).

Parameters	**CI**		**HA**
	Loop 1	**Loop 2**	
Knee points	74 dB	69 dB	40-48 dB
Compression ratio	Limiting	Limiting	NAL-NL2
Attack time	300 ms	5 ms	12 ms
Release time	2000 ms	100 ms	70 ms

To match the AGC between the CI and HA, Spirrov *et al.* (2020) applied similar parameters for the slow time constants (240 and 1500 msec. attack and release time) in both CI AGC (loop 1) and HA AGC, which was used in the study by Veugen *et al*. (2016a), with the knee point set at 65 dB SPL. They also changed the parameter of the fast-syllabic AGC in the CI (loop 2) to be similar to the Veugen *et al*. study (knee point at 71 dB SPL, 3 and 80 msec. attack and release time). Thus, the behaviour of the CI-matched AGC was mainly determined by the slow time constants loop.

Speech recognition in quiet and noise was assessed for 18 adult participants with both standard and matched AGCs in the monoaural CI-only and bimodal listening conditions. For the speech in noise, the speech was presented from the front whereas the noise was presented from three configurations: front (S0°N0°), CI side (S0°N_{CI}), and HA side (S0°N_{HA}). In the monaural CI-only condition, the matched slow AGC (CI AGC after changing parameters) improved the speech recognition in quiet insignificantly by approximately 7% at 50- and 65-dB A compared to the standard fast-syllabic AGC (CI AGC before changing the parameters). A similar trend was seen for speech recognition in noise when the noise was presented at the CI side. For the other two noise configurations (S0°N0° and S0°N_{HA}), there were no differences between the standard and matched AGCs in the monoaural CI-only condition. Additionally, they did not find significant differences between the two AGCs in speech recognition in quiet and in noise in the bimodal listening condition. They also calculated the bimodal benefit for each AGC setting (standard and matched AGC) by subtracting the results of the monaural CI-only condition from the bimodal condition for each noise configuration. For example, they calculated the bimodal benefit for both AGCs in the S0°N_{CI} test as (a bimodal condition with standard AGC-CI only with standard AGC) for the bimodal benefit with standard AGC and as (a bimodal condition with matched AGC-CI only with matched AGC) for the bimodal benefit with matched AGC. Then the bimodal benefit of the two AGCs was compared for each speech test. The results showed no significant difference in the bimodal benefit between the two AGCs in the speech-in-noise tests except in (S0°N_{CI}), where the matched AGC resulted in a significantly smaller benefit than the standard AGC. Similar to Veugen *et al.* (2016a), Spirrov *et al.* (2020) used the SSQ questionnaire to assess the two AGCs and found no significant differences with no clear preference trend for any AGC. The results from this study suggested that the advantage of matched AGC seems mainly dependent on the time constants rather than bimodal loudness matching as there was an improvement (although not significant) with using the slow time constants (matched AGC) in the monaural CI only in quiet and when the noise was at the CI side. As discussed earlier, fast-syllabic compression tends to reduce speech intelligibility, which was seen in monoaural CI conditions. However, the effect of loudness matching cannot be excluded as they did not find a difference in the bimodal benefit of the two in AGC, particularly when the noise was at the HA which was opposed to Veugen *et al.*(2016a). One possible reason might be related to different parameters of the CI AGC. For instance, the bimodal benefit for the standard AGC was calculated with slow CI AGC in the Veugen *et al*. study, whereas it was calculated with fast CI AGC in the Spirrov *et al*. study. In addition, there are two differences between the two studies that would justify the discrepancy in the findings. The Spirrov *et al*. study participants had better residual hearing than those in the Veugen *et al*. study. Furthermore, Spirrov *et al.* (2020) used a competing talker in Swedish while an international female masker was used in the Veugen *et al*. study, which is likely to be more distracting and difficult because of the informational masking effect (Francart *et al.*, 2011c).

Overall, the results from these two studies suggest that matching the AGC circuits between the HA and the CI sound processor to work on the same platform could add a favourable bimodal benefit greater than that of a standard HA. In addition, it would be interesting to assess the effect of matching AGCs between the CI and HA in more real-life situations where the target speech is not always fixed from the front and with other common background noise (i.e. stationary and multi-talker babble noise).

2.4.4 Current bimodal technology and new directions

CI manufacturers are constantly working on improving technologies to overcome signal-processing difficulties for optimal bimodal benefits. Table 2.3 summarises the features of current bimodal technology offered by the three major CI manufacturers on the market (Advanced Bionics, Cochlear, and MED-EL).

Table 2.3: Features of the current bimodal technology.

	Advanced Bionics: Naida Link Bimodal system	Advanced Bionics: Naida Link Marvel technology	Cochlear: Nucleus® 7 Sound Processor Bimodal Solution	MED-EL Bimodal Hearing
CI speech processor	AB's Naida Q70 and Q90 sound processors	• AB's Naida CI M90 sound processor • AB Sky CI M sound processor *	Cochlear™ Nucleus® 7 sound processor	SONNET audio processor
HA Compatibility	Phonak Naida Link Ultra Power (UP) and Naida Link RIC	• Phonak Naida Link M (SP) • Phonak Sky Link M (SP)*	GN Resound HA (LiNX 3D and ENZO 3D)	Universal compatibility
CI AGC	Dual-loop AGC with a compression ratio of 12:1	Dual-loop AGC with a compression ratio of 12:1	Dual-loop AGC (compression ratio is NA)	Dual-loop AGC with a compression ratio of 3:1 (similar to HA AGC)
HA AGC	2:1 Similar to Naida CI dual-loop AGC	2:1 Similar to Naida CI dual-loop AGC	Compression options: • linear • semi-linear (less compression is applied compared to full WDRC with gain for moderate level inputs set according to the prescription) • WDRC	
Fitting formula	• Adaptive Phonak Digital Bimodal— main purpose to align the acoustic signal to the electrical processing by: 1. more amplification for the low-frequency region (200-750Hz) is important to optimise bimodal hearing 2. match IP/OP function of CI and HA to match loudness growth 3. utilise Naida dual-loop AGC in the HA	• Adaptive Phonak Digital Bimodal— main purpose to align the acoustic signal to the electrical processing by: 1. more amplification for the low-frequency region (200-750Hz) is important to optimise bimodal hearing 2. match IP/OP function of CI and HA to match loudness growth 3. utilise Naida dual-loop AGC in the HA	NAL-NL —focus amplification on frequency regions that are important for speech (1000-4000Hz)	Any traditional formulas can be used (NAL-NL2, DSLi/o)

	• Traditional formulas (NAL, DSL etc if audiologically appropriate)	• Traditional formulas (NAL, DSL etc if audiologically appropriate)		
Loudness matching	Yes	Yes	NA	NA
Integrated bimodal functionality	Yes - matched signal processing and gain behaviour of both CI and HA.	Yes- matched signal processing and gain behaviour of both CI and HA. Both devices react and adjust at the same time to changing listening situation	No	No
Wireless bimodal streaming	• Bilateral streaming by using **Binaural Voice Stream technology (HiBAN)**, many features can be activated: 1- DuoPhone 2- ZoomControl 3- StereoZoom 4- QuickSync	• Bilateral streaming by using **Binaural Voice Stream technology (2.4 GHz platform)**, many features can be activated: 1- DuoPhone 2- ZoomControl (automatic) 3- StereoZoom (Speech in Loud Noise) - is dynamic, part of Autosense OS 3.0 or can be a manual program 4- QuickSync	• Bilateral streaming by using Apple iOS devices. The following can be streamed simultaneously into both ears from iOS devices: • calls • audio media (music) True Wireless™ freedom: help to understand speech in noise where the sound is simultaneously streamed to both the CI and HA by using Cochlear's True Wireless accessories	Using Roger 21
Wireless contralateral streaming	Yes - audio streaming and telephone calls with appropriate accessory conduit, situations where the desired sound is on one side (in a car)	Yes - audio streaming and telephone calls in stereo with Bluetooth Classic hands-free protocols, Roger Direct wireless integration with 50 metre range streaming, Airstream (Phonak Proprietary) TV and Mic accessories, situations where the desired sound is on one side (in a car)	No	No

Automatic operation	No	Yes- with using AutoSense OS 3.0 (a machine-learning algorithm that analyses the sounds in the listening environment every 0.4 seconds and identifies whether the user is for example in a noisy restaurant, car, at home, etc. It then engages the appropriate CI system features to customize and enhance the user's hearing experience based on the specific characteristics of the listening environment)	No	No
Fitting software	Two software: 1- SoundWave for CI fitting 2- Target 5 for HA fitting	One software Target CI Fitting (both devices) with Noahlink Wireless Programming (HA can be programmed by Phonak Target 7.0 if required)	Two software: 1. Custom Sound Pro for CI fitting 2. ReSound Smart Fit for HA fitting	Two software: 1. MAESTRO 9.0 for CI fitting 2. HA company software for HA fitting

NA= the information is not available

*Used with children

Advanced Bionics and Cochlear promote brand-specific bimodal solutions that rely on features only compatible with a very limited range of HA types (Phonak Naida Link and GN Resound, respectively). Consequently, the benefits are exclusive to these systems. On the other hand, MED-EL bimodal technology offers the more practical solution of universal compatibility between CI sound processors and any type of HA.

These technologies offer bimodal streaming where sounds can be streamed from an external device to a CI and a compatible HA at the same time. However, an integrated bimodal functionality feature is only available with Advanced Bionics bimodal technology (Naida Link and Naida Marvel). In this feature, the CI sound processor and HA can communicate wirelessly for a sound-processing algorithm, binaural streaming, and unified controls. This feature appears to be promising for optimal bimodal benefits.

2.4.4.1 Integrated bimodal technology

An integrated technology that has emerged recently onto the market from Advanced Bionics (AB) and Phonak is the Naida Link bimodal system. This technology has been designed to allow a CI and an HA to work on the same platform to enable greater synchrony and 'communication' between the two devices. The Phonak Naida Link HA is designed to work with the AB Naida CI Q70 or Q90 sound processor (Bionics, 2016c). The two devices provide matched compression algorithms and time constants. In addition, this technology uses a dedicated fitting formula, Adaptive Phonak Digital Bimodal (APDB), which adapts the AGC circuit of the Naida Link HA to match the AGC in the Naida CI processor. This technology allows CI users to take advantage of *Binaural VoiceStream Technology* that links the CI and HA together wirelessly to stream full bandwidth audio signals from ear to ear simultaneously (Bionics, 2016b). Preliminary results showed a benefit for speech understanding in noise and greater listening comfort with the matched AGC HA compared to using CI alone or with any standard HA (Veugen et al., 2016a). A detailed review and discussion about this technology and the outcomes for adult CI users are provided in Chapter 5.

Recently, further development of this technology has been introduced. The sound processor of the CI comprises an operating system that adapts to the listener's surroundings by automatically blending multiple features to create distinct settings for the user's unique listening environment. This technology is known as Naida Link Marvel technology. The CI sound processors analyse incoming sounds every 0.4 seconds to determine the listener's environment. Then, artificial intelligence automatically activates the appropriate blend of settings, programs and features to different listening environments. The automatic classification process might offer better speech in noise, sound quality, and music experience (Rodrigues and Liebe, 2018). In addition, Marvel CI and HA can be fitted using one software which can facilitate the fitting session for both the clinician and the CI users. Further details about this technology are presented in Table 2.8.

2.5 Real-life test battery

Current routine audiology practice includes audiometry and only basic tests of speech perception. Standard speech tests include speech and competing noise (commonly steady-state noise) presented from a single speaker placed in front of the listeners. However, these tests offer limited information about how people hear in real-life listening situations. Listening in real-life situations is often challenging, specifically with the presence of background noise because it includes a wide range of background noises and multiple talkers with different sound levels, such as group conversations at a dinner table. Moreover, speech and background noise in real life are commonly not fixed in one location. Therefore, standard speech tests often do not reflect different listening situations encountered in real life. This is particularly relevant for individuals with hearing loss and using auditory prostheses (i.e. HA or CI) as the scores from standard speech-perception tests often do not represent their listening abilities. The current audiometric tests are inadequate to determine the hearing difficulties and the benefits from hearing devices for hearing-impaired listeners (Working Group on Speech Understanding and Aging, 1988). For instance, many HA users can obtain relatively good scores in clinical tests, yet they report difficulties in speech understanding in their real life during conversations (Bracker *et al.*, 2019a). Therefore, it is important to use tests that give more information about the performance in real-life situations, particularly with advances in digital hearing devices and the growing number of device features for different listening situations (Keidser *et al.*, 2020).

In the last decade, a growing interest has been seen in hearing-related research concerning the ecological validity of the measurements. Based on the sixth Eriksholm Workshop in 2019, the ecological validity concept in hearing science refers to “the degree to which research findings reflect real-life hearing-related function, activity, or participation” (Keidser *et al*., 2020, p.7S), where ‘real-life’ in this context refers to situations that are not controlled by an experimenter or researcher (Keidser et al., 2020). In addition, the workshop discussion highlighted the need to consider the direct effect of the important independent variables on the level of ecological validity of such measurements in research studies. These independent variables are grouped into (1) sources of stimuli, (2) environment (presentation of stimuli), (3) context of participation (settings), (4) task (response), and (5) individual (participant). However, there are no formal guidelines or criteria to determine the level of ecological validity or whether the design of a study is more or less ecologically valid. Therefore, caution should be taken when using the term 'ecological validity' when describing or discussing the design or the outcome of research. Instead, the term 'more representative of real-life situations' is used throughout this thesis.

There were attempts to establish real-life listening features into the standard clinical tests either by using different stimuli that commonly present in real-life situations or by introducing novel test environments and tasks. For instance, some studies have recommended using different types of noise instead of steady-state stationary noise (Rhebergen *et al.*, 2008, Lee *et al.*, 2015). It has been shown that speech perception in real-life situations is affected by the type of noise, SNR levels, and the age of the listeners (Lee *et al.*, 2015). The background noises in such situations have more complex characteristics in spectral and temporal features when compared to the steady-state noise, which is typically used in standard clinical tests. Therefore, noises such as speech-shaped noise and multi-talker babble noise would make the test more representative of real-life situations.

In addition, there were attempts to enhance the real-life representation of speech-perception tests by using a roving-level method for both speech and noise during the test, such as in *Boyle et al.* (2009), Haumann *et al.* (2010) and Boyle *et al.* (2013). All the standard speech perception-in-noise tests use a fixed presentation level for the target speech to some degree, such as Hearing in Noise Test (Nilsson *et al.*, 1994). There are two main methods used to present target speech and competing noise in standard speech-perception tests: (1) fixed procedure and (2) adaptive procedure. In the first method, the target speech and the competing noise are fixed at a certain method. In the adaptive method, either the target speech or the competing noise is fixed at a certain level. However, in real-life listening situations, the target speech and the competing noise are commonly varying in levels where the SNR is mainly changed by the talker who selects the voice level according to a complicated set of factors, such as noise level and the distance from the listener. Although it is possible to use different presentation levels of the target speech, they are usually administered across the test lists. Therefore, standard speech tests still cannot provide adequate information about the performance in real life. Boyle *et al.* (2009) and Haumann *et al.* (2010) investigated the difference between different sound processor types for CI users using a speech test with roving levels across sentences. The preliminary results showed differences between different sound processor models when using roving levels, which were not found when a fixed speech presentation level was used. Then, Boyle *et al.* (2013) developed the Sentence Test with Adaptive Randomized Roving levels (STARR), where the speech and noise presentation level varies within a complete list of sentences. The sentences in the STARR test are presented in a speech spectrum-shaped noise from a loudspeaker placed in front of the participant. The test was administered to NH listeners and adult CI users. The results showed that the performance of CI users was noticeably affected by using the roving-level method, whereas the effect of the roving level for NH listeners was minimal (Boyle *et al*., 2013). Therefore, roving-level speech tests would represent real-life situations more than standard speech tests.

Another important aspect is the location of the speech and the competing noise. In real-life listening situations, the target speech and the competing noise often come from a range of locations. For instance, one of the common challenging situations for listeners with hearing loss is understanding speech in a group conversation where different talkers of interest frequently change with other people who are talking at the same time. This situation is not reflected in standard speech tests. To the best of the researcher's knowledge, very few previous studies have measured speech perception when the location of the target speech varies (Jensen et al., 2011, Best et al., 2015, Bizley et al., 2015). Jensen *et al.* (2011) measured the SRT for 16 adult HA users with mild-to-moderate hearing loss with fixed- and random-target locations, where sentences were presented randomly from one of three loudspeakers at 0° or ±45° azimuth. The results showed a significant increase in SRT of 1 dB in the random-target locations condition compared to the fixed-target location. Bizley et al. (2015) used a rig of 18 loudspeakers arranged at 15° intervals from -127.5° to +127.5° to assess binaural hearing ability in NH listeners, specifically speech perception and spatial discrimination in noise, using a single task. The task involved a pair of monosyllabic words that were sequentially presented from two adjacent loudspeakers in a pseudorandom order and multi-talker babble that was presented from all the loudspeakers. The participants were asked to identify both words from a closed set of four options and then to identify whether the second word was presented to the right or left of the first. The participant's performance in the spatial discrimination was higher in and around the frontal midline compared to lateral locations whereas the speech perception was improved at the lateral locations compared to the midline. The measurement of test-retest reliability of this task indicates a satisfactory level. The findings suggest using a complex, realistic listening set-up could provide a useful measure for different binaural hearing skills. Bizley et al. (2015) recommended using a such test set-up would be potentially suitable to assess the performance of a wide range of listeners including CI users in clinical settings.Best *et al*. (2015) used two paradigms to assess the performance of two experimental binaural beamformers for 27 adult HA users. In the first approach, the sentences were presented from a loudspeaker at 0° azimuth in multi-talker backgrounds, whereas in the second paradigm, the sentences were roved randomly from five loudspeakers placed at 0°, ± 22.5°, and ± 67.5°. There was an improvement in the performance when using two binaural beamformers, relative to conventional directional microphones, for the first paradigm when the sentences were fixed from front loudspeakers. However, the performance was not improved when the speech was roved randomly from different loudspeakers. The findings from these studies suggest that current standard speech tests do not necessarily reflect the performance in real-life situations. Moreover, standard speech tests seem to be less sensitive to demonstrate the benefits of possible management or the difference between two possible managements, particularly for adult CI users. More recent evidence showed that the performance of bilateral CI users was better than unilateral CI users in a complex listening set-up when the location of the target speech roved randomly (van Hoesel, 2015, Dorman *et al.*, 2020); further discussion of the findings from these two studies is provided in Chapter 6. Therefore, it would be useful to apply the feature of uncertain locations of target speech in the speech-perception tests.

On the other hand, using speech-perception tests only could not estimate the extent to which the benefits of hearing devices can be used, particularly for the other essential listening skills in real life, such as identifying the source of sounds, music perception, and using the telephone. Furthermore, it would be useful to assess the perceived benefits from the listener's perspective. Dillon (2012) claimed that a hearing device would have a good chance of success and uptake when listeners perceive the benefits found in the performance tests. Therefore, using a test battery that incorporates both performance and subjective measurements would be useful to provide a clear profile of the benefits obtained from a hearing device. Recent studies by Bracker *et al.* (2019a), Bracker *et al.* (2019b) applied a battery of real-life listening features tests to 20 participants with normal hearing and 56 hearing-implant users (acoustics stimulation system (EAS), cochlear implant (CI), and vibrant sound bridge (VSB) users). In these studies, hearing performance was evaluated using speech-perception in background-noise tests, sound quality and subjective benefit questionnaires and listening efforts. They used the Roving Level Test (RLT), the Just Understanding Speech Test (JUST), and the Performance Perceptual Test (PPT) to assess speech-perception abilities in background noise. The RLT is similar to the STARR test, where the test material (OLSA sentences) is presented at three interleaved levels in stationary noise matched to the long-term spectrum of the OLSA sentences, whereas the PPT used the same procedure as RLT; it is just administered at one level (65 dB SPL), and the participant states if the whole sentence is understood or not. The Visual Analogue Scale (VAS) measured listening effort and the Hearing Implant Sound Quality Index questionnaire (HISQUI) measured the perceived sound quality. The results of these two studies showed the importance of using a test battery that include both self-estimated and verified performance measurements in simulated real-life listening situations to obtain a realistic and comprehensive profile about hearing abilities. This is particularly important for individuals with an implant device as the results showed a discrepancy between the performance and self-reported benefits measures of hearing difficulties.

In summary, using both performance and subjective rating measurements would be meaningful to provide clinicians with a test battery that would reflect hearing performance in real-life listening situations. This would help the clinicians to provide better guidance and information to the listeners using a hearing device (HA and CI users). Moreover, it would help them provide the most suitable device settings and rehabilitative strategies.

2.6 Summary and aims

The main points of this literature review are as follows:

- The normal auditory system is remarkably sensitive to the interaural differences in the arriving time and the level of sounds at the two ears. Adults with normal hearing can detect ITDs of 10 µs and ILDs of 0.5 to 1 dB.
- Binaural hearing is important for everyday auditory functions, particularly understanding speech in noise and localising the sound sources.
- Hearing impairment affects the binaural processing and the transformation of binaural cues; therefore it can impair the ability to understand speech in the presence of a background noise and localise the sources of the sounds.
- Cochlear implantation becomes the standard treatment for listeners with bilateral severe to profound hearing loss associated with an improved ability to perceive speech and a higher quality of life.
- Adults typically receive one cochlear implant due to cost constraints. Limited access to binaural cues affects the CI user's ability to localise the sources of sounds and to understand speech-in-background noise.
- Bilateral implantation and bimodal hearing can restore some binaural hearing functions for adults with unilateral cochlear implants. However, binaural cues (ITDs and ILDs) might not be accurately presented due to device and sensory limitations.
- Studies showed that bilateral implantation could provide benefits in terms of speech perception, localising sound sources, and self-reported benefits. Excessive costs associated with providing the two implants seem to limit the cost-effectiveness of bilateral implantation for adults.
- Studies showed that bimodal hearing could provide some binaural benefits, particularly in understanding speech in noise and improving music perception for many adults with unilateral cochlear implants. Cochlear implant manufacturers are constantly working on improving technologies to overcome signal-processing difficulties associated with bimodal hearing (i.e. introducing integrated bimodal technology where the cochlear implant and hearing aid work on the same platform).
- The standard speech–perception-in-noise tests used in clinical and research settings do not reflect different listening situations encountered in real life because the speech and

noise are presented from a single speaker placed in the front of the listeners. Therefore, there is a need to develop a test battery that comprises more real-life representative tests for CI users to determine the hearing difficulties and the benefits from the hearing devices (bilateral implantation versus bimodal hearing).

Based on the literature review discussed in previous sections, the **main aim** of this thesis is to investigate the outcomes of adult unilateral, bimodal and bilateral CI users versus NH listeners on a real-life test battery. To realise this aim, the following sub-aims were formulated:

1. To determine bimodal and bilateral CI-service provision for adults around the world
2. To develop a real-life test battery that can be used to assess the performance of adult CI users with more representative outcome measures of real-life listening situations
3. To assess the measurement precision and obtain reference data for the newly developed tests included in the real-life test battery on adult NH listeners
4. To compare the outcomes and experiences of adult CI users when using the integrated bimodal technology (Naida Link bimodal technology) versus the CI only
5. To compare the outcomes and experiences of adult bilateral CI users when using two implants versus one CI
6. To compare the outcomes and experiences of integrated bimodal and bilateral CI users versus NH listeners.

Chapter 3 International survey of bimodal hearing and bilateral cochlear implant service provision for adults

3.1 Introduction

Bilateral implantation is already becoming the standard of care for children, but unilateral CI is still the standard treatment for adults in many countries (Smulders *et al*., 2017). Although there is some evidence in support of bilateral CI benefits (Nopp *et al*., 2004, Schleich *et al.*, 2004, Verschuur *et al.*, 2005, Litovsky *et al.*, 2006a, Litovsky *et al.*, 2009, Cullington and Zeng, 2011, Schafer *et al.*, 2011, van Schoonhoven *et al.*, 2013), the perceived cost benefit is often questioned (Crathorne *et al.*, 2012, van Schoonhoven *et al.*, 2013*)*.

Adult CI users tend to be offered an HA in the non-implanted ear (bimodal hearing) to offer a degree of binaural hearing. The reported percentage of CI users that use a HA in the non-implanted ear (bimodal hearing users) varies. Some earlier studies reported a rate of 10 to 25% of bimodal hearing users among their populations (Tyler *et al.*, 2002b, Fitzpatrick *et al.,* 2009). Another study conducted by Yamaguchi and Goffi-Gomez (2013) found a prevalence of 12% of 82 adult CI users who were using HAs in the non-implanted ear. An international survey reported that 32% of unilateral CI users use an HA in the non-implanted ear (Scherf and Arnold, 2014). A more recent study conducted by Devocht *et al*. (2015) showed a rate of 63.3% bimodal hearing users among 77 adults with unilateral CI after one year of CI experience. Similarly, Neuman *et al*. (2017) reported a rate of 85% of continued HA users among 94 CI users. One possible reason for this variability is that in the earlier studies, the criteria for implantation were more restricted (Devocht *et al*., 2015, Neuman *et al.*, 2017). The higher rate of HA retention shown by recent studies could be related to expanding the inclusion criteria in recent years. For instance, the mean pure-tone average (PTA) of thresholds at 500, 1000, and 2000Hz for the CI users who continued to use an HA in Neuman *et al*.'s study (2017) was 78 dB HL, which is substantially better than the average hearing loss reported for participants in the previous studies (Fitzpatrick *et al*., 2009, Devocht *et al*., 2015). Another possible reason is the recent improvements in technology that allow for streaming to both devices in bimodal hearing (Wolfe *et al.*, 2016b) as well as the integrated bimodal technology, such as the Naida Link bimodal system from Advanced Bionics (AB) and Phonak ((Bionics, 2016c). These developments could majorly contribute to increasing the number of bimodal users.

On the other hand, many adult CI users are reported to discard their HAs (Fitzpatrick *et al*., 2009, Fitzpatrick and Leblanc, 2010). Limited research has been carried out to investigate the reasons for the rejection of using a HA in the non-implanted ear and the related factors from either clinicians' or users' perspectives. Fitzpatrick and Leblanc (2010) administered a questionnaire to examine the factors influencing adult CI users' decisions to use an HA in the non-implanted ear. They pointed to three main factors that affect ongoing HA use in adult CI users: (1) the user's perception of their experience with HAs before CI; (2) their views of the superiority of CI in comparison with HAs; and (3) their perceptions of the interference with sound quality when they are using the HA and CI simultaneously. However, there are a few limitations with this survey. The number of respondents was small (only 28) and mostly female (71.4%), so the sample does not necessarily capture the perspectives of the majority of bimodal hearing users. Moreover, the respondents were recruited from a single CI programme centre in Canada. In addition, most participants who discarded the HA use (18 out 28) either did not use the HA at all or used it for less than one week. Therefore, their reported reasons were not based on an adequate trial of bimodal hearing to determine whether or not the HA was beneficial or not.

A more recent study by Neuman *et al*. (2017) used a modified questionnaire originally developed by Fitzpatrick and Leblanc (2010) to explore the experiences of bimodal hearing users with their HA before and after CI. All the participants have used an HA in the non-implanted ear for at least three months after implantation. 14 of the 94 participants had discontinued use of the HA. Most of the participants cited lack of helpfulness of the HA and unclear speech when using an HA as the most frequent reasons for discontinuing HA use. Other reasons were the interference between HA and CI, 'too much bother' to use both devices and the additional expense of using the HA. However, these findings should be interpreted with caution as the reported findings were based on just 14 participants who discontinued using the HA.

CI professionals reported that some adult unilateral CI users rejected the contralateral HAs (HA in the non-implanted ears), most often due to a lack of benefit and the balance of sound between the two devices (Scherf and Arnold, 2014). Furthermore, Scherf and Arnold (2014) pointed out that many adult CI users might reject using an HA in the non-implanted ear because the HA is often not refitted immediately after the CI switch-on. This is because some clinicians may have concerns about the reliance on the HA input, particularly at the early stage after CI, or the lack of experience in HA within the CI service.

Additionally, the HA and CI are often funded and fitted separately (i.e. the CI at a CI service and the HA at the local audiology department), which could be a potential drawback affecting the optimal perception of bimodal benefits and therefore cause rejection of the use of an HA (Siburt and Holmes, 2015, Veugen *et al.*, 2016a). The two devices are most likely to be programmed independently with different parameters and fitting formulae; therefore lack ensuring the optimal perception of binaural cues. For instance, a survey to explore bimodal-hearing provision and practice for 20 UK CI centres revealed that no centre indicated making any attempt to match devices' parameters such as frequency allocations or compression settings (Fielden and Kitterick, 2016). Studies showed that ILDs are better preserved when an HA frequency response and loudness are similar to the CI (Ching *et al.*, 2007, Potts *et al.*, 2009, Francart and McDermott, 2013, Veugen *et al.*, 2016a). An integrated model of bimodal-hearing service provision (fitting the CI and HA at the same service) would provide smoother and cohesive care and optimise the fitting of the CI and the HA (Fielden and Kitterick, 2016), which would encourage CI users to continue using an HA in the non-implanted ear.

3.2 Previous surveys that looked at bimodal-hearing practice

A few studies have investigated the clinical practices and provisions for bimodal hearing in adult unilateral CI users through surveying the professionals in the field of CI. In the UK, current provisions, practices and clinical experience of bimodal hearing were explored by Fielden and Kitterick (2016). An online questionnaire was circulated to 20 UK CI centres, and responses were received from 19 centres. The respondents felt that bimodal hearing is more beneficial than using an implant alone, especially when considering fitting the two devices (the CI and the HA) to work together. However, 15 out of the 19 centres indicated that they do not take responsibility for fitting and maintaining the contralateral HA after implantation. They usually refer patients to the local audiology team for HA fitting and maintenance. In addition, the results have shown some potential inconsistencies in the provision of bimodal hearing at a minority of centres that take full responsibility for fitting and maintaining the contralateral HA. For instance, only one centre used an agreed protocol for 'bimodal switch-on' in the clinic by considering both devices when creating the first CI map, whereas other centres did not report taking the HA parameters into account during CI programming. The results of this study were in line with Siburt and Holmes (2015) in terms of the presence of inconsistency in the current practice of fitting and programming of bimodal hearing. In that study, an online survey was sent to 360 CI programming centres in the USA with a response rate of 26% for the overall survey. The responses indicated the use of different methodologies for HA fitting and verification measures. In addition, results showed that the programming is often completed by different clinicians and frequently at different centres. These findings indicated the importance of developing guidelines to shape routine clinical practice for bimodal hearing in adult unilateral CI users.

In another survey administered by Scherf and Arnold (2014), the current approach to bimodal-hearing fitting across different countries was investigated. 65 clinicians working with HAs and/or CI from 12 different countries responded to the survey. The results showed that the fitting of an HA in the non-implanted ear of CI users is now well established as part of standard clinical practice; however there is a considerable variation in the approach to the bimodal-hearing fitting from country to country with a lack of experience in fitting HAs within the CI service. There were no specific criteria followed for selecting bimodal-hearing candidates. Additionally, there was no clear strategy to balance the HA with the CI for any adults as a standard practice. In addition, the survey explored the reported benefits by CI users and reasons for rejecting the device. The results showed that the improvement in overall sound quality was the most reported benefit by recipients, whereas the lack of benefit is the main reason for some users that reject the device. More than half of the respondents (61%) in that survey recommended that the same clinician should do both the HA and CI fitting to improve the delivery of future practice for bimodal-hearing users. However, the survey's results might not truly represent the current approach and practice of bimodal-hearing fitting worldwide, as 35% of the respondents were from Belgium. Furthermore, the method used to develop and validate the questionnaire was not described clearly, nor was a copy of the questionnaire included in the study or an appendix.

Currently, it appears that there are no clear guidelines in the UK and/or elsewhere for balancing the programming of HA with CI. The results of the studies discussed above underscore the importance of establishing recommended guidelines and procedures for bimodal-hearing fitting to reduce inconsistency in practice and enhance the optimal performance of bimodal hearing. Although Scherf and Arnold's (2014) international survey offered valuable insights to the approach to bimodal-hearing fitting across different countries, there is now a need for a more current snapshot of international bimodal-hearing and bilateral CI service provision for adults. The information will offer an insight into the current practice across different countries. Thus, it will allow the sharing of information and contribute to developing new guidance to assist CI professionals in providing optimal support and maximising hearing in adult CI users.

3.3 Aims

The main aim of this international survey was to determine bimodal-hearing and bilateral CI service provision for adults around the world.

To realise this aim, the following sub-aims were formulated:

- Determine the percentage of adult unilateral CI, bimodal-hearing and bilateral CI users

- Determine how unilateral, bilateral CI and the HA in the non-implanted ear for adults are funded
- Explore the reasons why adult unilateral CI users wear or do not wear an HA in the non-implanted ear from the professionals' perspective
- Explore CI professionals' current practice versus recommendations for best practice when fitting and maintaining the bimodal-hearing technology
- Explore the use of integrated bimodal-hearing technology use in adult CI users' and professionals' perspectives.

3.4 Methodology

3.4.1 Study design and ethical considerations

This study used a cross-sectional survey design, conducted from 15th May 2018 to 31st October 2018. Ethics approval was given by the University of Southampton Ethics Board (ID:40048). The research complied with the Data Protection Act 1988. All the responses from participants were anonymous. All participants were required to provide electronic consent before completing the survey.

3.4.2 Participants

Professionals currently working within the field of CI worldwide were eligible to participate in the survey. This international survey was done using an online questionnaire. Information about the survey, with a link to the questionnaire, was circulated to professionals in the 25 countries who took part in the international survey of Vickers *et al.* (2016), which looked at candidacy criteria. Additionally, the invitation was sent to CI services using open-access search engines listing the names of CI services across the world. Moreover, the invitation was distributed to the members of Euro-CIU (the European CI users' association) via their newsletter. In total, professionals from 75 countries were invited to participate in the survey. Appendix F lists the countries that were included. 64 responses were obtained from 25 different countries across the world.

3.4.3 Online questionnaire

The data were collected using an online questionnaire administered using the iSurvey platform at the University of Southampton.

3.4.3.1 Content and questions

The questionnaire (Appendix G) comprised three sections (Section A: Participant demographic information, Section B: Bimodal-hearing and bilateral CI service provision, and Section C: Integrated bimodal-technology service provision). There was a total of 24 questions.

Section A was designed to gather information about the participants, i.e. the CI professionals. This included their job description, years of experience fitting CIs and HAs and country of residence.

Section B focussed on the service provision of bilateral CI and the HA in the non-implanted ear for unilateral CI users. In this section, CI professionals were asked how unilateral, bilateral CI and contralateral HAs are funded. In addition, they were asked to give an approximate percentage of adult unilateral and bilateral CI users and those who wear an HA in the non-implanted ear. Participants were also asked to select from a range of multiple-choice answers why adult unilateral CI users might choose to wear or not wear an HA in the non-implanted ear after implantation. An ‘other’ option was included to allow additional answers beyond the pre-determined options. Participants’ opinions were gauged regarding who should be responsible for fitting and maintaining the HA in the non-implanted ear of adult unilateral CI users, i.e. CI services, local audiology departments or private practitioners. Participants were asked to justify their answers.

In Section C, participants were asked about their perceptions of integrated bimodal technology (Naida Link Bimodal HAs).

In developing the online questionnaire, the guidance of (Czaja and Blair, 2005) was used to ensure that the questions were relevant and easy to understand. Different formats of questions were used, for instance multiple-choice and open-ended questions, to capture information in a quick, accurate and interesting way for participants. Care was taken to ensure that language use was clear and concise, given that English was not likely to be the first language of many of the participants.

3.4.3.2 Questionnaire validation

It is noteworthy that many international surveys in the field of audiology, e.g. Scherf and Arnold (2014), Eikelboom and Swanepoel (2016), and Manchaiah *et al*. (2021), have not addressed validation in the online questionnaires that they used, with the exception of Vickers *et al*. (2016). The process followed by Vickers *et al*. (2016) was used in the development of the online questionnaire used in this survey.

Validity refers to whether the questionnaire accurately measures what it claims to measure. It is a very important and fundamental component of preparing a questionnaire for use (Jackson and Furnham, 2000). There are several different types of validity: apparent validity, content validity, construct validity and concurrent validity.

To ensure apparent validity, Jain *et al*. (2016) suggest that the questionnaire questions should be generated in consultation with experts' opinions and participants themselves. In addition, they suggest that all the questions should be logical to achieve apparent validity. Content validity refers to the accuracy with which the questionnaire's items adequately represent the qualities or concepts they are intended to measure (Jackson and Furnham, 2000, Rattray and Jones, 2007). Content validity is usually measured by determining if a panel of experts agree that the items can measure what the questionnaire is intended to measure by judgement sought from medical review or pilot studies (Jackson and Furnham, 2000, Jain *et al*., 2016).

Although content validity is an important and initial step in establishing the validity of the questionnaire, Rattray and Jones (2017) consider that it is not sufficient by itself. Concurrent validity should also be demonstrated. This requires comparing the questionnaire's scores with related and dissimilar well-established ones. A high correlation indicates concurrent validity (Jackson and Furnham, 2000). Therefore, it is important to evaluate the development of a questionnaire to include additional established measures that have proven validity within the research design (Rattray and Jones, 2007). However, concurrent validity could not be applied to this questionnaire because there was no similar validated questionnaire where the main purpose was to survey CI professionals about contralateral HA use in adult CI users around the world. In addition, there is no benchmark against which particular surveys can be evaluated in terms of meeting the highest levels of validation. In other words, this questionnaire is considered as a starting point to obtain a snapshot. It could be used as a base for future research to evaluate concurrent validity.

Another type of validity is construct validity which refers to how well the items in the questionnaire reflect the concepts to be measured (Rattray and Jones, 2007, Jain *et al*., 2016). It is a quantitative value rather than a qualitative method used to determine whether each item of the questionnaire is 'valid' or 'invalid' (Parsian and Dunning AM, 2009). To establish construct validity, factor analysis can be used to determine the constructs or the domains developing the questionnaire. Factor analysis is a statistical method used to cluster items into common factors. The related items that define the part of the construct can be grouped together, and the unrelated items that do not define the construct should be deleted (Parsian and Dunning AM, 2009). Although construct validity is an important aspect of the questionnaire validation process, this could not be achieved for two reasons. To perform an exploratory-factor analytical approach, the questionnaire should be administered to a sample of a sufficient size of 100 respondents or at least five respondents per item (Rattray and Jones, 2007). This cannot be achieved as the targeted participants of this questionnaire (professionals who are working with CI users) are limited even across countries. Another reason is that this questionnaire is not an assessment questionnaire (outcome measure); instead, it is a questionnaire designed to survey the professionals' views and recommendations for the current practice. Therefore, the construct validity for this questionnaire is not achieved. Artino *et al*. (2014) suggested that reviewing the descriptive statistics and histograms of the pilot results to demonstrate the distribution of responses by item can help identify items that may not function in the way the questionnaire is intended. Furthermore, they recommend using advanced statistical techniques such as factor analysis to measure the internal structure of the questionnaire. However, this could not be carried out because the main purpose of the questionnaire is to survey CI professionals' opinions, and it is not an assessment tool.

Overall, the validity of the online questionnaire used in this international survey was achieved by apparent validity and content validity. Concurrent and construct validity could not be achieved due to the nature of the questionnaire itself, as discussed earlier. Figure 3.1 depicts the process used to validate the questionnaire, where the questionnaire went through three stages of validity review preceding circulation.

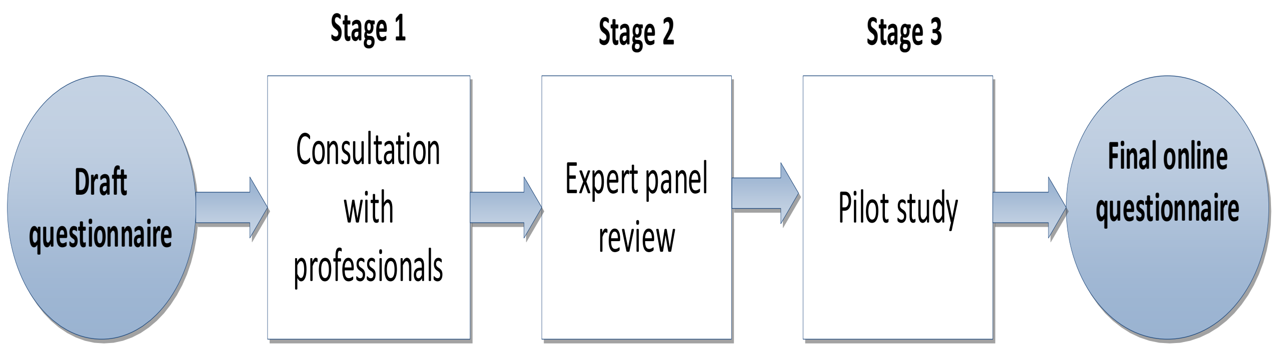

Figure 3.1: A flow chart showing the process used to validate the questionnaire.

3.4.3.2.1 Stage 1

The first version of the questionnaire was sent to two professionals in the field of CI in a Word document format with a request to review the content to ensure that the questions addressed the main and sub aims. The questionnaire was modified based on their feedback (as summarised in Appendix H). After that, an online version was developed using the iSurvey software available at the University of Southampton.

3.4.3.2.2 Stage 2

The second stage of the validation was an expert panel review. Expert validation is an important step in developing a new online questionnaire as using experts to systematically review its contents can substantially improve the overall quality and representativeness of the items in the questionnaire (Artino *et al.*, 2014). The first step in this stage is selecting a panel of experts based on specific criteria. There is no consensus in the literature on the number of experts that should be used for expert validation; however Artino *et al*. (2014) state that the number impacts the quantitative techniques used to analyse experts' input. Four experts with a varied experience pool in the field of CI were invited by email to participate in the panel review. The panel was made up of two expert researchers in the field, the leader of the adult CI users' programme, and a clinician.

A link to the online questionnaire in the iSurvey software was sent to experts with a form to fill in their feedback and comments. The panel was asked to provide feedback on the following points:

1. The content of the questionnaire and whether anything should be added or changed
2. The clarity of the language used and whether everything was understandable
3. The length of the questionnaire in terms of the time taken to complete it
4. Any further recommendations or suggestions they wanted to add.

Feedback and suggestions given at this stage were used to make amendments to the questionnaire (Appendix H). The approach used to evaluate reviewers' feedback and the response made was based on the approach advised by (McKenzie et al., 1999). They recommend that the researcher looks for consensus among the reviewers' feedback and suggestions that would be an indicator that a change should be made. If there is no consensus, it would be the researcher's 'call' to decide what should be included or reject. The researcher's judgement is based on the relevance of the feedback or suggestions to the questionnaire aims and the practicality of the questionnaire. For instance, one suggestion was to limit the multi-selects to only three options for the question asked about the benefits of using the HA in the non-implanted ear for unilateral CI users. The suggestion was not implemented because, based on the literature review, all of the listed options play a role and limiting the choices could result in losing valuable information.

3.4.3.2.3 Stage 3

Finally, a pilot study was undertaken by sending the third version of the questionnaire to two CI professionals who were not involved in the expert panel review and were not included in the final participant group. According to Gillham (2007), piloting the questionnaire is a very important step to determine the response rate (whether it is low or very low) and detect any misunderstandings about what a question means or how participants are supposed to answer it. After completing the questionnaire, these pilot participants were asked to give feedback about the wording and clarity of the questions. In addition, they were asked to comment on the time taken to complete the questionnaire and provide any further comments or recommendations.

The two participants had different backgrounds and experiences. One was a speech-language therapist and the other an audiologist. Following that, the questionnaire was finalised (Appendix G).

3.4.4 Procedure

An invitation (Appendix I) with the link to the online questionnaire was sent out to professionals working in the CI service in 75 countries. The participant information sheet, which contains further details about the study, was attached to the invitation email. The contact details of the researchers were provided to the participants for any enquiries. The questionnaire was open for completion for one calendar month, and a reminder email was sent after two weeks. However, the availability of the questionnaire was extended for a further four months to obtain more responses. The questionnaire was open from 15th May 2018 to 31st October 2018.

3.4.5 Data protection and anonymity

Questionnaire data were collated on a spreadsheet in an anonymised format on a password-protected computer. In accordance with the University of Southampton research data management policy, all significant data should be held for a minimum of ten years.

3.5 Results

3.5.1 Demographic information of participants and CI services

In total, 64 respondents completed the questionnaire, representing 25 countries. Two of the respondents were excluded from the analysis. The first had prior CI experience but was not currently working at a CI service, and the second respondent’s questionnaire was incomplete. As a result, the total number of respondents considered in this study is 62. The demographic information of the respondents and CI services are presented in Table 3.1. It should be noted that the respondents were allowed to select more than one answer for the question about the participant's job description because many of them work in different positions within the CI service. For example, one respondent acts as a head of service and an audiologist. Similarly, the respondents were allowed to select more than one answer for the question about the companies of CI devices used by the patients at their service.

Table 3.1: Demographic information of respondents and CI services (n=62).

Variable	N (%)
World regions	
• Europe	• 26 (41.9)
• Asia	• 20 (32.3)
• Americas	• 11 (17.7)
• Oceania	• 3 (4.8)
• Africa	• 2 (3.2)
Job description (*)	
• Audiologist	• 41
• Head of Service	• 16
• Psychologist	• 0
• Speech and Language Therapist	• 11
• Surgeon	• 13
• Rehabilitationist	• 4
• Other	• 1 (Audio-vestibular medicine specialist)
Years of CI experience	
• < 1year	• 2 (3.2)
• 1-4 years	• 9 (14.5)
• 5-9 years	• 18 (29)
• 10-19 years	• 19 (30.6)
• >20 years	• 14 (22.6)
Years of HA experience	
• < 1year	• 1 (1.6)
• 1-4 years	• 7 (11.3)
• 5-9 years	• 21 (33.9)
• 10-19 years	• 15 (24.2)
• >20 years	• 18 (29)
Number of adult CI recipients at service	
• 1-50	• 18 (29)
• 50-100	• 5 (8.1)
• 100-500	• 19 (30.6)
• More than 500	• 20 (32.3)

CI devices used /offered at service (*)	
• Advanced Bionics	• 47
• Cochlear	• 59
• MED-EL	• 58
• Oticon Medical	• 15
• Nurotron	• 1

*Participants were allowed to select more than one answer

3.5.2 Percentage of adult unilateral CI, bilateral CI and bimodal-hearing users

The participants were asked to select one from four ranges representing the total number of CI users at their CI service. They were also asked to give an approximate percentage of adult unilateral and bilateral CI users at their service and the percentage of unilateral CI users using an HA in the non-implanted ear. The total number of CI users at the participants' CI service and the percentage of adult CI users in the five world regions are shown in Table 3.2. The results showed that the average estimated percentage of adult unilateral CI users is higher than bilateral CI users. In addition, the results showed that approximately half of the adult unilateral CI users were using an HA in the non-implanted ear.

Table 3.2: Total number of CI users at the CI service and the estimated percentage of total adult unilateral CI users, those who use an HA in the non-implanted ear, and adult bilateral CI users as reported by the respondents. Asterisk (*) indicates an average of the estimated percentage. (*Th estimate % of total unilateral and bilateral CI users may not add up to 100 because these are estimated values as reported by the respondents*).

World regions	N	Total number of CI users at service (No. of responses)	Estimate % of total that are unilateral CI users	Estimate % of unilateral CI users wearing an HA in the non-implanted ear	Estimate % of bilateral CI users
Europe	26	1-50 (1)	95	60	5
		50-100 (1)	45	25	35
		100-500 (11)	88*	51*	12*
		More than 500 (13)	84*	57*	16*
		Average	78	48.25	17

Asia	20	1-50 (15)	69.8*	36*	7.8*
		50-100 (3)	47*	20*	12*
		100-500 (2)	55*	72.5*	45*
		Average	55	42.8	21.6
Americas	11	1-50 (2)	93*	45*	7*
		50-100 (1)	100	10	0
		100-500 (4)	75*	76*	25*
		More than 500 (4)	85*	45*	15*
		Average	88.3	44	11.75
Oceania	3	100-500 (1)	85	70	15
		More than 500 (2)	65*	40*	35*
		Average	75	55	25
Africa	2	100-500 (1)	80	50	20
		More than 500 (1)	65	70	35
		Average	72.5	60	27.5
Total	**62**	**Weighted mean**	**74.2**	**46.4**	**18.3**

3.5.3 Funding

Figure 3.2 shows the primary funding source for unilateral CI for adults across the five world regions. The participants were allowed to select more than one option. For Europe and Asia, state funding seemed to be for adult unilateral CI, as indicated by 83% and 63% of responses, respectively, while for the Americas region, state funding (39%) and private insurance (33%) were the main providers for unilateral CI for adults. Approximately half of the responses (50%) in the Oceania region indicated that private insurance provided unilateral CI for adults. A different trend was seen in Africa, where 40% of responses indicated that unilateral CI was provided through private insurance and self-funding.

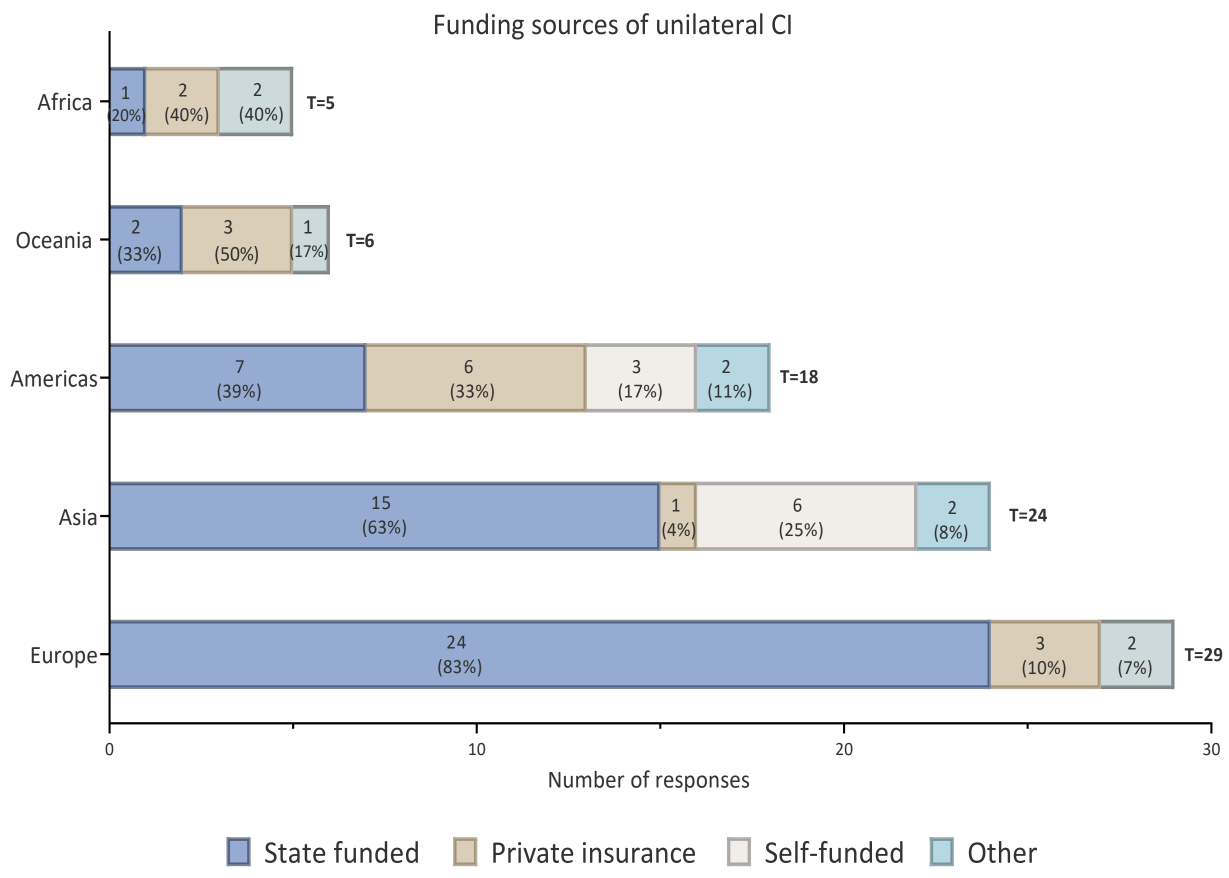

Figure 3.2: Stacked bar chart showing the main source of funding for the adult unilateral CI in the five world regions: Europe, Asia, Americas, Oceania, and Africa. Participants were allowed to select more than one option. Each shaded section indicates the exact number of responses for each funding source with a percentage shown. The total number of responses in each region is indicated by 'T'. Self-funded means that the CI users pay using their own money, and 'Other' includes any other funding source such as mixed sources like self-funded but partially state-funded scientific clinical trials, and research settings.

The funding sources of simultaneous and sequential bilateral CI for adults are shown in Figure 3.3. The participants were allowed to select more than one option for these questions. Generally, there was a similar trend of funding sources for simultaneous and sequential bilateral CI across the five world regions. In Europe, bilateral CI (both simultaneous and sequential) was mainly provided by state funding or other forms of funding, such as when the unilateral CI user participated in scientific clinical trials or research. In addition, state-funded bilateral CI for adults was provided without additional criteria in some countries such as France, Hungry, and Italy. In comparison, state-funded bilateral CI for adults in the UK was provided for only those with additional sensory impairment based on NICE guidelines.

In Asia, approximately 55 to 57% of responses indicated that the bilateral CI (both simultaneous and sequential) was provided by state funding. About 30 to 32% of responses indicated that bilateral CI could be obtained through self-funding.

The bilateral CI for adults seems to be provided through different sources in the Americas region. Approximately 31 to 35% of responses indicated that bilateral CI was funded via private insurance, and 24 to 25% of responses reported that state- and self-funding were other funding sources. Additionally, about 19% of responses reported that the CI service was funded bilateral CI (simultaneous or sequential) for a limited number of patients above and beyond their provincially funded allotment.

Private insurance seems to be the main source for funding adults' bilateral CI in Oceania, as reported by 75% of responses, while both private insurance and self-funding were equally main routes to obtain bilateral CI in Africa. Moreover, one respondent reported that simultaneous bilateral CI in Africa could be funded through charity support.

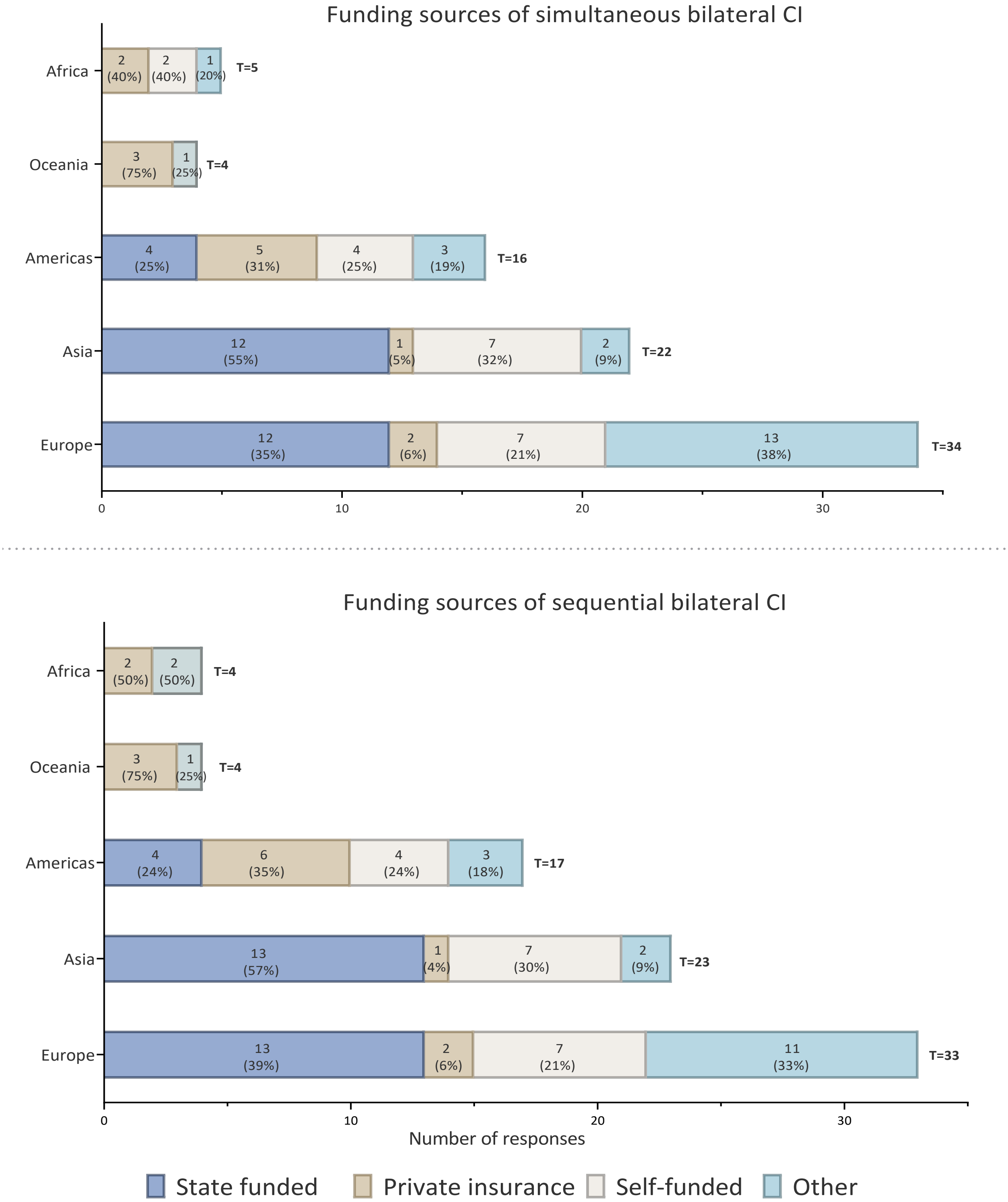

Figure 3.3: Stacked bar chart showing the main source of funding for adult simultaneous (upper panel) and sequential (lower panel) bilateral CIs in the five world regions: Europe, Asia, Americas, Oceania, and Africa. Participants were allowed to select more than one option. The total number of responses in each region is indicated by 'T'. Self-funded means that the CI users pay using their own money, and 'Other' includes any other funding source such as mixed sources like self-funded but partially state-funded, scientific clinical trials, and research settings.

Funding sources of the HA in the non-implanted ear for adult unilateral CI users are presented in Figure 3.4. Approximately half of the responses (50%) from Europe reported that the contralateral HA was state-funded. Self-funding was also another source, as indicated by 25% of responses. In addition, mixed funding sources (e.g. 70% state-funded with 30% self-funded) was a trend reported by 16% of responses. State- and self-funding were the main sources for providing the HA for adult unilateral users in Asia, the Americas and Oceania. In addition, private insurance was another potential funding source for the contralateral HA in the Americas and Oceania. In Africa, private insurance and self-funding were the main routes of funding the HA, as reported by 40% of responses.

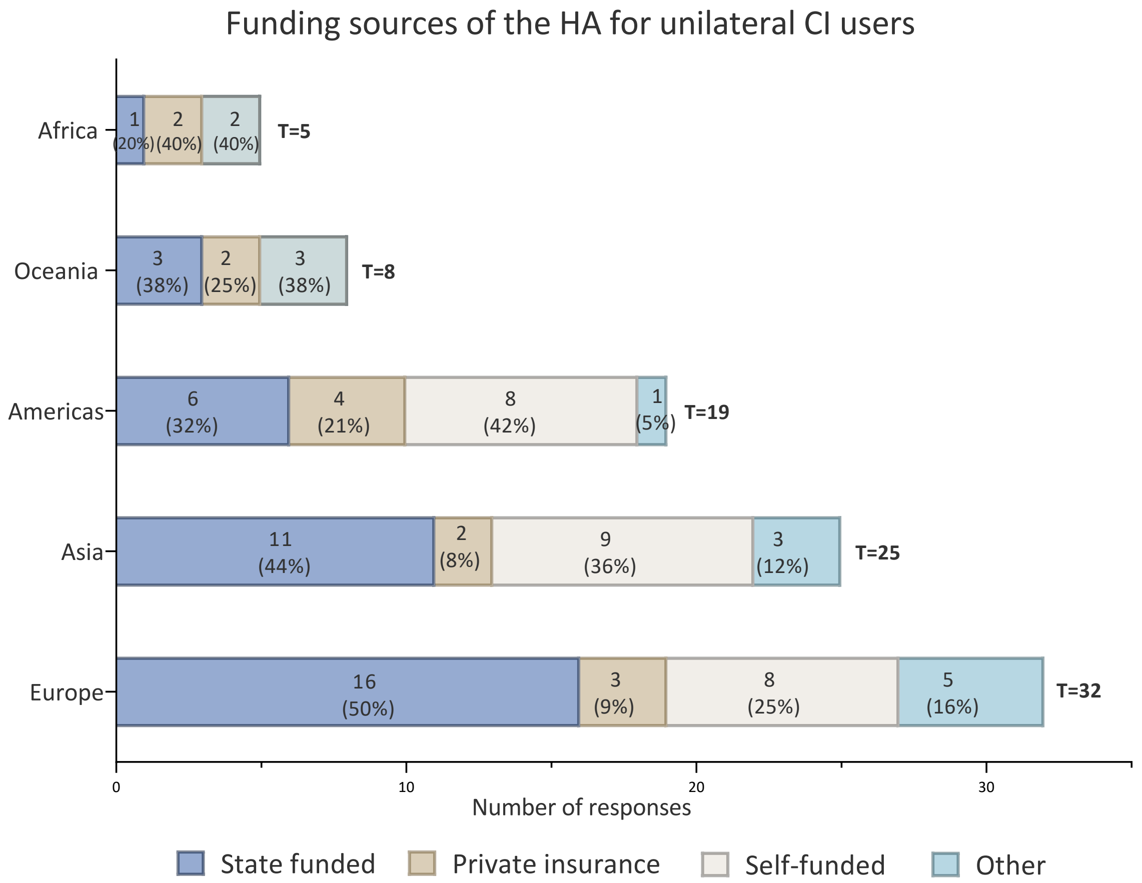

Figure 3.4: Stacked bar chart showing the main source of funding for HA in the non-implanted ear for adult unilateral CI users in the five world regions: Europe, Asia, Americas, Oceania, and Africa. Participants were allowed to select more than one option. Each shaded section indicates the exact number of responses for each funding source with a percentage shown. The total number of responses in each region is indicated by 'T'. Self-funded means that the CI users pay using their own money, and 'Other' includes any other funding source such as mixed sources like self-funded but partially state-funded, scientific clinical trials, and research settings.

3.5.4 Professionals' perspective on why adult unilateral CI users wear or do not wear an HA in the non-implanted ear

Table 3.3 shows the reasons why adult unilateral CI users choose to wear an HA in the non-implanted ear after implantation from the professionals' perspective. The participants were allowed to select more than one option. Improved localisation and balanced hearing were the most reported reasons for using the HA. This was followed by better sound quality and improved speech recognition in noise.

Table 3.3: CI professionals' perception about the reasons why adult unilateral CI users choose to wear an HA in the non-implanted ear after implantation.

Category	Frequency
Improved localisation	47
Balanced hearing	46
Improved speech recognition in noise	42
Better sound quality	41
Reduces listening effort	40
Greater enjoyment of music	34
Reduces the head shadow effect	30
Improved speech recognition in quiet	19
Others	5 • Concerns about losing the residual hearing • Personal preference • Little value in terms of understanding speech. • Better perception of voices (more natural + better perception of the fundamental frequency) • Maintain auditory pathways for future second ear CI

The reasons for not using an HA in the non-implanted ear after implantation for adult unilateral CI users from the professionals' perspective are shown in Table 3.4. The participants were allowed to select more than one option. The results showed that receiving no benefit from the HA was the main reason for not using the HA in the non-implanted ear for adult unilateral CI users.

Table 3.4: CI professionals' perception of the reasons why adult unilateral CI users choose not to wear an HA in the non-implanted ear after implantation.

Category	Frequency
Receive no benefit from a hearing aid	56
The sound of the cochlear implant and hearing aid are too different to be integrated meaningfully	31
No longer wish to wear an earmould	24
A hearing aid cannot be fitted for audiological or medical reasons	21
Additional expense	14
Others	3 • Better speech discrimination with CI only, whereas using the HA became a source of sound distortion • Better hearing on the CI side (CI superiority) • Heat/sweat issues with the mould in the summer

3.5.5 Fitting and maintaining the contralateral HA for adult unilateral CI users

3.5.5.1 Current practice

Figure 3.5 shows the current practice of fitting and maintaining the contralateral HA for adult unilateral CI users in the five world regions. The responses showed that the current practice of fitting and maintaining the HA varies across the world regions.

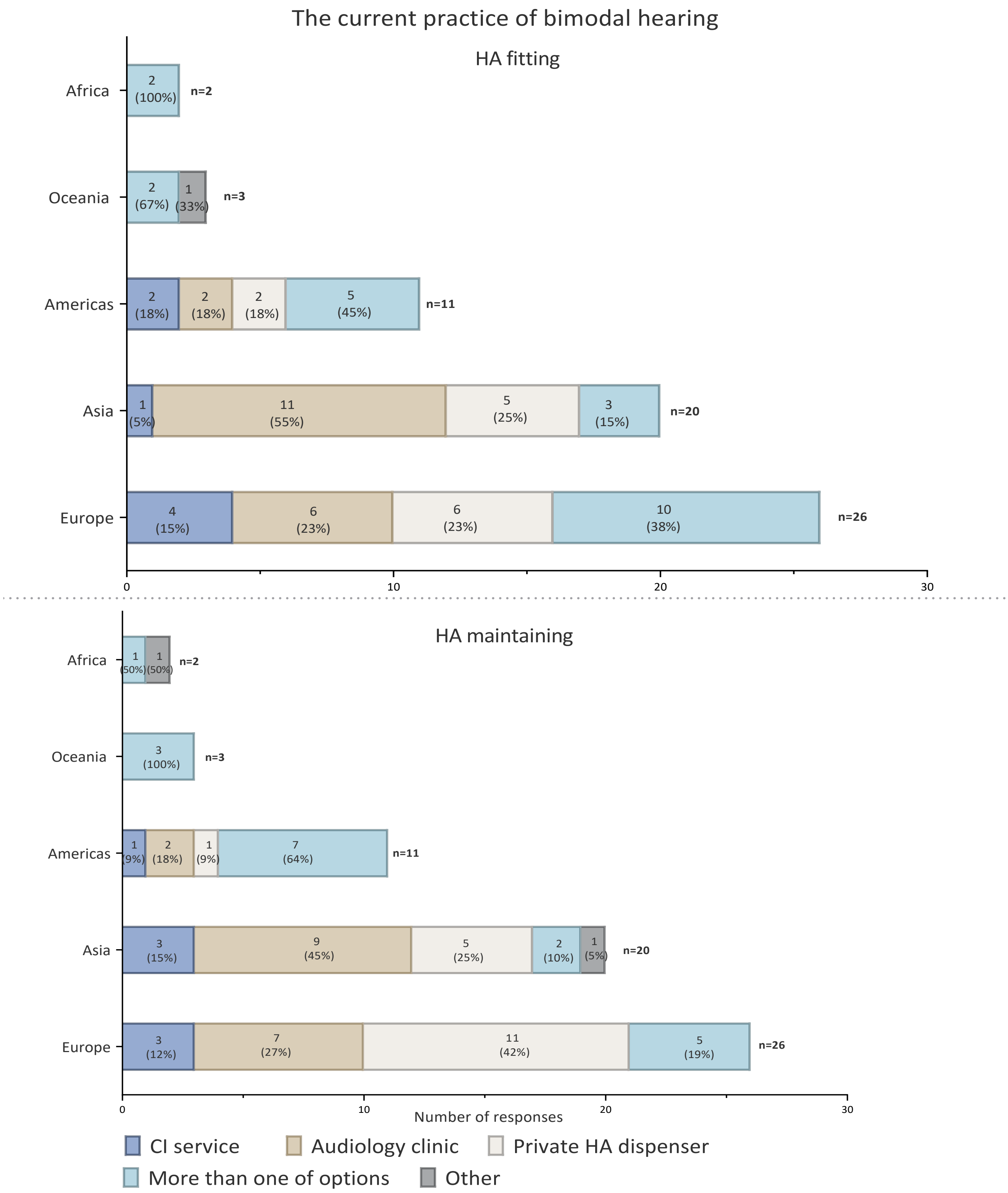

Figure 3.5: Stacked bar chart showing the current practice of fitting (upper panel) and maintaining (lower panel) the HA in the non-implanted ear for adult unilateral CI users in the five world regions: Europe, Asia, Americas, Oceania, and Africa. Each shaded section indicates the exact number of responses for each funding source with a percentage shown. 'Other' includes any other places, such as an integrated clinic.

In Europe, there was no specific practice pattern for fitting the contralateral HA as 38% of the responses indicated that the HA could be fitted at more than one of the three places: (1) CI service, (2) local audiology departments (government-funded hospital or audiology clinic), or (3) private HA dispensers. At the same time, 42% of responses reported that the private HA dispensers were responsible for the HA maintaining. However, this trend does not necessarily present in all the countries in Europe. For example, fitting and maintaining the contralateral HA in France was done only by private HA dispensers.

In Asia, approximately 55 and 45% of responses reported that the local audiology departments were mainly responsible for fitting and maintaining the contralateral HA, respectively. In addition, private HA dispensers seemed to be another contributor to fitting and maintaining the HA, as indicated by 25% of responses. One participant indicated that HA maintaining was done at 'other' places; however the participant did not explain the answer.

For other world regions (Americas, Oceania and Africa), different places deliver the HA fitting and maintain it for adult unilateral CI users. Some participants reported that the HA fitting and maintaining was done at 'other' places. For example, a response from Oceania reported that the HA fitting was done at their private integrated clinic, including CI professionals and audiologists. Another response from Africa stated that the patient was responsible for HA maintaining.

Approximately half to most of the responses in the five world regions reported that they have an opportunity to fit and balance the HA and CI simultaneously, as illustrated in Figure 3.6 (upper panel). This can be done when they have the software and hardware for programming both devices, while others explained it could be done in joint sessions at the CI centre. On the other hand, some of the respondents explained why they cannot fit and balance both devices simultaneously. The most reported reasons are time constraints of fitting and balancing both devices, lack of protocol and guidelines, the policy of the CI service not being responsible for fitting the HA or technical limitations in fitting rooms.

Similarly, most of the responses in the five world regions reported that they do not follow a specific protocol for introducing the HA following implantation, as shown in Figure 3.6 (lower panel). The remaining responses indicated that they fit the HA after a short duration from the first switch-on date of the CI. However, there is a considerable variation in the duration across countries. Some fit the HA after a couple of months (two to six months) from the CI fitting, while others after 24 hours of using the CI. Furthermore, there is a variation within countries. For example, in the UK, some practitioners fit the HA from the CI switch-on date while others advise not to use the HA at the initial switch-on and fit or reintroduce the HA after a number of weeks (six to eight weeks). Similarly, in Saudi Arabia, some of them introduce the HA after two to three months or according to the patient's preference. Others introduce the HA after the implantation based on the use before the implantation. If the patient does not regularly use the HA before the implantation, the HA would be introduced once a stable map is reached. If the patient regularly uses the HA before having the CI, they advise the patient to continue using it. Additionally, other countries such as Belgium follow the protocol provided by the CI companies.

The level of CI service experience in the field of HAs varies across and within the five world regions (Figure 3.7, upper panel). For instance, approximately 14 and 7 respondents (54 and 64%) in Europe and the Americas respectively, reported that their services have significant experience in the field of HAs. Moreover, one response from Europe indicated that their CI service has an 'other' level of experience as there is a considerable difference in the professionals' experiences, ranging from no experience to significant experience, whereas 45% of responses (9 respondents) from Asia tended to consider their CI service as experienced.

On the other hand, all the respondents thought their services were roughly well informed about updates and developments in the field of HAs, as shown in Figure 3.7 (lower panel), except for a few responses in Asia and the Americas which thought their services were not informed about the recent developments in the field of HAs.

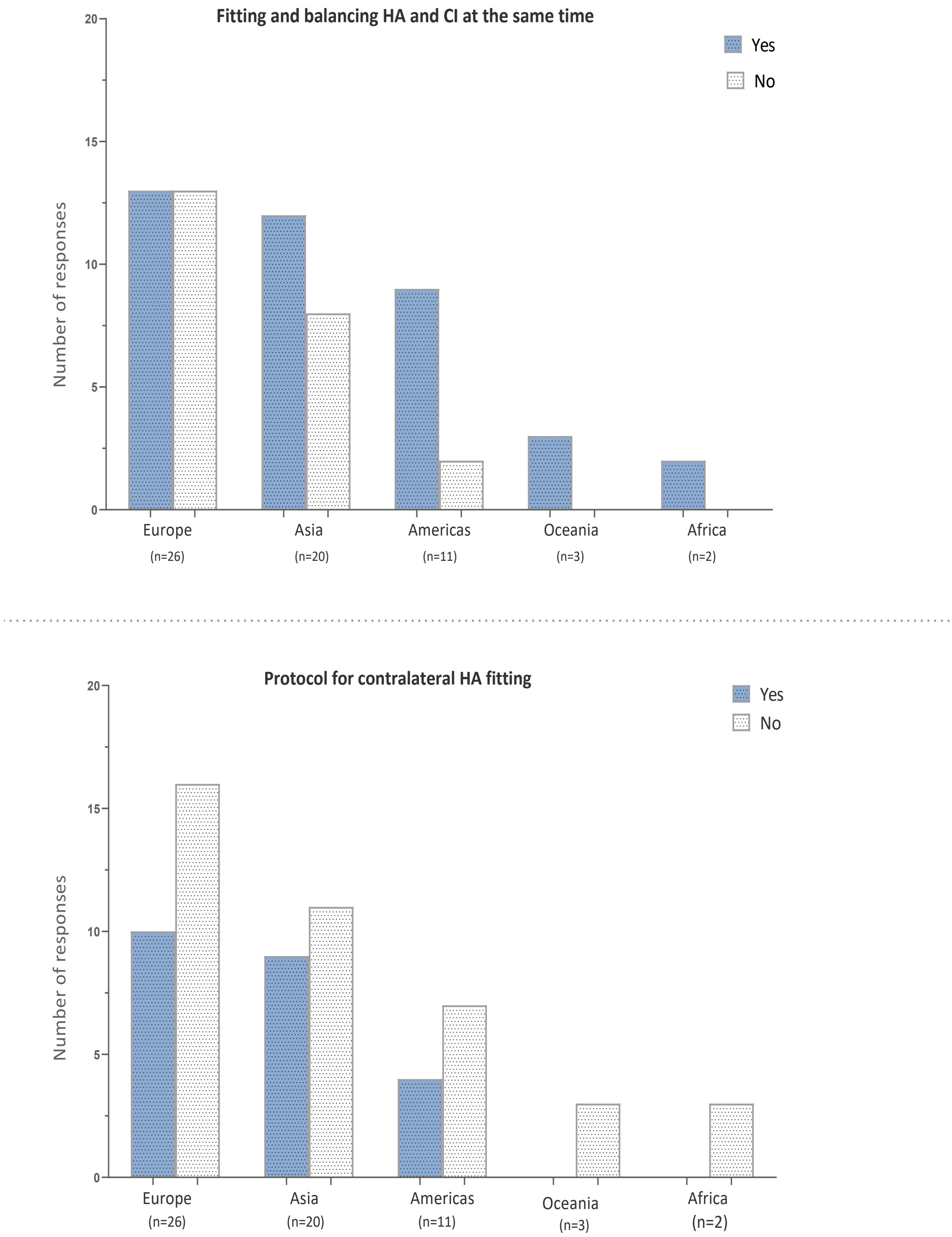

Figure 3.6: A clustered bar chart showing the current practice of fitting and balancing the HA and CI at the same time (upper panel) and the use of a specific protocol for HA fitting for adult unilateral CI users (lower panel) across the five world regions: Europe, Asia, Americas, Oceania, and Africa.

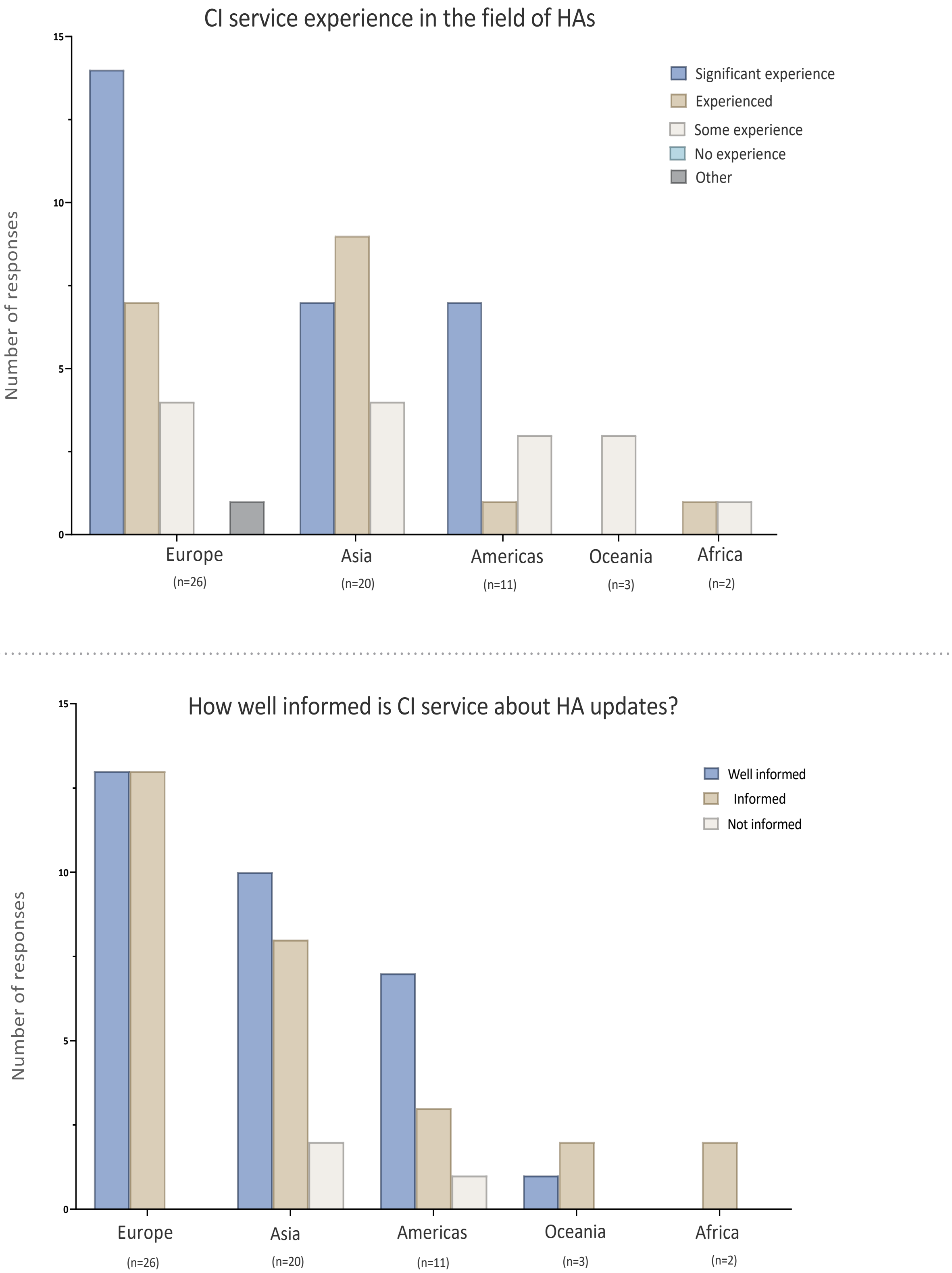

Figure 3.7: A clustered bar chart showing how experienced the CI service is in the field of HAs (upper panel) and how well informed the CI service is about the updates in the field of HAs (lower panel) across the five world regions: Europe, Asia, Americas, Oceania, and Africa.

3.5.5.2 Future practice

Figure 3.8 shows respondents' recommendations for the future practice of fitting and maintaining the contralateral HA for adult unilateral CI users. Approximately 48 to 75% of respondents in Europe, Asia and the Americas felt that the CI service should do HA fitting for the following reasons: (1) to ensure the optimal benefit and to balance the two devices as they need to work together, (2) the CI service knows more about the patient's goals and plan and can prioritise them accordingly, (3) the CI service has more experience in performing any adjustment or further fine-tuning for both services than the local audiology or private HA dispensers, (4) it is easier for management, follow-up and counselling, (5) it is more convenient to the patient to attend one appointment and (6) the new HA generation needs to be fitted with CIs. Most of the responses in Oceania and Africa and several responses in Europe and Asia recommended that fitting of the HA should be done at the local audiology department. On the other hand, a few responses recommended having an integrated clinic that includes CI and audiology services in one place or having a flexible option to fit the HA at any place, which would be more convenient to the CI users and would have better accessibility where easy adjustments and follow-up can be done.

For HA maintaining, most of the responses in Europe and Asia recommend that HA maintenance should be done at the local audiology department and by private HA dispensers. On the other hand, nearly half of responses in the Americas and a few responses in Europe recommended that HA maintaining should be done at either of these two places to reduce long travel distances to CI services and to reduce workload in CI services due to limited CI staff. Another reason for their recommendations is that these two places could have better supply, resources, and information about different HAs. Few responses gave another recommendation to have an integrated clinic that can provide all the services needed for CI users. On the other hand, few responses in the Americas and Oceania consider that HAs should be maintained at the CI service. It would be easier for the CI user to go to one place, and it would be better for follow-up and counselling.

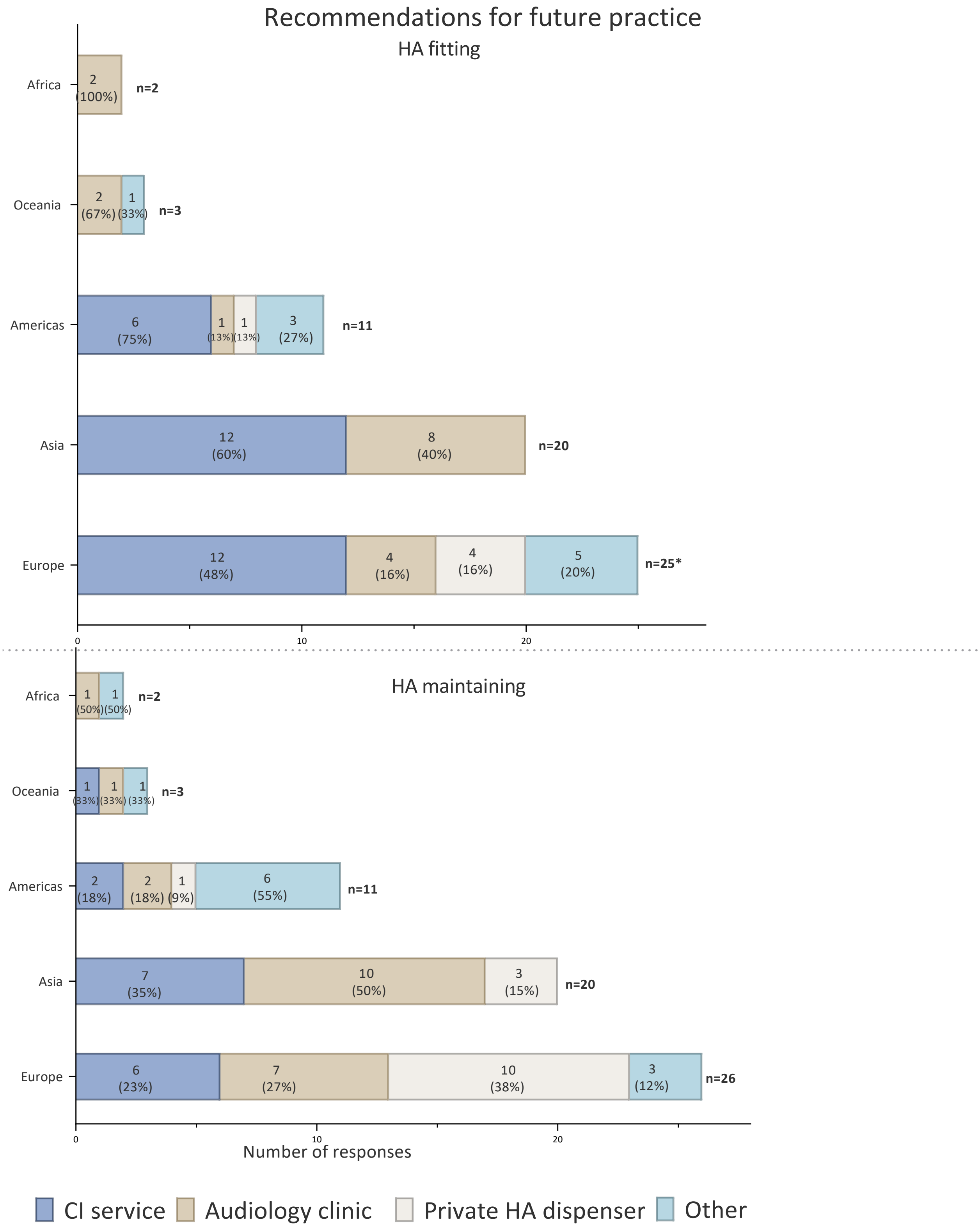

Figure 3.8: Stacked bar chart showing recommendations for fitting (upper panel) and maintaining (lower panel) the contralateral HA for adult unilateral CI users in the five world regions: Europe, Asia, Americas, Oceania, and Africa. Each shaded section indicates the exact number of responses given with the percentage shown. 'Other' includes any other place or option such as integrated clinic and patient.

3.5.6 Integrated bimodal technology

Approximately 36 respondents reported that they have adult AB unilateral CI users who use the Naida Link HA. The percentage of users of this technology differs across countries; however the estimated mean percentage of the AB unilateral CI users who have Naida Link HA around the world is 33%. Approximately 43% of respondents considered the Naida Link HA could offer more benefits than standard HAs, while 52% did not see any differences between them. On the other hand, few responses (5%) considered no difference between the Naida Link HA and the standard HA as the features of Naida Link HA (e.g. ZoomControl) are only beneficial in limited settings.

Table 3.5 shows the respondents' perception of the advantages of Naida Link HA compared to the standard HA. The participants were allowed to give more than one answer. The perception of the benefits of the Naida Link HA varied considerably among the respondents. Some respondents (n=22) thought that the Naida Link HA could improve speech in noise, whereas other respondents thought it could improve telephone use (n=15), provide comfort between people in a conversation (n=13), reduce the level of stress about getting a good seat at dinner, meetings or in a car (n=12), and improve the localisation (n=10). Moreover, a few respondents thought that the Naida Link HA could provide more compatibility, connectivity, and synchronised binaural control.

Table 3.5: CI professionals' perception about the advantages of the Naida Link HA compared to the standard HA.

Category	Naida Link HA Frequency
Improved speech recognition in noise	22
Improved telephone use	15
Comfort between people in a conversation	13
Reduced level of stress about getting a good seat at dinner, meetings or in a car	12
Improved localisation	10
Improved speech recognition in quiet	6
Improved ability of tracking moving sounds	6
Greater enjoyment of music	6

Others	4 • Better communication and compatibility with the Naida CI Q90 sound processor • Better connectivity • Better binaural control synchronised settings

3.5.7 Summary of main findings

- The estimate average percentage of adult unilateral and bilateral CI users across the five world regions is approximately 74.2 and 18.3 %, respectively. Approximately 46% of unilateral CI users use an HA in the non-implanted ear.
- Improved localisation and balanced hearing are the most common reasons CI users choose to wear an HA in the contralateral ear.
- The main funding source of unilateral CI varies across the world regions. State funding is the primary funding source in Europe and Asia, while a mixed model of funding sources is available in the Americas, Oceania and Africa.
- Simultaneous and sequential bilateral CI for adults is primarily funded through state or self-funding in Europe and Asia, whereas private insurance and self-funding are the primary sources in Oceania and Africa. Adults in the Americas have different funding sources to get simultaneous and sequential bilateral CI.
- State- and self-funding are the primary funding sources for providing the contralateral HA for adult unilateral users in all the world regions, except Africa, where private insurance is one of the primary sources.
- There is no specific practice pattern of fitting and maintaining the contralateral HA in most of the world regions as different places contribute to providing the service. However, the Asia region's responses showed a tendency to fit and maintain the contralateral HA at the local audiology departments.
- Most of the responses indicated that they do not follow a specific protocol for introducing the HA after implantation.
- More than half of respondents (48 to 75%) in Europe, Asia, and the Americas recommend that fitting of the contralateral HA should be done at CI services for more benefits, and many respondents recommend that maintenance of the HA can be done at the local audiology department or by private HA dispenser for better accessibility.

- The benefits of integrated bimodal technology are not clear yet, particularly whether it could provide more benefits than standard technology. More research and clinician training are needed.

3.6 Discussion

The survey sought to determine the bimodal-hearing and bilateral CI service provision for adults worldwide. The response rate (62 respondents from 25 countries) was favourable compared to similar international surveys (Vickers *et al*. 2016, i.e. 28 respondents representing 17 countries, and Scherf and Arnold 2014, i.e. 65 respondents representing 12 countries). In addition, compared to the international survey conducted by Scherf and Arnold (2014), the current survey explored further aspects: funding access, the current process of fitting and maintaining the contralateral HA, professionals' recommendations for future practice, and new integrated bimodal-hearing technology. Furthermore, more countries were targeted than in Scherf and Arnold's (2014) study.

The results indicate that, in line with recent literature, bimodal hearing is now a recommended option for adults with unilateral CI. The average percentage of adults using a contralateral HA (46%) is relatively higher than the percentage reported in Scherf and Arnold (2014), where the average percentage was 32%. The higher percentage of bimodal-hearing users in the current study could be related to the fact that more countries were included than in Scherf and Arnold's study. Furthermore, the higher percentage is most likely to reflect the expansion of candidacy criteria worldwide to implant more individuals with residual hearing in recent years. Additionally, the advances in HA technology since Scherf and Arnold's study might be another reason.

The most reported benefits that might have motivated CI users to use an HA in the non-implanted ear are improved localisation, sound quality, speech perception in noise, and balanced hearing. These benefits are in line with the reported benefits in Scherf and Arnold (2014) and Fielden and Kitterick (2016). Additionally, these are as expected from published studies (Ching et al., 2006, Olson and Shinn, 2008, Potts et al., 2009, Veugen et al., 2016a, Devocht et al., 2017). On the other hand, lack of benefit stands as the main reason for discarding the HA by many CI users, which is consistent with findings in Scherf and Arnold (2014) and Neuman *et al*. (2017). However, it should be noted that these findings were not collected directly from the CI users themselves, but via CI professionals; therefore these findings might tend to have a degree of reporting bias.

To the best of the researcher's knowledge, the current survey was the first survey that investigated the funding source of the contralateral HA for adult unilateral CI users across countries. Vickers *et al.* (2016) explored funding sources for unilateral and bilateral CI. A similar pattern was found with funding the contralateral HA. There is a considerable variation within and between countries. Although the source of funding HAs varied, it can clearly be seen that they are generally not state-funded. In addition, the funding source of unilateral and bilateral CI was explored in this survey. The findings were consistent with the findings of Vickers *et al*. (2016), where the unilateral CI is generally state-funded, specifically in the Europe and Asia regions.

In contrast, other sources (i.e. private insurance or self-funded) are the primary funding sources for both simultaneous and sequential bilateral implantation. The differences in funding sources between unilateral and bilateral implantation are as expected from the published literature that discussed the cost-effectiveness of bilateral CI implantation (Chapter 2, section 2.3). In other words, if there is clear evidence that shows that bilateral implantation is cost-effective, then it might be seen to be more state-funded.

The results showed that the current practice of fitting and maintaining contralateral HAs differs across and within the five world regions. However, a general trend can be seen across countries where the HA was fitted and maintained in places other than CI services, such as at the local audiology department or private HA dispensers. This contrasts Scherf and Arnold's findings as they showed in their survey that the fitting of HAs was most often done in CI services. However, their finding does not truly reflect the practice around the world as most of the respondents were from Belgium. The differences in places of fitting and maintaining HAs shown in this study might be related to differences in the access to the contralateral HA. As discussed earlier, contralateral HAs can be funded by different sources, suggesting that different places would be responsible for fitting and maintaining HAs. For example, if an HA is self-funded, the fitting and maintenance would be done at a private HA dispenser centre and not in the CI service. The CI service could not have enough resources of professionals and equipment to provide the service of contralateral HAs to their patients. Consistent with Scherf and Arnold (2014) and Fielden and Kitterick (2016), more than half the respondents felt that contralateral HAs should be fitted at the CI services with the contribution of audiology departments and private HA dispensers in general maintenance and support. This might help develop and use a specific protocol for introducing HAs, ensuring the optimal benefit, and balancing the two devices. This is very important as the results showed that most of the respondents in the five world regions do not follow a specific protocol for introducing and balancing the HA following implantation. Studies reporting the benefits of using a HA in the contralateral ear highlight the importance of a well-fitted HA to improve the benefit and acceptance (Morera *et al*., 2012, Potts *et al.*, 2009). This can be achieved when both CI and HA devices are fitted in one place by the same clinician. In addition, it would be more practical for both the CI user and professional if the maintenance of the HA were delivered by the local audiology department or HA dispenser as they have better supply and resources for different types of HAs. As indicated by respondents, it would reduce travel distance to the CI service and the workload of CI professionals.

The number of CI users having the integrated bimodal technology (Naida Link HA and CI) is increasing, as indicated by the results; however over half of the respondents are unsure of the benefit of this technology. This could be because this type of technology has just recently appeared on the market, and more time is needed for the professionals to observe the difference with the standard technology. Moreover, this survey was the first one conducted to gauge the use and benefit of the integrated bimodal technology. Further research is needed to substantiate the potential benefit of this technology compared to standard HA technology.

The survey may have a few limitations. The first is that the number of expert panel members who reviewed the survey was relatively small. McKenzie *et al.* (1999) suggest that the panel should consist of at least five members to provide constructive feedback and suggestions. The invitation to participate in the panel review was sent to five professionals; however responses were received from only four of them. Another concern is that the responses from the five world regions were not equally balanced. The number of respondents from Europe and Asia was higher than those from Oceania and Africa. It would be better to have balanced responses across world regions; however this could not be obtained as the survey collects a random sample. This limitation is commonly seen in survey studies, particularly in international surveys (i.e. as in the Scherf and Arnold (2014) study), as a result of the accessible contacts in the country of the researchers. Furthermore, general data protection regulation (GDPR) came into force after sending out the survey for the first time and affected sending reminder emails to the UK and EU countries. Another possible limitation is that some responses in the open question or justify box were not included in the analysis of the results because they were either irrelevant or difficult to analyse and interpret. However, a free-text comments box was used as it can help in future questionnaire development by detecting poorly constructed questions or defining new items for future questionnaires (Rattray and Jones, 2007).

3.7 Conclusion

The results of this international survey showed that, despite some variations within and between countries, there are general trends: (1) contralateral HAs are largely not state-funded, (2) CI professionals recognise the value of fitting contralateral HAs at CI services, with audiology departments and private hearing-aid dispensers playing an ongoing role in general maintenance and support, and (3) CI professionals are unsure of the benefit of integrated bimodal technology. This could be due to limited clinical experience, but equally, there is a need for further research to substantiate the potential benefit of emerging technology. In light of the recent generation of integrated bimodal technology entering the market and widening CI criteria, it is timely to consider future clinical practice and service delivery. Furthermore, in line with earlier surveys, there is a need to develop well-constructed clinical guidance for HA introduction after implantation.

Chapter 4 Development of a real-life test battery and the results of adults with normal hearing

4.1 Introduction

As discussed in Chapter 2 section 2.5, it would be meaningful to use a test battery that can reflect the performance of adult CI users in real-life listening situations. However, to the best of the researcher's knowledge, most studies tend to use standard clinical or research tests which mainly focus only on speech perception with standard set-ups of using a single loudspeaker to present speech and noise for assessing the performance of adult CI users. Although there are a few studies that have incorporated more real-life listening measures when testing CI users, such as van Hoesel (2015) and Gifford and Dorman (2019), there is still a need for the development of a test battery including both performance tests and subjective rating scales to assess the listening skills needed in real-life situations.

This chapter is divided into two main sections. The first section (Section A) describes the rationale for selecting the tests included in the test battery and stages of a real-life test battery development. The second section (Section B) discusses the measurement precision and applicability of the newly developed tests included in the test battery. It provides data about the performance of adult normal-hearing (NH) listeners on the real-life test battery.

4.2 Section A: The development of the real-life test battery

4.2.1 Motivation and rationale for the development of a real-life test battery

The performance of adult CI users is typically assessed with free-field audiometry or standard speech-perception tests that use a single loudspeaker to present both the target and masker stimuli. However, these tests do not reflect different listening situations encountered in real-life. In addition, the standard speech-perception tests may underestimate the value of some management options for adult CI users, such as bimodal hearing or bilateral CIs. Given recent advances in technology for adult CI users (i.e. binaural beam formers), more complex listening set-ups are needed to assess these technologies' effectiveness. Using a test battery that includes performance tests, more representative of real-life listening situations, as well as subjective rating scales (self-reported benefits) are needed. Outcomes can guide rehabilitative practice and the use of assistive listening technologies. A real-life test battery thus has the potential to help inform clinical practice and could also contribute to shaping national policy and the funding of CIs.

In light of the above discussion, the present study sought to develop a real-life test battery that can be used to assess the performance of adult CI users with more representative measures of real-life listening situations. The measures included in the real-life test battery are shown in Figure 4.1. The AB-York Crescent of Sound rig (discussed under Section 4.2.2.1), developed by Kitterick *et al*. (2011), was used to develop new tests and administer the real-life test battery for the study.

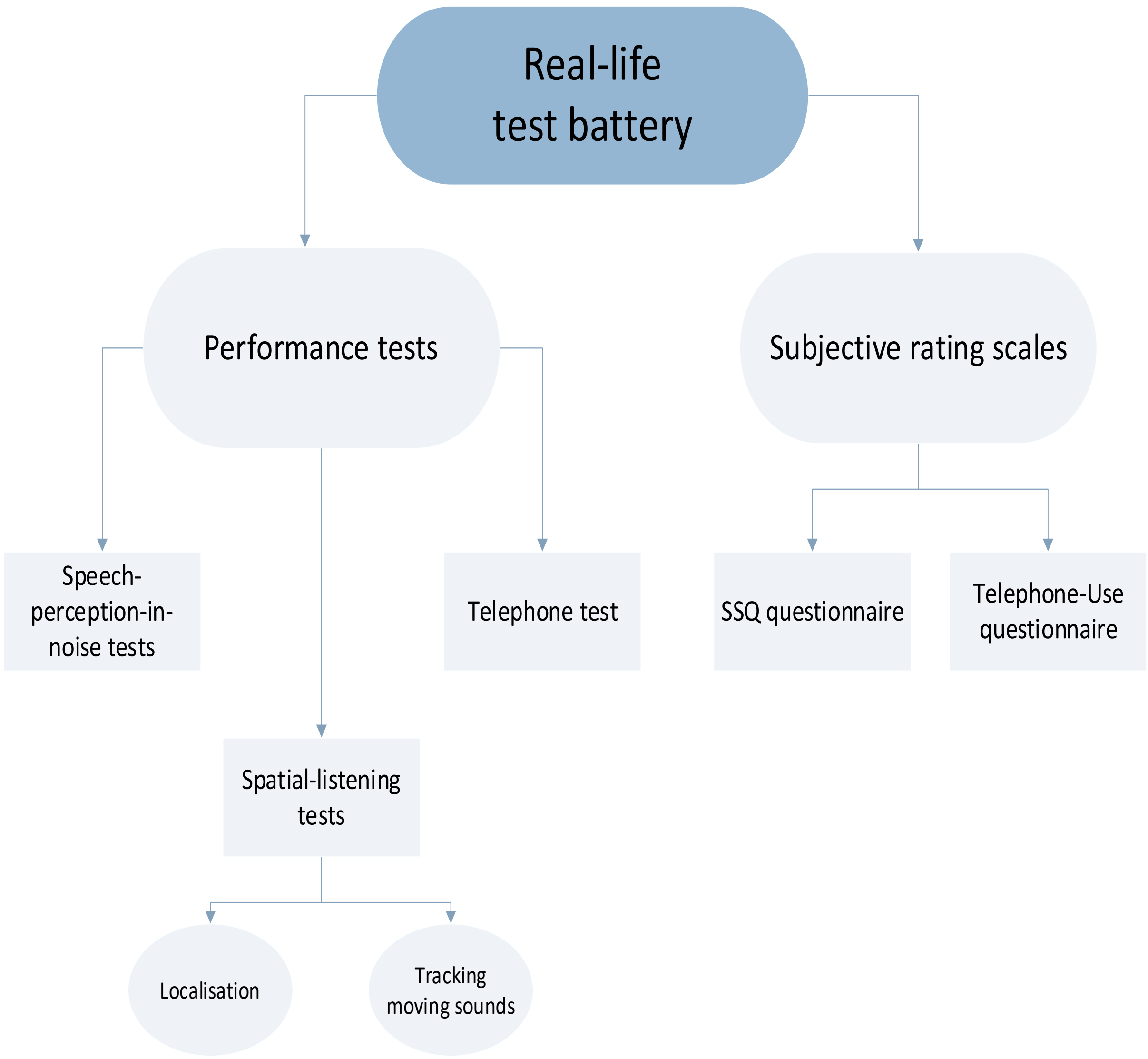

Figure 4.1: Schematic illustration of outcome measures included in the real-life test battery.

The rationale for selecting each of the outcome measures included in the test battery is presented here. Section 4.2.2 describes the development of the newly developed real-life tests as well as the testing set-up and procedure for each test.

4.2.1.1 Speech perception in noise

Speech-in-noise measures are more representative of the challenges experienced every day than those in quiet conditions (Gifford *et al.*, 2008). Dorman *et al*. (2015) has suggested that a speech-in-noise measure is a better metric to assess the potential benefits of hearing devices. In addition, when speech and noise are spatially separated, binaural benefits can be assessed, such as head-shadow effects and binaural squelch (Avan *et al*., 2015).

Most of the CI studies looking at speech perception in noise have used sentences as the test material (Armstrong *et al*., 1997, Ching *et al*., 2004, Dunn *et al*., 2005, Mok *et al*., 2006, Berrettini *et al*., 2010, Bouccara *et al*., 2016). Using sentences provides face validity, as they are a more valid representation of speech in the real world than using nonsense syllables or monosyllabic words (Killion *et al*., 2004). However, using sentences has higher predictability than using words and it is easier to fill in parts not heard. Another issue that should be considered when using sentences is memory, especially when the length of the sentences is not fixed. Individuals may hear the sentences correctly but not have the memory to repeat what they have heard.

The Bamford-Kowal-Bench (BKB) sentence test (Bench *et al*., 1979) is an example of test materials that have been used in CI studies (Ching *et al.*, 2004, Ching *et al*., 2006, Kokkinakis and Pak, 2014). BKB sentences are simple and short, with 21 lists available (Nilsson et al., 1994). These factors help reduce familiarisation and demands on listening, making them suitable to be used with CI users. Furthermore, the BKB sentences test is one of the two-sentence tests available for British English speakers. Other tests, such as the STARR test, are more challenging for CI users, with considerable variability among users (Boyle *et al*., 2013, Joffo and Boyle, 2013). Most CI users (22 from a group of 25) showed a mean SRT of + 28 dB SNR that reflects the difficulty in understanding the speech material in noise (Boyle *et al*., 2013). For these reasons and because of the purpose of the study, the BKB sentence test was chosen.

The BKB speech materials used at USAIS are MRC Institute of Hearing Research recordings of the BKB sentences spoken by a male speaker. The male-speaker recordings were chosen as this is the default used at CI services within the UK, and many CI studies have used the male-speaker recordings (Ching *et al*., 2004, Kong *et al*., 2005, Ching *et al*., 2006, Gifford *et al*., 2007). This would facilitate the comparison of the results with existing published research. Although the inclusion of female-voice recordings and male-voice recordings was considered for the test battery, time constraints and participant fatigue were overriding factors for the decision to include only the male-speaker recordings. In addition, the BKB sentences were recorded with a male speaker using received pronunciation (RP), the accent traditionally regarded as standard for British English. The speaker used for the male recording has a slower rate than the female-voice recordings, which would have introduced an additional variable beyond the scope of this study.

Multi-talker babble is a preferred masker for speech signals and is used extensively in experiments investigating speech perception in CI users, e.g. Armstrong *et al*. (1997), Ching *et al.* (2004), Dunn *et al*. (2005), Mok *et al.* (2006), Dorman *et al*. (2008), Berrettini *et al*. (2010), Jang *et al*. (2014) and Bouccara *et al*. (2016). This type of masker has more ecological validity than other maskers, such as speech-shaped noise, pink noise, white noise etc. (Silbert *et al*., 2014). In addition, the SRTs of CI users with multi-talker masker were worse than with steady-state noise (Qin and Oxenham, 2003, Cullington and Zeng, 2008, Zirn *et al.*, 2016), which suggests that using steady-state noise, for a given SNR, may underestimate the difficulties that CI users experience in real-life listening situations. Accordingly, multi-talker (20-talker) babble masker was chosen in this study.

Speech perception in noise is measured clinically using either a fixed- or an adaptive-testing procedure. In the fixed-testing procedure, the speech and noise levels are fixed at a predetermined level, and the performance is evaluated as the percentage of words identified correctly. In the adaptive procedure, the threshold is measured as dB SNR (signal-to-noise ratio) for predetermined performance criteria (e.g. 50%), where the intensity of the speech is relative to a fixed level of noise (Schafer *et al*., 2011). Schafer *et al.* (2011) summarised the major three differences between the methodologies of the two paradigms as follows: (1) the fixed procedure scores result in a non-linear performance-intensity function. This means that to obtain significant differences between test conditions for mid-range scores, a greater critical difference is required than for lower and higher scores; (2) fixed procedures are more susceptible to floor and ceiling effects than adaptive procedures; (3) only one measurement can be obtained for each condition with a fixed procedure, while the adaptive procedure produces an SRT from repeated measurements for the same condition. Looking at the literature for measuring speech perception in noise for CI users, it can be seen that there is some variation in testing procedures; the adaptive procedure has predominately been used to avoid floor and ceiling effects (Morera *et al*., 2012, Mok *et al*., 2006, Kokkinakis and Pak, 2014, Iwaki *et al.*, 2004, Hua *et al*., 2017). A meta-analysis (Schafer *et al*., 2011) comparing speech perception in noise with bilateral CI and bimodal hearing users showed that the fixed-testing procedure is more sensitive for detecting the effects of binaural squelch performance than the adaptive procedure. Schafer *et al.* (2011) reckoned the reason for the adaptive procedure not yielding a significant binaural squelch might be related to the adaptive procedure being a more difficult task than the fixed procedure. This is because the adaptive procedure is conducted at the thresholds level whereas the fixed procedure is conducted at suprathreshold levels. Therefore, the binaural squelch that was measured with a fixed procedure would reflect what the CI users perceive when fitted with bilateral CI or bimodal hearing in real-life listening situations. For measuring binaural summation and head-shadow effects, the sensitivity of the two testing paradigms is similar (Schafer *et al*., 2011). Since significant binaural summation and head-shadow effects have been shown in adult CI users (Schafer *et al*., 2011), and because of the greater susceptibility of fixed-testing procedures to floor and ceiling effects, an adaptive-testing procedure was chosen for this study.

Lastly, three test set-ups were selected in the present study to represent common listening situations in real life. The first test set-up mimics having a group conversation in a noisy place where different talkers frequently change, and others are speaking at the same time. In this set-up, the sentences were presented randomly from different loudspeakers (i.e. 'roved' in terms of location) with multi-talker babble masker presented from two loudspeakers placed at ± 60° azimuth. The second test set-up simulates one-to-one conversation in the noisy background again with competing speech. The sentences in this set-up were presented from the loudspeaker placed in front at 0° azimuth, and the multi-talker babble masker was presented from two loudspeakers placed at ± 60° azimuth. The third test set-up simulates having a conversation where someone sits next to them, i.e. having a conversation while driving a car. For this set-up, the sentences were presented to the side of the participant (90° azimuth) while a multi-talker babble was presented from the opposite loudspeaker (90° azimuth). A more detailed description of the development of the new set-ups is provided in Section 4.2.2.2.

4.2.1.2 Localisation

Localising sound sources is a vital perceptual ability, particularly in real-life environments. It is essential for identifying now only where speech is coming from but also for safety and threat detection. The advantage of using two ears to localise sounds is well known (Butler, 1986, Feuerstein, 1992, Wightman and Kistler, 1992, Macpherson and Middlebrooks, 2002).

A variety of study designs have been used to assess the performance of adult CI users in localisation tasks. Many studies (Ching *et al*., 2004, Seeber *et al.*, 2004, Dunn *et al*., 2005, Verschuur *et al*., 2005, Laske *et al.*, 2009, Potts *et al*., 2009, Morera *et al.*, 2012, Rana *et al*., 2017) used 10 to 15 loudspeakers with short increments ranging between angles of 10° and 18°, while other studies used 2 to 5 loudspeakers with a larger inter-loudspeaker separation (Tyler et al., 2002b, Flynn and Schmidtke, 2004, Mosnier et al., 2009). Even a larger number of loudspeakers with smaller increment angles has been used, such as Grantham *et al*. (2007) who used an array of 43 loudspeakers placed from -90° to +90° azimuth to assess the ability of bilateral CI users to localise different signals. Moreover, some studies have tested CI users with different test settings (different test conditions). For example, Goman (2014) assessed the localisation ability of 12 bimodal users and 12 bilateral CI users in three different settings with three inter-space loudspeakers (three loudspeakers with 60º separation, five loudspeakers with 30º separation and five loudspeakers with 15º separation). The performance of the bilateral CI users using the two CIs was statistically significantly better than one CI in the three test settings, whereas the performance of bimodal users using the two devices was only significantly better than using the CI only in the test setting of five loudspeakers with 15° separation. Goman (2014) suggested that the few trials in the first two test settings were a possible reason for the discrepancy in the performance of bimodal users in the three test settings.

Based on the literature search discussed in the previous paragraph, there was inconsistency in the test settings when measuring the localisation ability of CI users. In addition, localising sounds from very narrow angles is not essential in real-life listening environments. For instance, identifying whether the sounds are coming from the right, left, front, or back seems to be enough to follow what other people are saying or to avoid any threat in the horizontal plane. Therefore, for this study, an array of five loudspeakers with an inter-speaker angle of 30º azimuth was used. The apparatus used in the current study (the AB-York Crescent of Sound) has three options for test settings for localisation tests (discussed in Section 4.2.2.1): (1) three loudspeakers with 60º separation, (2) five loudspeakers with 30º separation and (3) five loudspeakers with 15º separation. A sentence such as *"Hello, what's this?"*, spoken by one of five different talkers, was used as the test stimulus. Speech was chosen because speech signal has more ecological validity and familiarity in everyday listening environments (Litovsky et al., 2006b). It may provide more accurate performance than the noise-in-localisation tasks, due to spectral differences in the signals, the presence of envelope ITD cues in speech signals, or factors related to the salience gap of speech signals (Grantham *et al.*, 2007). Furthermore, speech signals are localised better than tone bursts and pink noise stimuli (Verschuur *et al*., 2005). The speech stimulus was presented at levels between 65–75 dB SPL with 11 roving intensity levels, with 0 to 10 dB of attenuation applied in 1 dB steps. The roving presentation level was used to prevent the participants from using the loudness level as a cue to help them localise the signal (Harkonen et al., 2017, Veugen et al., 2016a). This is because CI users rely more on ILDs than ITDs in the localisation of the sources of sounds (Goman, 2014, Seeber and Fastl, 2008).

4.2.1.3 Tracking of moving sounds

Many sounds are not stationary in real-life environments, such as moving vehicles or a person walking towards or away. The perception of moving sounds can be represented as the movement of the actual sound source or the listener's head and body movement (Carlile and Leung, 2016). Tracking a moving sound is a fundamental perceptual skill for everyday-life listening environments; for instance, it is critical to track moving sounds that might be life-threatening situations or equally opportunities. However, most previous research has only focused on stationary-sound localisation. Carlile and Leung (2016) pointed out that technical difficulty in producing adequately controlled moving stimuli limits to some extent research on the perception of moving sounds. In addition, the perception of moving sounds is difficult to quantify as it includes a complicated interaction of sensory, motor, and perceptual systems and proprioceptive feedback resulting from self-motion and head movement (Moua *et al*., 2019, Warnecke *et al.*, 2020).

Nevertheless, the perception of moving sounds has started to receive attention in recent years. Lovett *et al*. (2010) and Lovett *et a*l. (2012) developed a battery of tests of spatial listening for NH and CI children. The battery included tests to assess the ability to perceive speech in noise, localise sources of sounds, and track moving sounds. They used a semi-circular array of 13 loudspeakers to present a sequence of acoustic stimuli from publicly available recordings. Two testing scenarios were developed. In the first one, the testing started with a doorbell, followed by a door opening, footsteps, and a door closing. For the second scenario, the test started with a bugle, followed by a horse's neigh, hoof beats, and a second horse's neigh. The two testing scenarios were presented into four trajectories of movement as: (1) left-front-right, (2) right-front-left, (3) left-front-left, (4) and right-front-right. These studies showed that NH children had significantly better scores than CI children. Additionally, the results showed that children with bilateral CI had significantly higher scores than those with unilateral CI. Goman (2014) used a similar apparatus (similar testing scenario and movement trajectories, but with a semi-circular array of 9 loudspeakers) to assess the ability to track moving sounds for adult CI users, including 12 bimodal and 12 bilateral CI users.

For the bilateral CI participants, the mean performance was significantly better when using two CI (80.21%) compared to when using one CI (31.25%). For the bimodal participants, the mean performance with two devices was better (41.7%) than with using only the CI (27.1%); however the difference was not significant. For both groups, the performance with using the two devices was significantly greater than chance (25%), but performance using one device was not significantly different from chance.

In a more recent study, Moua *et al*. (2019) compared the ability to tracking moving sounds in adult bilateral CI users and NH listeners using an array of 37 loudspeakers that spanned from -90° to +90°. Their findings indicated that bilateral CI users had poorer sensitivity to identify and track a moving sound source than NH listeners. Warnecke *et al*. (2020) investigated the role of signal-envelope and TFS cues on moving-sound perception to understand why bilateral CI users had difficulty perceiving moving sounds. Acoustic chimaera stimuli, which allowed for the investigation of the contributions of ENV and TFS cues, were presented as either moving or stationary to NH listeners. The results showed that removing low-frequency TFS reduces sensitivity to track moving sounds. This finding would explain why CI users had difficulty in tracking moving sounds given that low-frequency TFS cues are discarded in the current clinical CI devices.

The above findings suggest that the ability of adult CI users to track moving sounds is poorer than NH listeners. However, limited research has addressed this problem. Therefore, the tracking-moving sounds test has been included in the test battery for the present study. The test set-up used is similar to the set-up used in Goman's (2014) study, but further modifications have been done. A detailed description of the test set-up and these modifications is provided in Section 4.2.2.4.

4.2.1.4 Telephone test

Using the telephone facilitates independent living, social communication and self-esteem (Cray *et al*., 2004). In addition, understanding speech via this medium is often essential in emergencies. Rumeau *et al.* (2015) found a significant correlation between the ability to use the telephone and quality of life. They found that the improved ability to use the telephone led to higher outcomes in the health-related quality of life (HRQoL) questionnaire for CI users. An international survey (Anderson *et al*., 2006) involving 196 adult CI users indicated that 71% and 54% of CI users could use a landline telephone and a mobile phone to some extent respectively. In a more recent study (Rumeau *et al*., 2015), 35% of the CI participants (n=26) could not use the telephone.

The evidence shows that many CI users experience difficulty conversing over a telephone, especially in noisy environments (Adams *et al*., 2004, Castro *et al*., 2005, Anderson *et al*., 2006, Castro *et al*., 2006, Tan *et al*., 2012). Several studies have investigated the difficulties experienced by CI users. For example, Di Nardo *et al*. (2014) and Giannantonio *et al*. (2014) showed that the score of word recognition (in quiet) over the phone for unilateral CI users was reduced by approximately 30% compared with those presented in acoustic-sound field presentation in an anechoic booth. Similarly, CI users in the study by Castro *et al.* (2006) showed poorer word-recognition scores when using a mobile phone in both quiet (37-59%) and noise (28-41%). Several factors might be contributing to these difficulties, including lack of confidence, lack of visual cues (e.g. speech reading), the limited frequency response of the telephone (300–3000Hz), and the presence of competing noise in the environment (Kepler *et al*., 1992, Latzel *et al*., 2014, Wolfe *et al*., 2016a). Another reason for difficulty using the telephone is restricted optimal phone placement with the sound-processor microphone (Liang and Marcinkevich, 2016). Moreover, distortion or interference can potentially be produced when a telephone is held next to the CI sound processor or the HA (Mantokoudis *et al*., 2012, Wolfe *et al.*, 2016a).

HA and CI industries have attempted to develop solutions and features that can help optimise speech understanding on the telephone. For instance, amplified telephone receivers, electromagnetic induction (telecoil), direct connection using an auxiliary cable, and wireless-streaming technologies (Marcrum *et al.*, 2017, Miller *et al.*, 2021). Wireless streaming is a more recent technology that sends the speech signal wirelessly from the telephone to a monaural sound processor (or a HA) via an intermediary streaming accessory. Compared to using acoustic coupling and telecoil conditions, using the intermediary wireless-streaming accessory device has shown improved speech recognition in quiet and in noise (Wolfe *et al*., 2016a, Wolfe *et al*., 2016b, Marcrum *et al*., 2017).

DuoPhone is one of the Binaural VoiceStream Technology™ techniques available that can be used for both the Phonak and Advanced Bionics CI users. DuoPhone allows direct streaming and binaural hearing when using a telephone without additional tools or equipment. In addition, the listener can use the telephone naturally by placing the handset next to the ear (Wolfe *et al.*, 2015). Furthermore, it can be used with both mobile and landline telephones. Binaural wireless streaming has been shown to improve telephone-speech recognition and subjective ratings of ease and comfort for a group of adult bilateral HA users (Picou and Ricketts, 2011, Picou and Ricketts, 2013, Wolfe *et al.*, 2015). To date there are only a few published studies that have evaluated the effectiveness of DuoPhone in improving speech recognition in bimodal and bilateral CI users (see Chapter 5 section 5.5.3 0for further discussion), and therefore it would be valuable to assess the benefits of DuoPhone for adult CI users. Despite the importance of using telephone in real life, a telephone test was included to be a part of the real-life test battery to assess the effectiveness of DuoPhone for adult CI users as the primary aim

However, there are no standardised tests in the literature that have been developed specifically to assess speech-perception performance over the phone. Different approaches have been used to investigate telephone use among CI users. Some studies have used questionnaires to assess experiences of telephone use, such as Adams *et al.* (2004) and Cray *et al*. (2004). Although questionnaires are a helpful tool to assess subjective experiences, performance-outcome measures are needed.

There are two methods that have been used mainly in the literature. The first approach is using simulated telephony. Hu *et al.* (2013) used simulated telephone-frequency signals to evaluate telephone-speech recognition among bimodal hearing users. A bandpass-filtered telephone speech stimulus (300–3,400 Hz) was presented via a loudspeaker in front of the participants. Performance was compared with other conditions (wideband speech, high-pass filter speech and low-pass filtered speech). Although this approach may be feasible in experimental settings, it does not account for factors in real-life situations, such as the participants' experience of using and holding a telephone.

The second approach involves using an actual telephone to measure speech perception. Only a few studies have used this approach. Castro *et al.* (2005) used monitored live voice presentation as a test stimulus through the telephone. In this study, a male speaker located in another room presented words and sentences via live-voice presentation into a landline telephone. At the same time, a second researcher stayed with participants to record their responses. They assessed performance in both quiet and noisy conditions where 65 dB SPL white noise was presented from two loudspeakers located one metre in front of the participants. In a further study (Tan *et al.*, 2012), the telephone was also tested by live-voice presentation of the Australian version of BKB sentences. The examiner sat in another room while saying the sentences on a standard landline. The participant received the call while sitting in the test room via a standard landline and using their personal phone. However, the authors did not mention if any monitoring for the live presentation was considered. This approach may allow assessment of the ability to use the telephone in real-life situations, but using monitored/live voice presentation might result in considerable variability, potentially affecting the reliability and generalisability of the findings (Mendel and Owen, 2011). A source of variability might result from articulation errors or inconsistent speaker-loudness levels/speech rate during the presentation.

Another way that might be more controlled is using recorded speech materials presented to participants via a landline receiver or a mobile phone, such as in Latzel *et al.* (2014), Wolfe *et al.* (2016a). This approach allows the testing of telephone use in quiet or noisy conditions by presenting noise from loudspeakers in the test room. Several possible strategies may deliver the telephone signal to the HA or CI. These involve acoustic, electrical and wireless techniques. This approach is feasible to set up, even in a clinical practice setting and has good face validity. Furthermore, the output from the telephone can be measured, and the use of recorded speech materials may provide more reliable results. Di Nardo *et al*. (2014) and Giannantonio *et al.* (2014)

have used test settings that mimic a real-life listening situation to assess the effectiveness of a telephone map for CI users. The microphone of a landline phone was positioned 40 cm away from a loudspeaker in an anechoic sound booth with recorded word lists presented from the loudspeaker. The participants sat in another anechoic booth and were given a second landline phone. The two landline phones were connected via a conventional telephone network to transmit speech signals from first to second. The participants were asked to listen to the second phone, place the receiver as they would in their daily life and repeat the words. Using test settings that represent as close as possible real-life situations may offer a better understanding of the difficulties experienced by the CI users in real life.

A telephone test using a real-life set-up, as described in the preceding paragraph, was developed and included in the test battery for this study to assess the benefits of using DuoPhone for adult CI users. A detailed description of the development of the telephone test is provided in Section 4.2.2.5.

4.2.1.5 Self-rated scales

Ramakers *et al*. (2017) showed that the performance tests do not fully reflect the subjective performance of CI users in real-life listening situations. They found significant weak to moderate correlations between the subjective rating scales (self-reported questionnaire) results and the speech-perception-in-noise results. Accordingly, they point out the importance and the necessity of including self-reported questionnaires in the performance evaluation of CI users.

Therefore, subjective rating scales were included in the test battery to assess hearing functions in real-life listening situations. There are several advantages of this kind of measurement. Self-rating scales are easy to administer. They can provide rich information about how the participants are coping in real-life situations. Furthermore, they can be used to determine to what extent the performance according to the performance tests relates to functional performance in real-life listening situations.

There are different approaches in the literature that have been used to assess the subjective benefits of CI. Some studies have used non-standardised questionnaires specially designed for their experiments (Tyler *et al.*, 2002b, Ching *et al.*, 2004, Flynn and Schmidtke, 2004). Others used standardised questionnaires such as the speech, spatial and qualities-of-hearing scale (SSQ) (Noble *et al*., 2008, Noble *et al*., 2009, Potts *et al.*, 2009, Farinetti *et al*., 2015), the Nijmegen cochlear implant questionnaire (NCIQ) (Farinetti *et al*., 2015), the abbreviated profile of hearing aid benefit (APHAB) (Morera *et al.*, 2012), the hearing handicap inventory for the elderly (HHIE) (Noble *et al.*, 2009) and the hearing handicap questionnaire (HHQ) (Noble *et al*., 2009).

There are several advantages of using standardised over non-standardised questionnaires. Standardised measurements are more accurate as they have known levels of reliability and validity (Stapleton and McBrearty, 2009). In addition, results from standardised measurements are quantified in finer detail rather than personal judgment (Sauro, 2012). It would also be possible to compare the results from standardised measurements across different studies. Moreover, many standardised measurements have normalised reference data (Sauro, 2012). Table 4.1 illustrates the most common standardised self-report questionnaires that have been used with CI users.

Table 4.1: Standardised self-report questionnaires used with CI users.

Questionnaire	Purpose	Format/description
Speech, spatial, and qualities-of-hearing scale (SSQ)	Designed to assess a wide range of hearing (dis)ability, with some focus on hearing functions that are considered to rely on binaural processing	• 50-item scale covering 3 domains: 1. Speech understanding in different situations 2. Spatial hearing 3. Quality of hearing • Uses 0–10 rating scale for each item (where 0 indicates the least ability and 10 the greatest ability)
Nijmegen cochlear implant questionnaire (NCIQ)	Designed to assess the quality of life of adult CI users	• 60 questions divided into 6 subdomains: 1. Basic sound perception 2. Advanced sound perception 3. Speech production 4. Self-esteem 5. Activity limitations 6. Social interaction • It uses a rating scale from 1–5 (never–always) and is not applicable

The abbreviated profile of hearing aid benefit (APHAB)	Designed to document the outcome of a hearing-aid fitting, compare several fittings, or evaluate the same fitting over time.	• 24 questions divided into 4 subscales: 1. Ease of communication 2. Reverberation 3. Background noise 4. Aversiveness of sounds • Uses a rating scale with 7 levels: A to G (where A indicates 'always' and G indicates 'never')

The speech, spatial and qualities-of-hearing scale (SSQ) (Gatehouse and Noble, 2004) is a self-reported measure that assesses a range of hearing disabilities across several domains: speech, spatial and 'other qualities' of hearing. The scale evaluates several hearing functions that implicate the advantages of the binaural system. It consists of 14 scored items on speech hearing, 17 on spatial hearing, and 19 on the other functions and 'qualities of hearing' such as signal segregation, clarity and naturalness of sounds, ease of listening. Responses to each item are made on an 11-point scale from 0 (indicates the least ability) to 10 (the greatest ability). The SSQ has been shown to be sensitive to showing differences in monaural and binaural hearing, including the difference between bilateral versus unilateral HAs (Noble and Gatehouse, 2006) and one versus two implants (Noble *et al.*, 2008, Noble, 2010). Noble (2010) compared the self-rated listening on the 49 items of the SSQ for 69 unilateral HA, 34 bilateral HA, 14 unilateral CI, and 18 bilateral CI users. The results showed that two devices offer an advantage for challenging situations, spatial hearing and reduced listening effort. The SSQ scale was chosen to be included in the test battery of the present study to assess the self-reported benefits because the scale is a standardised measure and sensitive to showing the benefits of binaural hearing.

There are different methods for scoring ratings on the SSQ. One method calculates an overall score by taking the mean score across all the items. Another approach is to calculate the average score for each of the three subscales (speech, spatial and qualities of hearing). Gatehouse and Akeroyd (2006) used another approach where the scale is broken down into ten sub-sections, as shown in Table 4.2. This approach offers a better understanding of participants' functioning in real-life listening situations.

Table 4.2: The individual SSQ items to each of the subscale labels as having been used by (Gatehouse and Akeroyd, 2006).

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

As discussed in the previous section, using the telephone is a challenging task for many CI users, especially in noisy environments (Adams *et al.*, 2004, Castro *et al.*, 2005, Anderson *et al.*, 2006, Castro *et al.*, 2006, Tan *et al.*, 2012). Therefore, it would be useful to quantify these difficulties from the CI users' perspectives. To the best of the researcher's knowledge, there is no standardised questionnaire aimed to gauge the telephone use of CI users in their real-life listening situations. For these reasons, a Telephone-Use questionnaire (Appendix L) was developed and included in the test battery of the study. In addition, the questions related to telephone use in the SSQ questionnaire were examined separately.

4.2.1.6 Music perception

Although CI users perceive musical rhythm similarly to NH listeners, they score significantly lower on pitch-based tasks than NH individuals and those with HAs (Looi *et al.*, 2008, Looi *et al.*, 2012, Gfeller and Lansing, 1991). This is problematic, as pitch perception is an essential element of music perception (Galvin *et al.*, 2007). In addition, CI users tend to rate the quality of musical sounds lower than those with normal hearing (McDermott, 2004). A possible reason for these difficulties might be the limited spectral and pitch information conveyed by CIs. Most current CI-processing strategies discard TFS information, and only the envelope information is used to process the signal (Cullington and Zeng, 2011). Furthermore, poor spectral resolution in CIs limits the resolution of harmonics, which are essential for pitch perception, timbre perception and distinction of musical instruments (Galvin *et al*., 2007).

CI users reported improved sound quality and music perception when they used a HA in the contralateral ear compared to using a CI (Armstrong et al., 1997, Tyler et al., 2002b, Ching et al., 2004, Hamzavi et al., 2004). Bimodal users have also shown improvement in identifying familiar melodic tasks than when using a CI alone (Kong *et al*., 2005, Dorman *et al*., 2008, El Fata *et al.*, 2009). However, few studies have assessed music perception in adult CI users. In addition, there are only a few standardised tests, and they are often based on melody-recognition tasks. For instance, Cullington and Zeng (2011) used the Montreal battery for the evaluation of amusia (MBEA). While MBEA is a standardised, sensitive, reliable, and comprehensive test that can be used to assess different music abilities, the pitch subtests were too difficult for CI users to participate in (Cullington and Zeng, 2011).

It would have been valuable to include a music-perception test into the test battery for the current study. However, this could not be achieved because of the limited availability of standardised music-perception tests with appropriate duration and the time constraint of the test battery. Therefore, future work would consider incorporating music-perception measurement within the test battery. Nevertheless, the current study attempted to obtain a general overview of music perception for adult CI users by examining the questions related to music listening in the SSQ questionnaire.

4.2.1.7 Summary of the rationale of the real-life test battery development

The real-life test battery developed for the present study incorporates a combination of performance tests and subjective rating scales that would allow assessing the essential listening skills in real life, including:

1. Speech perception in noise involves three test set-ups simulating common real-life situations:
    - group conversation
    - one-to-one conversation
    - conversation while driving a car
2. Localisation
3. Tracking moving sounds
4. Telephone use in quiet and in noise

5. SSQ questionnaire
6. Telephone-Use questionnaire.

In addition, the assessment of music perception was considered, but not included in the test battery due to time constraints. However, scores on the SSQ questionnaire for the questions related to music perception (specifically, questions 5, 7 and 8 on the qualities-of-hearing subscale) have been examined separately to obtain a baseline of CI users' abilities.

4.2.2 Development of the real-life test battery

This section describes the apparatus used to administer the real-life test battery and the set-ups for each test included in the battery. In addition, it outlines the development of the new speech-in-noise tests and the telephone test.

4.2.2.1 The AB-York Crescent of Sound

The AB-York Crescent of Sound is an apparatus developed by Kitterick *et al*. (2011) to assess different spatial-listening skills. This rig has been used to develop the new tests and administer the real-life test battery used in this study.

The AB-York Crescent of Sound consists of nine audio-visual stands (Plus XS.2, Canton loudspeakers) arranged in a semi-circular array with a radius of 1.45 m. Loudspeakers are placed at ±90°, ±60°, ±30°, ±15°, and 0° azimuth, where 0° is straight ahead of the listener. The axis of each loudspeaker is suspended at the height of 1.1 m. A 15" visual display unit (VDU) is placed below each loudspeaker from -60° through to +60°. A separate touchscreen is placed in front of the participant to record their response directly if required. Figure 4.2 shows the AB-York Crescent of Sound at the University of Southampton Auditory Implant Service (USAIS). The Crescent of Sound is situated within a double-walled sound-treated room. A control station to administer the listening test, record and analyse the response is situated in the same room. It consists of a VDU, a keyboard and a mouse. A detailed description of the apparatus can be found in Kitterick *et al*. (2011).

The AB-York Crescent of Sound comprises a Clinical Interface (also called Clinical Controller) and a Research Interface. The Clinical Controller is designed to facilitate the assessment of the spatial-listening skills of children and adults with cochlear implants using tests developed by Lovett *et al*. (2010) for children with unilateral and bilateral CIs. Table 4.3 provides a brief description of the tests considered in the current study. These tests are previously validated for use with patients (Lovett *et al.*, 2010). Additionally, these tests are suitable both for adults and children, and the level of test difficulty can be adapted based on the hearing ability of the listeners. As a result, the apparatus can be used to administer the tests to normal-hearing listeners, HA users, and CI users. The AB-York Crescent of Sound is a standard piece of equipment within the USAIS, used in clinical practice and for research.

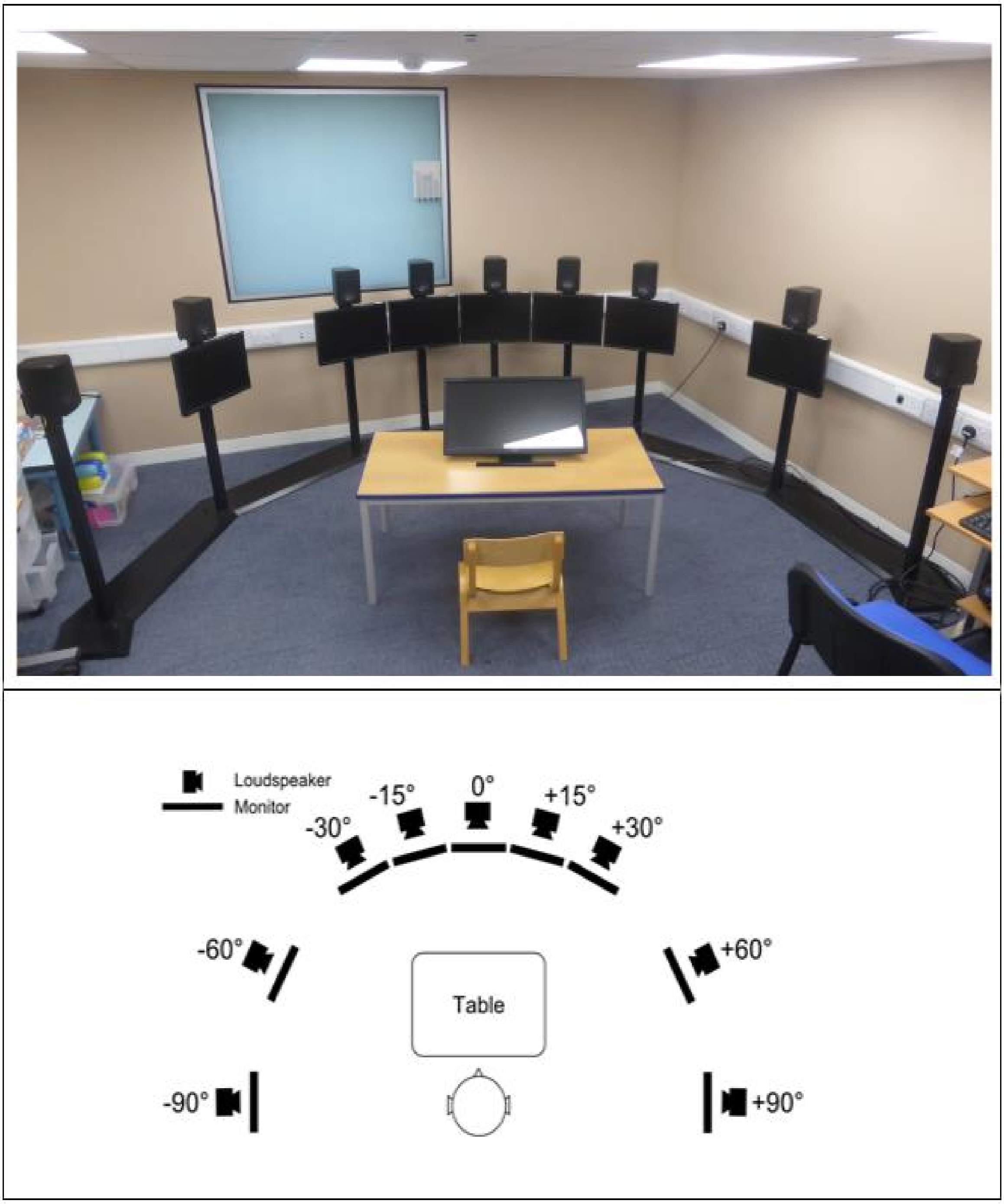

Figure 4.2: The upper panel shows the AB-York Crescent of Sound at the University of Southampton Auditory Implant Service (USAIS), while the block diagram in the lower panel illustrates the arrangement of the loudspeakers (Source of block diagram: AB-York Crescent of Sound manual).

Table 4.3: A brief description of spatial tests available in the clinical interface (Clinical Controller) of the AB-York Crescent of Sound.

Test	Description
Movement tracking	To assess a participant's ability to track a moving source of sound presented using the array of loudspeakers. There are four movement trajectories in this test: *left-centre-right, right-centre-left, left-centre-left, right-centre-right.*
Localisation	To assess a participant's ability to identify the location of a sound source out of 3 or 5 possible loudspeakers. There are 3 options of localisation: 60°, 30°, or 15°.
Sentences in noise	To measure the level at which a participant can repeat sentences presented in noise. The sentence materials are BKB sentences corpus that can be presented in speech-spectrum shaped noise or 20-talker babble noise. The tester can select one of the procedure versions: fixed or adaptive.

The Research Interface allows the development of additional listening tests using a custom-scripting language (coding). The codes have the functionality to control the presentation of stimuli and adaptively alter the parameters of the stimuli based on previous responses. This allowed for the modification of existing tests and the development of new tests for this study which included the following additional features:

- 'Roving' speech (instead of only being fixed from one speaker)
- Diffuse multi-talker babble noise from the two loudspeakers placed at ± 60° or ± 90 degrees simultaneously (instead of only from one direction at a time)
- Fixed speech from the right or left side (90°) of Crescent of Sound
- Two further trajectories for the tracking test: *centre-right-centre* and *centre-left-centre* (instead of only 4 trajectories)
- A continuous loop of multi-talker babble that can last for two-, three- and five-minute intervals (for the telephone test).

4.2.2.2 Real-life speech-in-noise tests

The AB-York Crescent of sound rig has several tests available in the Clinical Controller interface. One of these tests is the *speech-in-noise* test that measures the level at which a participant can hear and repeat sentences presented in noise (SRT). The BKB sentences are used as the speech stimuli and presented from straight ahead (0°). The noise can be presented from the front or 15-, 30-, 60-, or 90-degrees azimuth to the left or right. Two types of noise can be selected for this test: speech-spectrum-shaped noise or a 20-talker babble. The test can be run at a fixed SNR ratio (-30 to +30 dB), or the SNR can be varied adaptively to estimate the SRT at which the participant performs with an accuracy of 50%. In the adaptive version, the test starts with an SNR level at +25 to +35 dB. A sentence is considered to have been reported correctly if the participant repeats at least three keywords. The procedure has three phases where the step size varies as 10 dB (Phase1), 5 dB (Phase2), and 2.5 dB (Phase3). The test uses one reversal for phases 1 and 2. The test run finishes when 15 phrases have been presented in phase 3.

4.2.2.2.1 New speech-in-noise tests

The Research Interface was used to write code for new versions of the speech-in-noise test. The first new feature is to have four options to present the sentences instead of one option (from the front 0º). The three options added are speech that can also be:

1. Fixed right (+ 90º)
2. Fixed left (- 90º)
3. Roving (the sentences are randomly presented from different loudspeakers during the test run)

In addition, code was also written to be able to present uncorrelated diffuse noise from two loudspeakers placed at 60° or 90° to the left and right side simultaneously. A correction factor of 3 dB was applied for the SRT calculation when the diffuse noise is selected to avoid the binaural loudness summation effect (Sivonen and Ellermeier, 2006). This allows for noise to be presented in the following ways:

1. Front (0º)
2. Left and right 60 degrees (± 60°)
3. Left and right 90 degrees (± 90 °)
4. Left 60 degrees only (- 60º)
5. Right 60 degrees only (+ 60º)
6. Left 90 degrees only (- 90º)
7. Right 90 degrees only (+ 90º)

These new configurations were used to develop the three real-life speech-in-noise tests used in this study. Each test simulates a specific real-life listening situation:

1. **SrN±60°** (roving speech in diffuse multi-talker babble noise): this test simulates a group conversation in a noisy background.
2. **S0°N±60°** (fixed speech from the front in diffuse multi-talker babble noise): this test simulates a one-to-one conversation in a noisy background.
3. **S+90°N-90°** (fixed speech at one side and multi-talker babble noise at the opposite side): this test simulates having a conversation while driving a car.

Additionally, two further tests have been administered, namely **S0°N0°** and **S0°N-60°.** These are standard tests commonly used in the clinic and research settings. They were included in the Research Interface together with newly developed real-life tests. These two tests are included to measure the reliability and the validity of the new tests, i.e. to compare the scores of the tests in the Clinical Controller and Research Interface.

The sentence materials are BKB sentence corpus spoken by a male talker. Nine lists of 20 sentences were included, using the adaptive procedure. Each sentence had three keywords. The sentences implemented in the coding script were picked randomly from the original lists that were available in the Clinical Controller. The background noise can be either speech-spectrum-shaped noise or 20-talker babble noise. The latter was used in this study. Each sentence was presented 1 second after the noise started.

4.2.2.2.2 Adaptive procedure description

An adaptive procedure of the 1-up/1-down method was used to estimate the SNR that produced an accuracy of 50%. Each test run was obtained by presenting 20 sentences in one list. Sentences were scored according to the correct keywords repeated by the participants. The correct response was considered when the participant could repeat at least two out of three keywords.

The speech and background-noise level varied according to the participant's response. The test run consisted of three phases:

1. A large step size of the stimulus intensity of 4 dB with one reversal was used. The same sentence was repeated until a correct response was obtained (or incorrect if the participant could repeat the sentence correctly). This phase was used at the beginning of the testing to be in the right place on the psychometric function before actual testing started. It saved time and prevented the sentences from ending before reaching a well-defined endpoint after six typical reversals.
2. The test run had a smaller step size of 2 dB with one reversal. The second phase was used because the first two reversals were not included in the SRT calculation.
3. The third phase was a small step size of 2 dB with six reversals.

The first sentence was presented at 0 dB SNR with both speech and noise levels of 65 dB (A) SPL. If the participant could not repeat the sentence correctly (at least two of three keywords), the system produced a 4 dB more favourable SNR by decreasing the noise and presented the same sentence again. This process continued until the participant could repeat at least two keywords correctly. The test then presented the second sentence in the list and adapted the SNR using a 2 dB step to converge the SRT value. If the participant can repeat two or three keywords correctly at the 0 dB SNR, the same sentence was repeated with adverse SNRs until the participant said they could not understand any words or simply repeated one word. The system then presented the second sentence in the list and adapted the SNR. While eight reversals were used following the 2 dB step size, only the SNR for the last six reversals was averaged to estimate the SRT.

4.2.2.2.3 Calibration and pilot study

After developing the new test configurations, the next step was to conduct calibration measurements to ensure the starting presentation levels for both speech and noise were 65 dB (A) SPL. A Kamplex KM6 sound level metre (SLM) was used to measure the speech and noise levels.

Afterwards, a pilot study was carried out before proceeding to the main study to investigate whether the codes and the calibration factors would produce accurate measurements. Two adults participated in the pilot study. One participant was a native British English speaker, while the second was a non-native speaker but could speak British English fluently. They had normal hearing. They were asked to repeat the sentences that came from one of the loudspeakers for each test configuration in the multi-talker babble noise. Table 4.4 shows the SRTs of the newly developed tests in the Research Interface as well as the two tests available in Clinical Controller (S0°N0° and S0°N-60°) for both participants.

Table 4.4: The SRTs in dB SNR of NH participants in the pilot study.

Test	Participant 1		Participant 2	
	Research Interface	Clinical Controller	Research Interface	Clinical Controller
S0°N0°	-3.5	-3.4	-4.2	-3.8
S0°N-60°	-8.3	-7.4	-4.1	-8.1
SrN±60°	-5	NA	-4.3	NA
S0°N±60	-5.3	NA	-2.6	NA
S+90°N-90°*	-13.3	NA	-13.3	NA

NA= not available in the Clinical Controller.

***** Speech presented at the right ear and the noise at the left ear

The SRTs of the S0°N0° and S0°N-60° tests in both interfaces were compared to check whether the scores of newly developed tests in the Research Interface were valid and comparable to those obtained by the Clinical Controller. The scores of both tests for the participants in the Research Interface were close to those in the Clinical Controller (the difference was less than 1 dB) except for S0°N-60° test for the second participant where there was a 4 dB difference. It is not entirely clear whether there is any reason for this difference; however it could be related to the differences in the adaptive procedures between the two interfaces as described previously in Section 4.2.2.2. Overall, the pilot study results indicated that the codes seem to be appropriate to produce valid values.

4.2.2.3 Localisation

'Toy localisation' is one of the tests available in the Clinical Controller in the AB-York Crescent of Sound. The localisation test measures whether a participant can determine the location of a sound source from three or five possible locations. In the three-alternative localisation option, the three loudspeakers are separated by 60 degrees, whereas the loudspeakers in the five-alternative option are each separated by 30 degrees or 15 degrees depending on the test parameters. Mounted below each loudspeaker, there is a screen which displays a number or a picture of a different coloured toy block in the child's version. Given that the participants were adults, they were asked to say the number of the loudspeaker from which the voice was presented. A total of 30 trials were presented with a training trial at the start of the test. The outcome measure was the number of correct responses given as a percentage. The test stimulus is a phrase: *"Hello, what's this?"*, spoken by one of five different talkers presented at levels between 65–75 dB SPL with 11 roving intensity levels, and a 0 to 10 dB of attenuation applied in 1 dB steps. Attenuation was chosen at random from trial to trial.

Five locations with 30 degrees of separation were used as shown in Figure 4.3. The Clinical Controller was used to administer the test as no further modifications had been done to the original test.

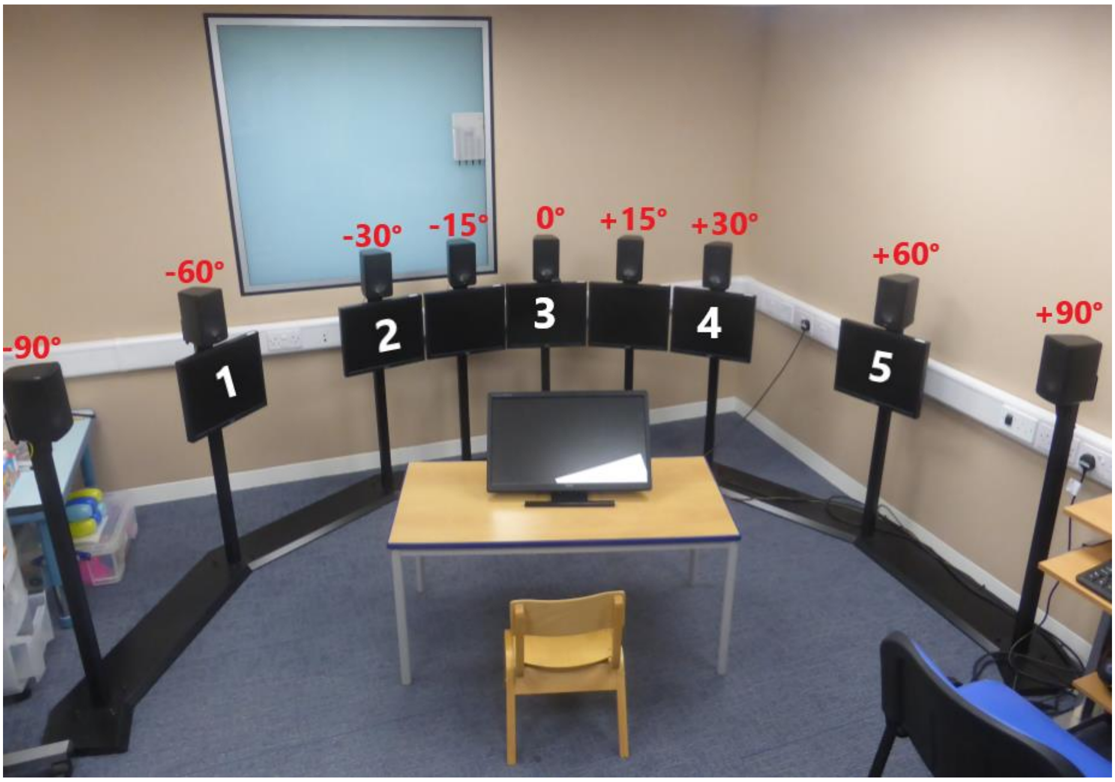

Figure 4.3: The arrangement of the five loudspeakers placed with 30° separation used in the localisation test.

4.2.2.4 Tracking

The movement-tracking test is another of the available tests in the Clinical Controller. A tracking test assesses a participant's ability to track a moving source of sound presented from an array of loudspeakers. In the original test there are four possible movement trajectories: *left-centre-right, right-centre-left, left-centre-left, right-centre-right.* Two types of stimuli can be chosen for this test which either simulate a person walking or a horse galloping. The stimulus is presented in a stepped manner at 65 dB SPL from the nine loudspeakers of the Crescent of Sound array.

Further modifications were done as part of this study to avoid the ceiling effect and reduce the effect of guessing behaviour. The Research Interface was used to code and script two further trajectories: (1) *centre-right-centre and (2) centre-left-centre*. In addition, codes were written to make each test run consist of a list of 12 trajectories where each trajectory was repeated twice in a pseudo-random order. The horse galloping was chosen to be the stimulus used for the tracking test in this study. The initial neighing sound was removed to prevent the participant from using this sound as a cue.

The participants were instructed that they would hear a horse galloping and were asked to indicate the direction of the sound as it moved, using pointing and a verbal response. The results were calculated as the proportion of trials in which the movement trajectory was judged correctly as a percentage.

4.2.2.5 Telephone test

A telephone use test was included as part of the real-life test battery. As discussed in Section 4.2.1.4, there is no consistent approach to assessing telephone use in CI users. There is also no commercially available standardised telephone test for CI users. There is a need to develop a telephone test that can be used to assess CI users. A secondary aim was to evaluate the benefit of DuoPhone for CI users using the Naida Link HA in the non-implanted ear. For these reasons, a telephone test was developed for the study, and the following subsections outline the steps of the test development.

4.2.2.5.1 Materials

The triple-digit test (TDT) was used as target speech stimuli for the telephone test. The TDT was chosen as it offers a closed-set test and has previously been used as a hearing-screening test by telephone. In addition, a recent scoping review (Van den Borre *et al*., 2021) for all TDTs and their variations in language, masking noise, test procedures and targeted population showed that TDT is highly reliable and effective in measuring the loss of functional hearing ability,.

The TDT was originally developed by Smits *et al*. (2004) to be used as speech material in developing a Dutch self-test for a hearing-screening test by telephone. The TDT was later used again as speech material in developing a diagnostic speech-in-noise test in Dutch known as digits-in-noise (DIN) (Smits *et al*., 2013). Smits *et al.* (2004) and Smits *et al*. (2013) argued that using digit triplets would be more suitable than using words or sentences in screening tests or measuring the SRT for hearing-impaired listeners, including CI and HA users, for several reasons. Digits are very familiar and frequently used in daily-life conversations. In contrast to sentences, digits are simple words and are usually presented in a closed-set paradigm; thereby, the effect of linguistic skills on the scores would be minimum.

Kaandorp *et al*. (2015) assessed the SRTs of HA and CI users with the DIN test. The results of their study showed that the DIN test is a feasible, reliable, and valid test for those groups of listeners having a wide range of hearing impairment and different linguistic and cognitive abilities. From a practical perspective, digit triplets can be repeated without the risk of learning effect because it is difficult to remember which triplets have been used compared to the sentences.

On the other hand, it may be argued that digits have low face validity as they do not represent the complete phoneme distribution of daily-life conversations (Kaandorp *et al.*, 2015). However, Smits *et al.* (2013) showed that vowel, consonant and word-length recognition are needed to recognise the digit triplets. Additionally, they showed that the digit triplets test is highly correlated (r= 0.90) with the standard-sentence SRT test developed by Plomp and Mimpen (1979). Thus, the digit-triplets test could provide a valid method to assess speech perception in noise, particularly for listeners with hearing difficulty or impaired/developing language such as CI users, HA users and children.

Due to the successful experience using TDT as a telephone-screening tool and a clinical diagnostic tool in the Smits *et al*. (2004) and Smits *et al.* (2013) studies, similar tests have been developed in other countries, including the UK (Lutman *et al*., 2006). The British English version of TDT involves English digits from 0 (pronounced 'oh' as is commonly used in the UK) to 9, with the exclusion of 7 because it has two syllables. The digits were recorded as digit triplets by a female speaker with a neutral southern accent, and then specially written software was used to generate 20 lists of nine triplets. A carrier phrase "The digits …" is preceded by each triplet. The triplets were presented in stationary speech-spectrum noise using earphones as the first stage of the test development (Hall, 2006). Then the digit triplets were implemented in the telephone test (Lutman *et al.*, 2006). There is no published data about validating the British English recoding of the digit triplets. However, a master's dissertation (Causon, 2012) showed that the test-retest reliability of the TDT was strong without significant learning effect and had good sensitivity and specificity as a hearing-screening test for detecting moderate hearing losses. Causon (2012) also reported the previous unpublished validation studies done as master's dissertations. Different methods (fixed vs adaptive SNR) and transducers were used in these projects. Therefore, it was impossible to conclude from these studies the validity and reliability of TDT, particularly as an outcome measure for hearing-impaired listeners. But it is worth mentioning that the TDT has been widely used as a screening test by the Royal National Institute for the Deaf (RNID).

Another recorded version of the British English digits (digits from 1 to 9, with the exclusion of 7) was created by the University of Southampton and used in a PhD project to develop a measure of auditory fitness for duty (Semeraro, 2015). This version recorded each digit separately by a male speaker with a standard southern British English accent. Similar to the version created by Lutman *et al.* (2006) and Hall (2006), only monosyllabic numbers were recorded. Further details of the recording process are available in Semeraro (2015). It was decided to use the version created by the University of Southampton in this study because the digits were recorded separately instead of as triplets, thereby reducing any possible variation when the digit is repeated in another set of triplets because of differences in intonation or vocal-fold effort. Code was written using MATLAB (version R2018b) to concatenate the digits into triples and to generate lists of 10 triplets. Each triplet was preceded with the carrier phrase "The digits …" and recorded using the same talker.

It would be interesting to use the latter recorded version of TDT in the presence of background noise. However, it was not possible to integrate the masker noise in the same equipment due to time constraints. Therefore, it was decided to use the loudspeakers of the AB-York Crescent of Sound to present the masker noise. A fixed-testing procedure was used with different SNR levels. Although using an adaptive procedure would be more representative of real life, it could not be applied at this stage from a practical perspective in terms of controlling two separate devices.

The Research Interface in the AB-York Crescent of Sound was used to write the coding for presenting a continuous loop of noise without a speech stimulus from one or two loudspeakers placed at ± 60° simultaneously (uncorrelated output from each noise speaker). The new script developed for presenting the noise-in-telephone tests has two features. The first feature is two noise-type options: Speech-spectrum-shaped noise and 20-talker babble noise. The second feature available is the level of noise. Three levels can be selected when running the script:

1. High level =60 dB (A)
2. Medium level= 55 dB (A)
3. Low level= 50 dB (A)

Three versions of the script were created that differed in duration (two, three and five minutes). It was decided to create these different versions to find the most appropriate duration when one TDT list was presented during the pilot study. The type of noise used in this study for the telephone test in noise was 20-talker babble as it has higher face validity than other types of noise in terms of it more closely resembling real-life listening situations (Moore *et al.*, 2019). Another reason is that it is consistent with the same masker noise used in speech-in-noise tests.

4.2.2.5.2 Telephone test set-up

Testing took place in a room housing the AB-York Crescent of Sound at USAIS. The room is divided into two sections: the first is an observation room, and the second is a double-walled sound-treated room (testing room) where the loudspeaker array and the control station are situated.

In the observation room, a Genelec 8020C loudspeaker was connected to a Dell laptop which had an Intel®Core™ i5-8265U CPU @1.60 Hz, 1800 processor to present the recorded TDT. The headset of a landline telephone was placed in front of the loudspeaker. The handset was positioned on a tripod to keep it stabilised in the same position during the testing for all participants. The distance from the handset microphone and loudspeaker was 15 cm to avoid any electrical interference. Audio interface talkback was used to allow the researcher to hear the participant's response.

In the other section (testing room), the participant was asked to sit in the same position as speech-in-noise tests facing the front loudspeaker. The digit triplets were presented to the participants via a mobile phone (Samsung Galaxy Note2) from the Genelec loudspeaker using the landline telephone in the observation room. For the noise condition, 20-talker babble noise was presented from the two loudspeakers in the AB-York Crescent of Sound rig placed at ± 60° and one metre from the location of the participant's head. The set-up of the telephone-use test is illustrated in Figure 4.4.

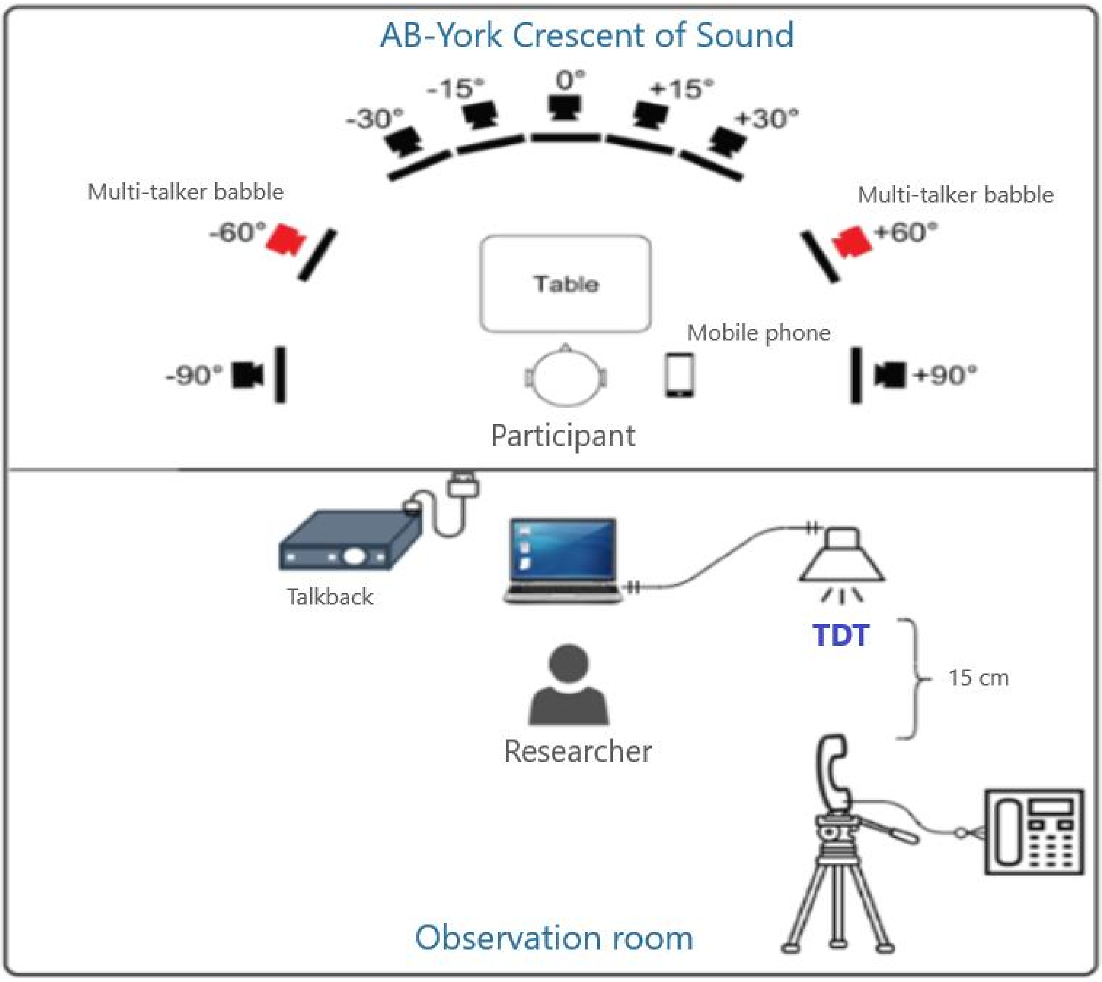

Figure 4.4: The set-up of the telephone test.

4.2.2.5.3 Calibration and pilot study

The TDT presented from the Genelec loudspeaker was calibrated daily before testing each participant to ensure the TDT level was at 65 dB (A). This was done by placing the sound-level meter (SLM) (Kamplex KM6) in the same position as the microphone of the landline headset. A calibration signal was generated by MATLAB code which consisted of a white noise lasting 20 seconds. This signal was presented from the Genelec loudspeaker while the sound level meter was positioned with the microphone facing forward. The sound level of the calibration signal was adjusted via the loudspeaker volume control until the SLM gave a reading of 65 dB (A). The masker (20-talker babble) was also calibrated by placing the SLM in the position at the centre of the participant's head while the noise was presented from the two loudspeakers at ± 60°. The noise level was adjusted by applying calibration attenuation factors in the script in the Research Interface. Then the process was repeated until the SLM read the desired level of noise (high= 60 dB (A), medium= 55 dB (A), and low= 50 dB (A)).

A pilot study was carried out with one NH listener and two CI users (CI user 1 was a unilateral CI user who used a HA in th non-implanted ear and CI user 2 was a bilateral CI user). The pilot study was conducted to investigate:

- The clarity and naturalness of the recorded and concatenated digit triplets
- The level of noise (SNRs) that would be used for the NH and CI participants
- Which script version would give the appropriate duration of the continuous loop of noise during administering the TDT list
- The time taken to conduct a telephone test in both quiet and noise conditions and to practise the procedure
- Possible issues that could occur prior to commencing the data collection.

Table 4.5 shows the results of the pilot study. The CI user 1 could initially not use the study mobile phone as the sound was not clear. It was suggested then to use their personal mobile phone. Therefore, the results reported in Table 4.5 for CI user 1 are the results with their personal mobile phone. It also should be mentioned that a noise-cancellation feature on the CI device of CI user 1 was switched ON during the testing. The researcher asked CI user 1 to try again to use the study mobile phone. The test in quiet was the only test that could be repeated, with the volume level being at the maximum. The score remained good as the participant achieved 96.7%. For CI user 2, testing was completed when using both CI devices, and the participant could use the study mobile phone. The NH participant reported that the digits were clear and sounded natural at the medium volume level of the mobile phone. The two CI users were asked about their impression of the noise levels used. Both reported the high-level noise (5 dB SNR) was 'too difficult and upsetting'.

Table 4.5: Pilot study results of telephone test.

	Quiet	Low noise level (15 dB SNR)	Medium noise level (10 dB SNR)	High noise level (5 dB SNR)
NH	100%	100%	100%	76.6%
CI user 1	100%[1] (96.7%)[2]	100 %	70 %	60%
CI user 2	96.7%	96.7%	100 %	90%

[1] CI user's mobile phone, [2] Study's phone used in the study

It was decided to use the script version of three minutes of continuous noise for all main study groups: NH, bimodal and bilateral CI participants. It was decided to use two noise levels for the NH group: medium (10 dB SNR) and high (5 dB SNR). The low noise level was excluded as the ceiling effect was highly expected. For CI participants, including bimodal and bilateral CI users, it was decided to use only one noise level, which was the medium level (10 dB SNR), for several reasons. First, the CI participants needed to be tested with more than one listening condition (one CI vs two CIs for bilateral CI group, and CI+HA vs CI+HA+ DuoPhone for the bimodal group). Consequently, more time would be needed to administer all the test conditions than for the NH group. Additionally, there were concerns about possible fatigue, given all the measurements included in the test battery.

4.2.2.5.4 Procedure

This section describes the procedure for the telephone test used in the main study with NH, bimodal and bilateral CI participants.

Before starting testing, the calibration of the TDT stimuli was carried out as described previously. Participants were seated in the centre of the AB-York Crescent of Sound loudspeaker array facing the front loudspeaker placed at 0°. They were handed the mobile phone with a demonstration of how to answer the call and adjust the volume levels to a more comfortable level. In addition, they were instructed to use their preferred "telephone ear" for NH participants, the implant side for the bimodal participants and their first implant side for the bilateral CI participants. Then the following instruction was given:

“I will be sitting in the observation room, and I am going to call you on this mobile phone. When you answer the phone let me know when are ready. You will hear then a list of digit sequences. Each sequence consists of three digits. Please repeat the digits you hear.”

Then, the researcher left the testing room with the door closed. Prior to testing, training was carried out to familiarise the participants with the test procedure and find the most optimal phone position for them, as well as to allow the participants to adjust the volume control of the mobile phone (and the sound processor for CI participants) to their most comfortable listening level. Then the volume control of the mobile phone (and the sound processor for CI participants) remained at the same level throughout the test session. The researcher used the landline to dial the mobile phone used in the study from the observation room. Once the person answered the call and informed their readiness, the researcher presented the TDT list via the Genelec loudspeaker placed in front of the handset of the landline by selecting one TDT list from the test folder on the laptop. For the noise condition, the researcher turned on the multi-talker babble from the AB-York Crescent of Sound control station, which is located in the testing room, before leaving the room. NH participants were asked to write down the digit triplets on an answer sheet instead of repeating them because the researcher could not hear their responses because of the masker noise. For CI participants, an assistant stayed in the testing room to write down their responses manually on an answer sheet. The assistant was there to reassure CI participants as many had reported being anxious about doing the telephone test. This is consistent with reports in the literature that using the telephone is challenging for many CI users and can lead to stress (Adams *et al*., 2004, Castro *et al*., 2005, Anderson *et al.*, 2006, Castro *et al*., 2006, Tan *et al*., 2012).

Table 4.6 summarises the test conditions for telephone tests used to test the NH and CI participants. Testing started with measurement conditions in quiet for all the participants. Then the noise conditions (noise levels for NH participants and listening conditions for CI participants) were counterbalanced. For each participant, a new list was used for each test condition. A digit-scoring method was used in this study with scores presented as a percentage correct out of 30 digits for each list.

Table 4.6: A summary of the testing conditions of the telephone test for NH and CI participants.

	NH participants	**CI participants** (Naida bimodal users)	**CI participants** (Bilateral CI users)
Quiet	✓	✓ Listening conditions: 1. CI+ HA 2. CI +HA+ DuoPhone	✓ Listening conditions: 1. One CI
Medium noise level (+10 dB SNR)	✓	✓ Listening conditions: 1. CI+ HA 2. CI +HA+ DuoPhone	✓ Listening conditions: 1. One CI 2. Two CIs 3. Two CIs +DuoPhone (for AB users)
High noise level (+5 dB SNR)	✓	Not tested	Not tested

4.2.2.5.5 Telephone test limitations

It should be noted that the newly developed telephone test in this study cannot be considered as a well-established and feasible test that is ready to be used in clinical practice. There are several limitations that should be acknowledged. Firstly, the version of the recording used does not include the number “zero” as it was recorded to develop a measure of auditory fitness for duty for British English speakers. Secondly, the method used to deliver the digits was not practical and easy to apply, particularly in clinical practice. Therefore, a standardised method for stimuli delivery is recommended. Thirdly, there was no adjustable control for presenting the continuous noise. This was not practical as some of the participants took less than three minutes to complete the test, and then they waited until the continuous noise stopped to administer the next conditions.

The test was developed to simulate having a telephone conversation in real life in terms of hearing in both quiet and noise. However, some controls were applied, especially on digits and noise-presentation levels in terms of using fixed levels. It should also be mentioned that several attempts were made to contact other professionals to help develop the telephone test. Latzel *et al*. (2014) used a computer with a special soundcard and telephone card to simulate a real landline connection. The computer was used to call a DECT phone and present the speech stimuli. The researcher contacted the first author (Dr Mathias Latzel) to discuss the technical set-up and the possibility of using a similar system. However, the company that designed the system (Hörzentrum Oldenburg GmbH) did not respond to the researcher. In addition, a telecommunications expert at the University of Southampton was consulted to discuss the possibility of uploading the sound waves of the recording of digit triplets done by Lutman *et al*. (2006) to the university voicemail system that could be dialled. The telecommunications expert has done similar work previously used in the rehabilitation programme at the USAIS, but they used a live voice recording through the handset of the telephone. When developing the study test battery, it was not possible to upload the sound waves of the digit triplets to a university landline number. Accordingly, it was decided to use the set-up and the method described earlier.

Further work is needed to improve the telephone test, particularly for the following:

- Implementation of the speech stimulus in software that allows presenting of the stimulus directly from the landline phone
- Incorporating both speech stimuli and noise in one apparatus
- An adaptable control for continuous noise presentation
- Options to use different procedures: fixed vs adaptive
- Recording the participant's response via a keypad that can be used by the participant or the examiner.

4.3 Section B: NH listeners' outcomes on the real-life test battery

4.3.1 Introduction

Upon completion of the development of the real-life test battery and prior to testing the CI participant, in this study a group of adults with NH were tested to establish preliminary normative data and evaluate the measurement precision of the new tests. The measurement precision of such instruments depends on their reliability and validity (Trajkovic, 2008).

4.3.1.1 Test-retest reliability

Test reliability refers to measuring the consistency or repeatability of the measurement. Bruton *et al*. (2000) explained that the observed score would be a summation of two components: a true score and a measurement error. The term 'error' in statistics refers to all sources of variation that are not caused by the independent variable. Although the error sources are generally not known, it would be possible to find an estimation of the amount of true measurement and the amount of measurement that might be related to the error.

The measurement errors can generally be divided into two types: (1) systematic and (2) random. Systematic errors are usually predictable, constant and biased. The errors occur in one direction (higher or lower). An example of systematic error is a learning effect that would improve the scores of the repeats compared to the first time the measurement is applied. Another example of systemic errors is fatigue, where the scores of the repeats worsen if the measurement is administered in one session without adequate breaks. On the other hand, random errors refer to random and unpredictable changes in the scores obtained over the repeated measures due to chance (Bell, 2001). Examples for random errors are luck, attentiveness of the examiner, and normal biological variability that might affect a certain score (Weir, 2005).

There are several statistical methods to calculate reliability. Based on a review of the literature, there is no consistency in the use of these methods. Table 4.7 summarises the most common approaches that have been used to calculate the reliability. In addition, it is worth remembering that there is no standard minimum acceptable level of reliability that can be used for all kinds of measurements as levels will differ according to the use of the measure (Bruton *et al.*, 2000).

Table 4.7: A summary of the common reliability measurements.

Statistical method	**Description**
Significance tests (e.g. paired t-test and analysis of variance)	• These tests can be used to detect systematic bias between groups of data by comparing the means of the data sets. However, they do not give information about individual differences • It is recommended not to use this procedure solely and they should be complemented by other procedures (Bruton *et al.*, 2000)
Correlation coefficients (r)	• It provides information about the degree of association between two data sets (e.g. two measurements). It also provides information about the consistency of position within the two sets of data • The correlation coefficient only gives information about how two sets of data vary together, but not how they agree. Therefore, correlation cannot be used to detect systematic errors
Intra-class correlation coefficient (ICC)	• ICC is a single index calculated using variance estimates that can be obtained by dividing the total variance into between- and within-subject variance (Bruton et al., 2000). It therefore provides information about both degree of consistency and agreement between the measurements

Standard error of measurement (SEM)	• SEM is defined as the standard deviation of measurement errors • Smaller SEM indicates greater reliability
Repeatability coefficient	• It can be used to present the measurement errors between two measurements • It is defined as the value below which the difference between the two measurements will lie with a probability of 0.95 (Bruton *et al.*, 2000)
Bland & Altman method	• It is an approach used to assess the agreement between different methods or between two measurements of the same method • It involves plotting the difference between the two measurements against the mean value of each measurement. Then, calculating the mean and standard deviation of the difference and the 95% limits of agreement

Significance tests (e.g. paired t-test and analysis of variance) are statistical methods that are used to measure systematic bias between the groups of data. However, these methods can only give information about the difference between the average means of the two groups, but not about the individual differences in the sample (Bruton *et al*., 2000). Therefore, significance tests should not be used in isolation when measuring reliability. Bartlett and Frost (2008) recommended using a standard error of measurement (SEM) when a study investigates and quantifies the reliability of measurements by a single method on the same participant over a short period under identical conditions. They justified their recommendations as the agreement between the repeatable measurements on the same participant depends only on within-subject standard deviation (SDω). SEM is caused by random error and provides an index of the expected noise in the repeated measures' data and determines the precision of individual scores on such measurements (Weir, 2005). The SEM is largely independent of the sample population; therefore it is not affected by between-subject variability (Weir, 2005). Again, the SEM should not be used in isolation when measuring the reliability as it only provides information about random error.

Pearson's correlation coefficient (r) is another method widely used in the literature to measure reliability. However, using correlation to measure the reliability might be misleading as a high correlation can be obtained between two measurements even if they are not the same because the correlation value provides information about how well two sets of data vary together, but not about how well the agreement between them is. This can happen if the scores differ by a constant amount, which occurs if the participants benefit from the learning effect. Bruton *et al*. (2000) explained that the correlation measurement could not detect systematic errors. In addition, the correlation is strongly dependent on greater between-subject variability of the test population than the within-subject variability (Bland and Altman, 1996b). Therefore, larger correlation coefficients will be obtained for a sample having greater between-subjects variability than a sample with very much no within-subject variability. Another problem with the use of a correlation coefficient occurs when the order of pairs is reversed as it gives a slightly different value of the correlation. Since the order of the repeated measurements of the same quantity is not important, thus it should use a correlation measurement that gives the same value even if the order of pairs is reversed.

To overcome some of the limitations of Pearson's correlation coefficient, using the intraclass correlation coefficient (ICC) was recommended (Bland and Altman, 1996b, Bruton *et al.*, 2000, Weir, 2005). ICC is a single index calculated using variance estimates that can be obtained by dividing the total variance into between- and within-subject variance (Bruton *et al.*, 2000, Zaki *et al*., 2013). It therefore provides information about both degree of consistency and agreement between the measurements where consistency considers only random error and agreement considers both systematic and random error (Zaki *et al.*, 2013). In addition, the ICC estimates the average correlation among all possible orderings of pairs; thus it avoids the problem when the pairs are reversed. The ICC values are unitless, and they can range from 0 to 1, where values closer to one indicate higher reliability. Rosner (2006) classified the level of reliability according to ICC as poor reliability (ICC< 0.4), fair to good reliability ($0.4 \leq$ ICC < 0.75), and excellent reliability (ICC ≥ 0.75) (cited in (Zaki et al., 2013)). For practical use, Chinn (1991) stated that any measure should have an ICC of at least 0.6 to be considered a useful measure. A systematic review (Zaki *et al*., 2013) indicated that the ICC is the most common method to assess the reliability of medical tools measuring continuous variables. However, the ICC has some limitations that make it inappropriate to use it solely to measure reliability. As with the correlation coefficient, the ICC depends on the between-subject variance. If the between-subjects variability is sufficiently high (heterogeneous sample), then reliability will tend to be higher than if the sample is more homogenous (Bruton *et al*., 2000).

The Bland-Altman plot is another method that has been used to assess reliability. This method was originally developed to assess the agreement between two different methods of clinical measurement (independent data) by constructing limits of agreement (Altman and Bland, 1983). The statistical limits of agreement (LoA) are calculated by the mean and standard deviation of the differences between two methods. The resulting graph plotted the difference of the two measurements against the mean of these measurements. To consider the present agreement, 95% of the data points should lie within ± 2SD of the mean difference (Bland and Altman, 1999). The Bland-Altman plots can help to assess the two aspects of the agreement: (1) how well the two measurements agree on average and (2) how well the two measurements agree for individuals (Bunce, 2009). The assessment of the two aspects is important because if one measurement gives lower scores than the other for half of the participants and higher than the other participants, then the overall average difference might be close to 0, even with the difference for individuals being high. Bland and Altman (1986) suggested that the LoA method can be used to assess the repeatability of a single measurement method. However, it has been criticised that the LoA is not appropriate for assessing the reliability (Bruton *et al.*, 2000, Hopkins, 2000, Zaki *et al.*, 2013, Koo and Li, 2016). Hopkins (2000) argued that the values of the LoA are biased depending on the sample size and number of trails. The bias can be ranged from less than 5 % (n< 25 with two trails or n> 13 with 3 trails) up to 21% (n=8 with two trails).

In summary, different methods quantify different aspects of the test-retest reliability. Bruton *et al.* (2000) suggested using a combination of approaches instead of a single procedure to have a wider picture of the reliability of such measurement. For instance, Summerfield *et al.* (1994) and (Lovett et al., 2013) measured the test-retest reliability of the IHR-McCormick automated toy discrimination test in quiet and in masker of noise using three methods: SEM, the repeatability coefficient, and correlation coefficients. In the current study the test-retest reliability of the new speech-in-noise tests was assessed by measuring the systematic and random errors for the difference between session 1 and session 2 for each test. For systematic errors, a two-way repeated-measures ANOVA and paired sample t-test were conducted to assess the mean difference in the SRTs between the sessions. The random error was measured by calculating the within-subject standard deviation (SDω) and repeatability coefficient. In addition, the correlation coefficient (ICC) of the SRTs between the sessions for each test condition was carried out.

4.3.1.2 Concurrent validity

Another important aspect of the measurement precision of such a test is test validity. The fundamental concept of test validity is defined as how well the test measures what it purports to measure (Colliver *et al.*, 2012). The validity of a new test can be approached by comparing the new test with an existing well-established test. The process of comparing a new measurement to a previously validated or criterion measure is known as criterion validity (George *et al*., 2003). It is also referred to as concurrent validity as the participants are often tested by the new and reference test concurrently. The concurrent validity can be assessed through a range of statistical procedures. The most common procedure is the mean difference between the new and valid tests using significance tests (e.g. paired t-test and analysis of variance). However, George *et al*. (2003)

advised avoiding using this method as individual variability and similarity of scores could obscure the results. Another common procedure that has been used in the literature to assess the concurrent validity is the correlation between the new test scores and valid reference test scores. Correlation analysis indicates the degree of individual score consistency; however it could be misleading. As discussed previously in Section 4.3.1.1, a high correlation does not indicate the agreement between measurement scores. Therefore, the correlation should not be used solely when measuring the validity, and it was recommended to use a combination of different procedures. The LoA method (Bland and Altman, 1999), as discussed earlier, is an approach used to measure the validity by assessing the agreement between the scorers of the two tests. The LoA method provides a range of agreement 'validity-range' presented in the units of the dependent variable (SRT scores) (George *et al*., 2003). The assessment of the agreement between the two methods in terms of LoA involves a visual inspection of the variability of the differences between these two methods.

Clinical Controller of the AB-York Crescent of Sound, as described earlier in Section 4.2.2.1, facilitates administering a variety of spatial-listening tests. These tests were previously validated for use with patients (Lovett *et al*., 2010) and used in clinical practice. The speech-in-noise test has limited options to present the sentences and noise from the loudspeaker array. The sentences can only be presented from the front speaker placed at 0° while the noise can be presented from one of the loudspeakers placed at 0°, 15°, 30°, 60°, or 90° to the left or right. To measure the validity of the newly developed real-life speech-in-noise tests which were developed using the Research Interface, two further tests have been developed by the Research Interface: S0°N0° and S0°N-60°. These two tests are available in the Clinical Controller and are used in clinical practice. Therefore, the validity of the tests developed by the Research Interface can be assessed by comparing S0°N0° and S0°N-60° tests in the two interfaces.

4.3.1.3 Normal range (reference interval)

In addition to assessing the measurement precision of a test battery, it is important to know what the values of a particular measurement on normal, healthy individuals are likely to be. The normal range (also known as reference interval) for a measurement refers to the range between which 95% of values for a particular population fall into where 2.5% of the time will be higher than the upper limit of this range and 2.5% of the time it will be less than the lower limit of this range. This would help to view outcomes for a particular group of listeners against a background of mainstream performance. For this reason, preliminary normative data was collected for the new tests in the real-life test battery, i.e.

1. Speech-in-noise tests developed by the Research Interface

2. Tracking tests with six trajectories

3. Telephone test in quiet and in noise.

4.3.2 Aims

The first primary aim was to assess the measurement precision of the new tests developed, particularly the new speech-in-noise tests. To achieve this aim, two sub-aims were formulated:

1. To measure the test-retest reliability of the new speech-in-noise tests using significance tests (mean difference), within-subject standard deviation (SDω), repeatability coefficient, and correlation coefficient (ICC) of the SRTs between the sessions for each test condition
2. To measure the concurrent validity of the new speech-in-noise tests using significance tests (mean difference) and the LoA method.

A second primary aim was to obtain the normative data (reference interval) for the newly developed tests. Figure 4.5 illustrates the aims of the present study.

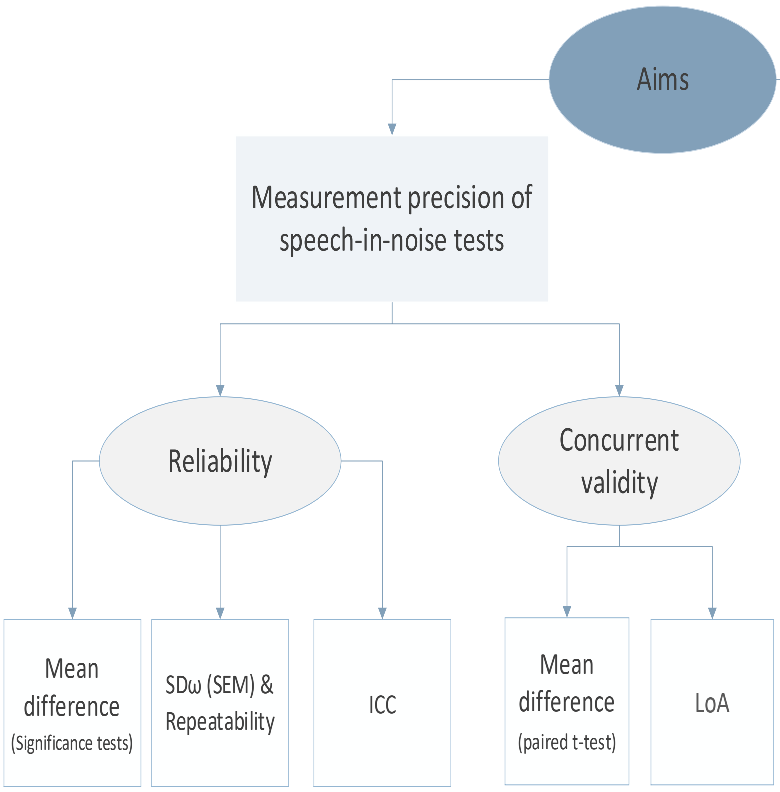

Figure 4.5: The block diagram illustrates the aims of the present study and the statistical tests that have been used to assess the measurement precision. ICC= intra-class correlation coefficient, LoA= Limits of agreements of the Bland & Altman method, SEM=standard error of measurement, SDω =within-subject standard deviation.

4.3.3 Method

4.3.3.1 Participants

45 NH adults were recruited from the student and staff population at the University of Southampton (24 females and 21 males). The inclusion criteria were: (1) native British English speaker, (2) aged 18 or over, (3) normal hearing, and (4) no reported history of ear problems. The exclusion criteria were: (1) having tinnitus and (2) having hyperacusis. They were invited to participate via email, standard publicity (wall posters) on campus, or word of mouth. Participants were all native speakers of British English and ranged in age from 18 to 44 years (mean age=24.4 years, SD=5.5 years). All the participants had normal hearing, defined as having a PTA threshold of ≤ 20 dB HL for the frequency range 0.25 – 8 kHz in both ears, and normal otology history (no tinnitus, hyperacusis or recent ear disease). Ethical approval was obtained for this study from the University of Southampton (ERGO ref: 46618.A1).

4.3.3.1.1 Sample-size calculation

There was no consensus on the required number of participants to get adequate stability for the reliability calculation (Weir, 2005). Therefore, an estimation of a sample size of 40-50 participants was made in order to assess the reliability and validity of the newly developed speech-in-noise tests and, secondly, to develop preliminary normative data for NH listeners.

To review the sample size used in this study, a sample-size calculation was carried out afterwards, and a power calculation was carried out using the G*Power 3 (Faul *et al.*, 2007). The mean and SD of the difference (systematic error) between the two sessions used in the power calculation were 0.5 and 1 dB respectively. The G*Power 3 using a 2-tailed test indicated that 34 participants were enough (45 were recruited) to detect a mean difference of 0.5 dB with a power of 0.8 and an alpha (i.e. type-I error rate) of 0.05. The sampling distribution of the estimate of SDω can be modelled as a chi-distribution with n degrees of freedom, where n is the number of participants. For n=45 (as in the present study), the 95% confidence interval for SDω is approximately +/- 0.21 time the true value of SDω (DeGroot, 1986). For example, if the true value of SDω is 1 dB, the 95% confidence interval for the estimate in SDω becomes 0.79 to 1.21 dB.

4.3.3.2 Procedure

The real-life test battery used in the current study included four test categories:

- First category: Speech-in-noise tests using the Research Interface
    1. S0°N0°
    2. S0°N-60°

3. SrN±60°
4. S0°N±60°
5. S+90°N-90° (the speech was presented at the right ear and the noise was at the left ear)

- Second category: Speech-in-noise tests using the Clinical Controller
    1. S0°N0°
    2. S0°N-60°
- Third category: Spatial-listening tests
    1. Localisation (30 degrees azimuth)
    2. Tracking moving sounds
- Fourth category: Telephone test
    1. In quiet
    2. In medium noise level (10 dB SNR)
    3. In high noise level (5 dB SNR)

The AB-York Crescent of Sound was used to administer all tests except for the telephone test which was administered with the set-up described in Section 4.2.2.5. All participants completed all testing required in two sessions held on separate days (one to two weeks apart). In the first session, all four categories of the test battery were administered. This session lasted about one hour, and participants were offered breaks as necessary. The order of test-battery categories and the tests within each category were counterbalanced across participants to reduce any possible order effect. The second session took approximately 20 to 30 minutes to repeat the measurements of the first category to assess the test-retest reliability of the newly developed speech-in-noise tests. The order of the tests was also counterbalanced across participants. Figure 4.6 shows the design and the test battery used in the present study.

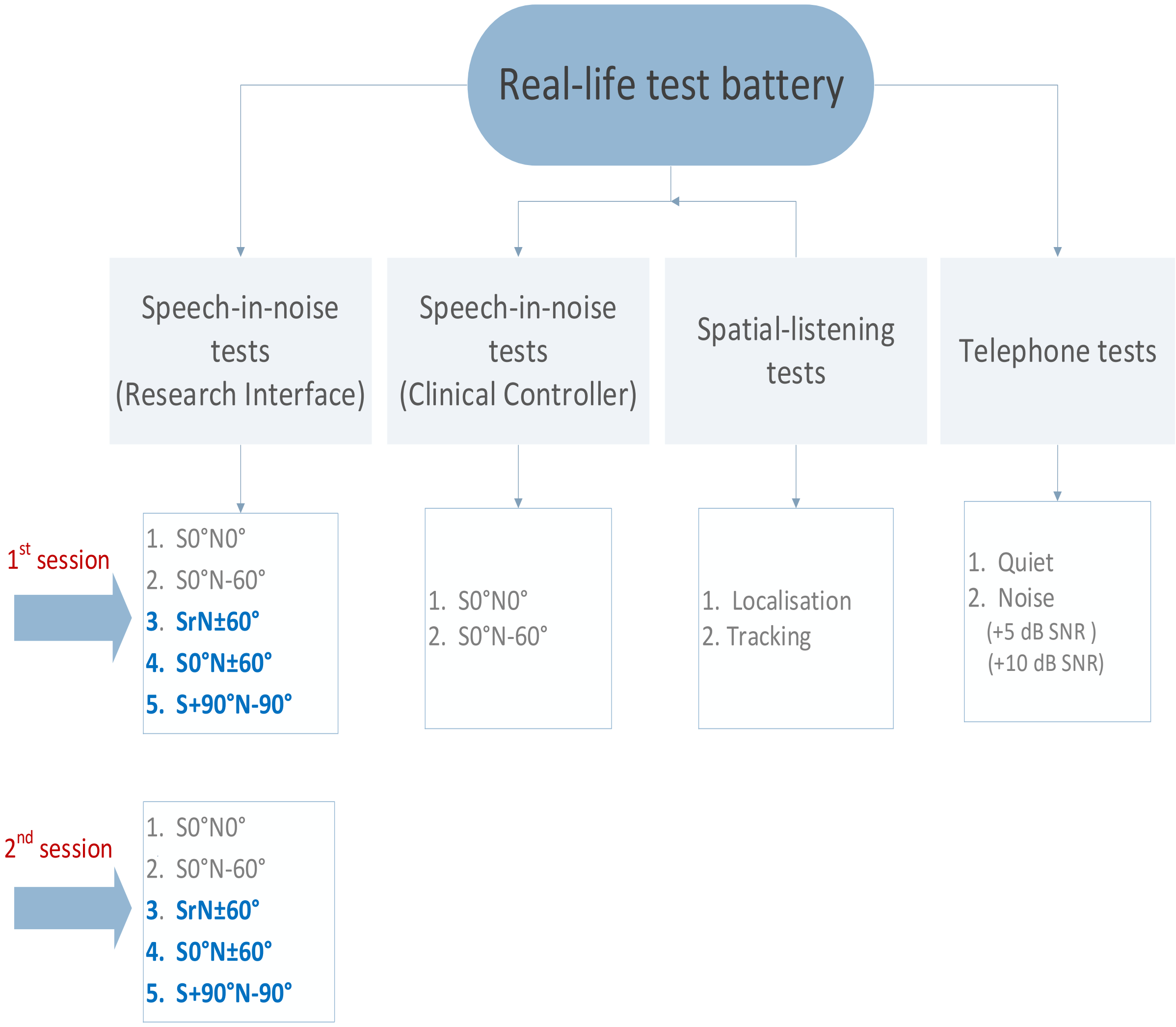

Figure 4.6: The block diagram illustrates the administration of the four test categories of the real-life test battery for adult NH participants. The newly developed speech-in-noise tests are highlighted in blue font.

The participant information sheet was sent to the participants via email at least 24 hours before the first session. At the beginning of the first session, the participants were asked to complete a short hearing-health screening questionnaire to ensure that they met the inclusion criteria (Appendix J). Participants were seated individually in the centre of the Crescent of Sound loudspeaker array one metre away from and facing the frontal loudspeaker, placed at 0 degrees azimuth. Table 4.8 provides an overview of the main procedure and key points of the instructions for each test. The detailed set-up and procedure for each test are described in Section 4.2.2.

Table 4.8: A summary of the main procedure and instructions for NH participants.

Test	Task instruction	Head movement	Practice	Response
Speech in noise (S0°N0°)	You are going to hear a man saying random sentences from the front loudspeaker with a background-noise masker	Fixed facing the front loudspeaker	No	Ignore the background noise and repeat any words you hear
Speech in noise (S0°N-60°)	You are going to hear a man saying random sentences from the front loudspeaker and a background-noise masker coming from the left-hand side	Fixed facing the front loudspeaker	No	Ignore the background noise and repeat any words you hear
Speech in noise (SrN±60°)	You are going to hear a man saying random sentences from one of these loudspeakers in front of you with a background-noise masker coming from both sides	Allowed	No	Ignore the background noise and repeat any words you hear
(Speech in noise) S0°N±60°	You are going to hear a man saying random sentences from the front loudspeaker and background-noise masker coming from both sides	Fixed facing the front loudspeaker	No	Ignore the background noise and repeat any words you hear
(Speech in noise) S+90°N-90°	You are going to hear a man saying random sentences from the loudspeaker placed on the right-hand side and a background-noise masker coming from the left-hand side	Fixed facing the front loudspeaker	No	Ignore the background noise and repeat any words you hear

Localisation	You are going to hear a sentence of “Hello, what is this?” coming from one of these five loudspeakers in front of you	Fixed facing the front loudspeaker	No	Indicate the number of the loudspeaker from which the voice was presented
Tracking	You are going to hear a moving sound. It may move from the right to the left, the left to the right, the right to the centre and back to the right, the left to the centre and back to the right or it may start at the centre and go to the right- or left-hand side and then back to the centre again	Allowed	No	Say or use your finger to show the direction in which you think the sound is moving
Telephone test	I will be sitting in the observation room, and I am going to call you on this mobile phone. When you answer the phone, let me know when are ready. You will hear then a list of digit sequences. Each sequence consists of three digits. Please repeat the digits you hear	Fixed facing the front loudspeaker	Yes	Repeat the digits you hear

4.3.3.3 Analysis

Statistics were computed using IBM SPSS Analysis Software (version 26), GraphPad Prism (version 9) and Excel Microsoft Office 2016. Before computing the statistics, the normality distribution of the data was assessed using the Shapiro-Wilk test.

Test-retest reliability of the newly developed speech-in-noise tests was assessed by measuring the systematic and random errors. In systematic bias, a two-way repeated-measures ANOVA and paired sample t-test were conducted for the SRTs between the sessions. The random error was measured by calculating the SDω and repeatability coefficient in addition to the ICC of the SRTs between the sessions for each test condition. Prior to conducting reliability measurement, it is important to ensure that the variance of the dependent variable is equal across different values of the independent variables. If this is not the case, using significance statistic tests will be inaccurate (Field, 2013). This is because the heteroscedasticity produces a bias and inconsistency in the standard error estimates used to compute parameter estimates such as confidence intervals and significance tests (Field, 2013). Therefore, Levene’s test was conducted to investigate the homogeneity of variance across the samples between sessions.

The concurrent validity of the newly developed speech-in-noise test has been assessed by measuring the mean difference in the SRT (paired sample t-test) and LoA between:

1. S0°N0° test on Research Interface and S0°N0° test on Clinical Controller
2. S0°N-60 test on Research Interface and S0°N-60 test on Clinical Controller

Finally, the reference interval (normal range and 95% confidence interval) for each measurement in the test battery was calculated in an Excel spreadsheet. It should be noted that localisation, tracking and telephone-in-quiet tests were administered only for 17 participants. The administration of these tests was stopped as all 17 participants’ scores reached a ceiling (100%) in these three tests. In addition, the availability of the Crescent of Sound room was limited to the researcher as the room is one of the USAIS rooms used with CI patients. Therefore, the decision was taken to effectively use the room availability and test more participants for the reliability measurements of newly developed speech-in-noise tests. Thus, the results for localisation, tracking and telephone-in-quiet tests represent the scores of the first 17 participants.

4.3.4 Results

4.3.4.1 Test-retest reliability

Most of the data sets were normally distributed except for three data sets. There is no consistent pattern that would indicate that test conditions or repeat would produce non-normality distributed data. A visual inspection of the box plots for these data sets showed no great difference in data distribution for these data sets compared to the other data sets. Therefore, it was decided to treat all the data sets as normally distributed. Levene’s test was conducted to investigate the homogeneity of variance across the samples between the two sessions. The dependent variable's (SRT) variances were homogeneous across all sessions.

4.3.4.1.1 Mean difference in SRTs between sessions

Systematic error of the SRT scores between the sessions was explored and analysed by comparing the means of each session and calculating the difference. Figure 4.7 shows the SRTs of the five speech-in-noise tests administered by the Research Interface in the two sessions.

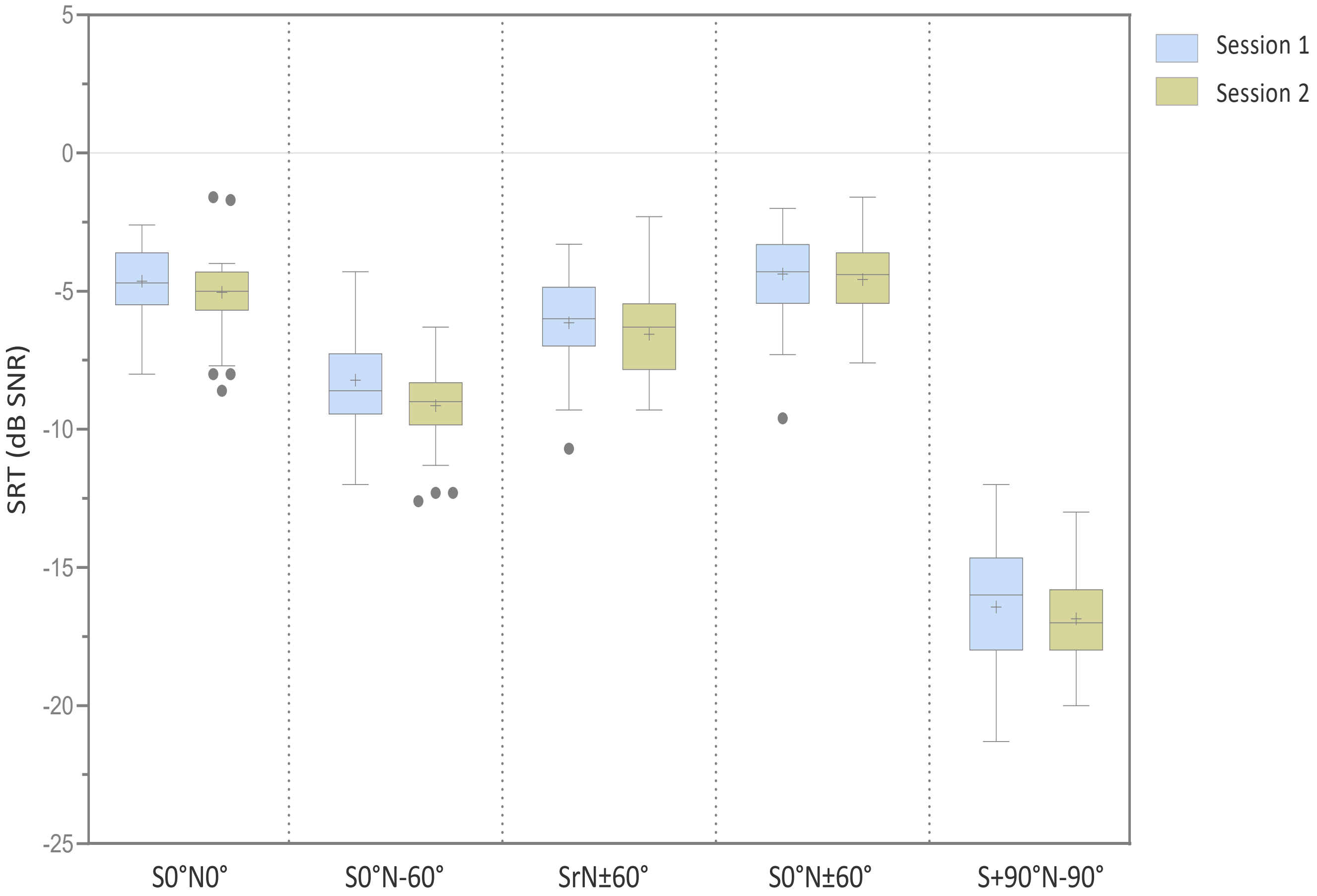

Figure 4.7: Box plots representing the SRTs in dB SNR for the five tests administered by the Research Interface: (1) S0°N0°, (2) S0°N-60°, (3) SrN±60°, (4) S0°N±60°, and (5) S+90°N-90°. The blue box plots show the SRTs in the first session, and the green box plots show the SRTs in the second session. The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The outliers are plotted as solid circles.

The mean difference ($\bar{d}$) between the sessions, the SD and the 95% confidence interval of the $\bar{d}$ for each test have been calculated and reported in Table 4.9. The 95% confidence interval of ($\bar{d}$) has been calculated by using the following equation (Field, 2013), where the SE is standard error of ($\bar{d}$)

Equation 4.1: $\bar{d} \pm (t_{n-1} \times SE)$

The mean differences between sessions were less than 1 dB for all the tests. All tests show an improvement in SRT scores from the first session to the second session. The p values (obtained from a paired sample t-test) for the difference between the two sessions for each test were also reported in Table 4.9.

Table 4.9: Mean SRTs for each test in the first and second sessions and averaged across sessions. Also, the mean difference between the two sessions with SD, 95% confidence and p values of the mean difference for each test are shown. The significant difference is highlighted in bold font.

Tests	**Mean Session 1** (dB SNR)	**Mean Session 2** (dB SNR)	**Averaged SRTs of the sessions** (dB SNR)	**Difference means** **($\bar{d}$)** (dB)	**SD of ($\bar{d}$)** (dB)	**SE of ($\bar{d}$) =** (SD of $\bar{d}$/ $\sqrt{n}$)	**95%CI of ($\bar{d}$)=** $\bar{d} \pm (t_{n-1} \times SE)$ $\bar{d} \pm (2.02 \times SE)$	***p* for $\bar{d}$**
S0°N0°	-4.6	-5	-4.8	0.4	0.98	0.1	0.1 to 0.7	**0.009**
S0°N-60°	-8.2	-9.1	-8.65	0.9	1.7	0.2	0.4 to 1.4	**<.001**
SrN±60°	-6.1	-6.6	-6.35	0.4	1.8	0.3	-0.1 to 0.97	0.1
S0°N±60°	-4.4	-4.6	-4.5	0.2	1.5	0.2	-0.3 to 0.6	0.4
S+90°N-90	-16.4	-16.8	-16.6	0.4	2	0.3	- 0.2 to 1	0.2
Overall	-7.9	-8.4		0.5				**< .001**

It was expected that there were differences between the five speech tests as a result of release from masking effect in the speech tests where target speech and masker noise were spatially separated. In addition, it would be useful to examine whether the difference between the sessions was the same or different between the five speech tests. Therefore, a two-way repeated-measures ANOVA to test condition and session as the independent variables was conducted. Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for the test condition $\chi2(2) = 21.8$, $p = .010$ and for the two-way interaction, $\chi2(2) = 19.4$, $p = .021$.Therefore, two-way repeated-measures ANOVA with Greenhouse-Geisser correction were used to find the main effect of the test condition and the main effect of the interaction on the SRT. The main findings were as follows:

- The main effect of the session was statistically significant, indicating that the average across all test condition SRT scores were significantly better in the second session than in the first session, p< .001. However, the difference was small, about 0.5 dB (95% confidence interval, 0.2 to 0.7)
- The main effect of the test condition was statistically significant, indicating that average SRT scores across the two sessions were significantly different between each condition. Post hoc tests revealed significant differences in the mean SRT scores (averaged across sessions) between each condition except between the test condition S0°N0° (M= -4.8 dB SNR, SD=1.2) and S0°N±60° (M=-4.5 dB SNR, SD=1.3) where the difference was not statistically significant different; mean difference= 0.4 dB (95% confidence interval from 0.2 to 0.9), p=0.7
- The session* test condition interaction was not statistically significant.

Briefly, the two-way repeated-measures ANOVA showed a statistically significant difference in the average SRTs (averaged across tests) between the two sessions, but the difference between the two sessions was not statistically different between test conditions. Table 4.10 summarises the results of the two-way (test conditions and sessions) repeated measures ANOVA.

Table 4.10: Two-way (test conditions and sessions) repeated measures ANOVA results.

Independent variables	Main effect	Interaction
Test condition (5 levels)	F (3.1,136.3) = 861.3**, p<.001**	Test * session = F (3.2,142.6) = 1.3, p= .29
Session (2 levels)	F (1,44) = 15.6, **p<.001**	

4.3.4.1.2 Variability and repeatability

Variability is also known as the standard error of measurement (SEM), which measures the variation between repeated measurements of the same quantity on the same subject. It is caused by random error and provides an index of the expected noise in the repeated measures' data and determines the precision of individual scores on such measurements (Weir, 2005). SEM is largely independent of the sample population; therefore it is not affected by between-subject variability (Weir, 2005). SEM is calculated as the within-subject standard deviation (SDω). There are different methods to calculate SDω. One method to calculate SDω is by using the following equation:

Equation 4.2: $$\text{SD}\omega = \sqrt{\left(\sum_i^n d_i^2\right)/2n}$$

where $\boldsymbol{d_i}$= the difference between the 1st and 2nd measurement for the i^{th} participant and $\boldsymbol{n}$ is the number of the participants (Bland and Altman, 1996a, Lovett *et al.*, 2013). If the measurement is repeated twice, the SEM can also be measured by calculating the SD of the difference of the two trails and then dividing it with the square root of 2 (Weir, 2005) as:

Equation 4.3: $$\text{SD}\omega = \frac{SD_d}{\sqrt{2}}$$

It should be noted that, the assumptions of equations 4.2 and 4.3 are different. The assumption of equation 4.2 is based on the mean squared difference which reflects the total error (both systematic and random) whereas the assumption of equation 4.3 is based on random error only, ignoring the systematic error. Table 4.11 reports the SDω values for each speech test. SDω has been used to define the boundaries around which the participant's true score might exist by reporting the 95% confidence interval for the participant's true score (Weir, 2005). A single score from any random participant is expected to lie within ± 1.96 × SDω with a probability of ≥0.95 (Bland, 2015). This means that for any random participant, the score will lie within (± 1.96 × SDω) the true subject score. Table 4.11 also reports the 95% confidence interval of the participant's true score.

The SDω can be used to define the minimum difference between two repeated measurements to be considered a real difference and is known as the repeatability coefficient (Weir, 2005, Lovett *et al.*, 2013) by using the following equation:

Equation 4.4: $$\text{Repeatability coefficient} = \sqrt{2} \times 1.96 \times SD\omega$$

The repeatability coefficient indicates that 95% of the population would reflect a real difference if their difference scores between the repeated measurements were greater than or equal to the repeatability coefficient. If the participant is tested twice under identical conditions, the difference between the two measurements is expected to be less than the repeatability value ($\sqrt{2} \times 1.96\ SD\omega$) for 95% of pairs of observations. When the difference is greater than or equal to the repeatability, that indicates that the difference between scores is statistically significant (p<.05) and is unlikely to have occurred by chance (Lovett *et al.*, 2013). The measure is useful in clinical practice, particularly when an individual is tested twice in different listening situations (e.g. using CI alone and with a bimodal technology). The repeatability coefficients for each test are reported in Table 4.11.

Table 4.11: Within-subject standard deviation (SDω) and repeatability coefficients for each speech-in-noise test. The 95% confidence interval for the participants' true scores are also reported.

Test	**SDω (dB)**		**Repeatability (dB)** $\sqrt{2} \times 1.96 \times SD\omega$	**95% confidence interval of true score** (± 1.96 × SDω)
	$= \sqrt{(\sum_i^n d_i^2)/2n}$	$= \frac{SD_d}{\sqrt{2}}$		
S0°N0°	0.7	0.7	2.1	± 1.4
S0°N-60°	1.3	1.2	3.7	± 2.5
SrN±60°	1.3	1.3	3.6	± 2.5
S0°N±60°	1.1	1.1	2.9	± 2
S+90°N-90	1.5	1.4	4	± 2.9

4.3.4.1.3 Intra-class correlation coefficient (ICC)

ICC was measured using SPSS through a two-way mixed-effect model with absolute agreement. The selection of the type of ICC was based on the guidance provided by Koo and Li (2016). Table 4.12 illustrates the ICC values with a 95% confidence interval for each test. The tests have shown good to excellent reliability based on the ICC values.

Table 4.12: ICC values (95% confidence interval of ICC) and p values for each speech-in-noise test.

	ICC (95% confidence interval)	*P*
S0°N0°	0.8 (0.6 to 0.9)	<.001
S0°N-60°	0.6 (0.2 to 0.8)	<.001
SrN±60°	0.6 (0.2 to 0.8)	0.003
S0°N±60°	0.7 (0.4 to 0.8)	<.001
S+90°N-90°	0.7 (0.4 to 0.8)	<.001

4.3.4.2 Concurrent validity

The concurrent validity of the newly developed speech-in-noise tests administered by the Research Interface was assessed by measuring the following:

1- Mean difference in SRTs
2- LoA method

It was between S0°N0° test on Research Interface and S0°N0° test on Clinical Controller, and S0°N-60 test on Research Interface and S0°N-60 test on Clinical Controller.

4.3.4.2.1 Mean difference in SRTs between Research Interface and Clinical Controller

The mean SRTs for both tests on the Research Interface and the Clinical Controller, and the mean difference between them for each test are illustrated in Table 4.13. The two tests presented by the Research Interface were administered twice into separate sessions, while the Clinical Controller's two tests were only administered in the first session. To avoid any bias that might affect the interpretation of concurrent validity results, the comparison was carried out between the Research Interface tests conducted only in the first session and the Clinical Controller tests. Data sets were normally distributed as assessed by the Shapiro-Wilk test. A paired samples t-test was conducted to investigate whether there is a significant difference between tests presented by the Research Interface and those presented by the Clinical Controller. There was no statistically significant difference between the SRTs on the Research Interface and the Clinical

Controller for both tests S0°N0° and S0°N-60° which indicates the similarities of the scores of each test between the Research Interface and the Clinical Controller.

Table 4.13: Mean SRT for S0°N0° and S0°N-60° tests on Research Interface and on the Clinical Controller. Also, the mean difference (95% confidence of the mean difference) and p values between the Research Interface and on the Clinical Controller for each test.

	Research Interface (1st session) (dB SNR)	**Clinical Controller (dB SNR)**	**Difference in dB (95% confidence interval)**	***P***
S0°N0°	-4.6	-4.7	0.1 (-0.3 to 0.5)	t (44) =0.4, p=0.7
S0°N-60°	-8.2	- 8.3	0.1 (- 0.4 to 0.6)	t (44) =0.4, p=0.7

4.3.4.2.2 Limits of Agreement

Bland and Altman plotted an approach that was used to assess the agreement between two methods (Bland and Altman, 1999). If the new measurement showed a good agreement with the other measurement, that would suggest a good validity. Therefore, the LoA method was used to investigate the concurrent validity of the new tests developed by the Research Interface.

Figure 4.8 shows Bland and Altman's plots to determine the difference between the SRTs on the Research Interface and the SRTs on the Clinical Controller for both S0°N0° and S0°N-60° tests. The mean SRTs of the two interfaces (Research interface and Clinical Controller) are plotted along the horizontal axis. The difference between the SRTs on the two interfaces is plotted along the vertical axis. The LoA of the mean difference and the 95% confidence intervals of the mean difference and the LoA were calculated (Table 4.14). The plots show there was no significant systematic difference between the SRTs on the Research Interface and the SRTs on the Clinical Controller for S0°N0° and S0°N-60° tests as the line of equality (dotted line) is within the confidence interval of the mean difference. Therefore, there was an agreement between the SRTs on both interfaces (Research Interface and Clinical Controller) for both tests.

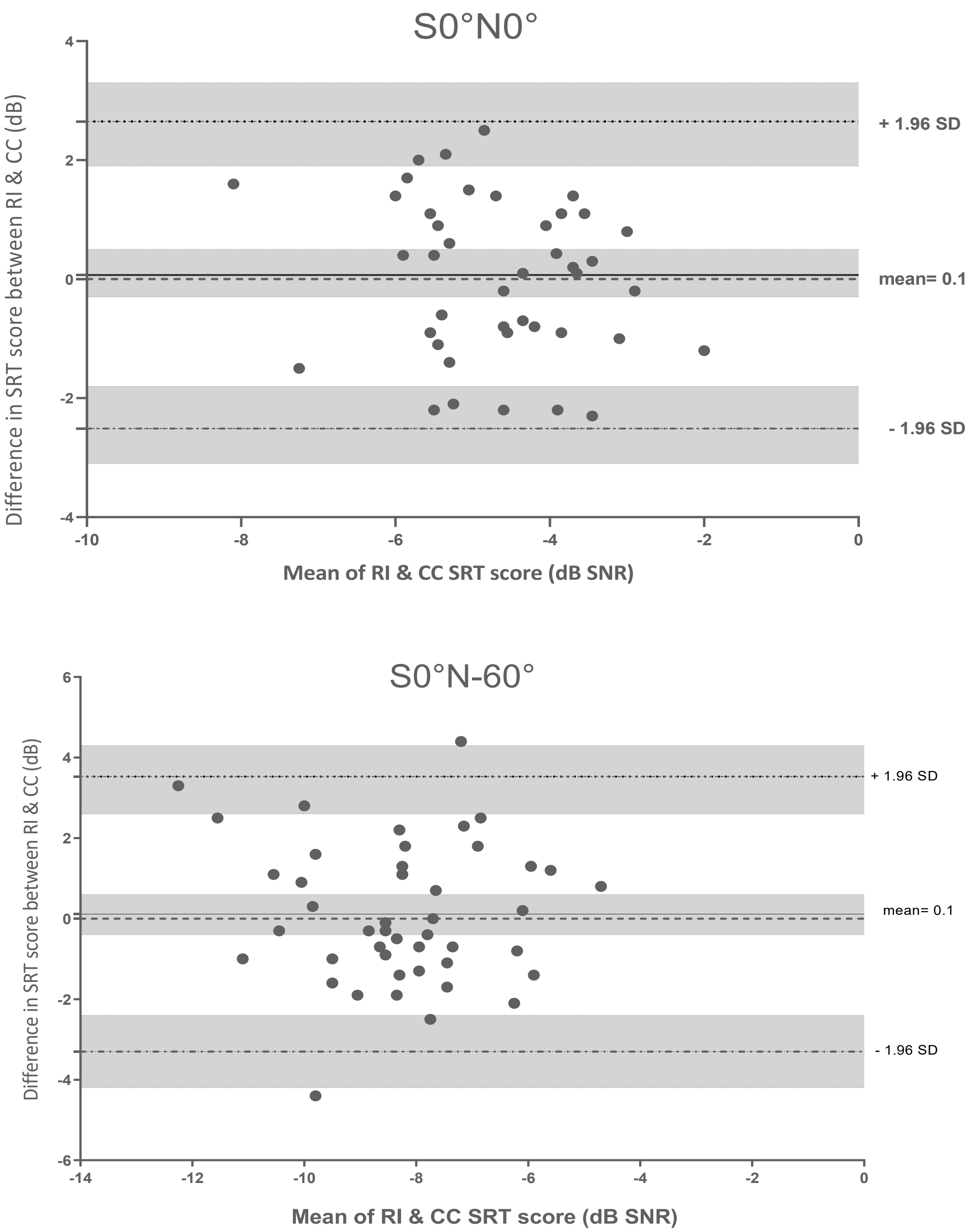

Figure 4.8: Bland and Altman plots for the difference in SRTs between the Research Interface (RI) and the Clinical Controller (CC) for S0°N0° (upper panel) and S0°N-60° (lower panel). The solid horizontal line indicates the mean difference between the RI and CC; the dashed horizontal line shows the limits of agreement (calculated as mean difference ± 1.96×SD). The grey shaded area shows the 95% confidence interval for the mean difference and the upper and lower limits of agreement.

Table 4.14: LoA and their 95% confidence interval for S0°N0° and S0°N-60° tests administered by the Research Interface and Clinical Controller.

Test	$\overline{d}$ (95% confidence interval)	SD of ($\overline{d}$)	SE of ($\overline{d}$) $\sqrt{\frac{SD^2}{n}}$	LoA ($\overline{d}$ ± 1.96×SD)	SE of LoA $\sqrt{3 \times SD^2/n}$	95% confidence interval of LoA
S0°N0°	0.1 (-0.3 to 0.5)	1.3	0.2	-2.5 to 2.6	0.3	• 95 % CI of lower limit: (-2.5 ±1.96×SE) = -3.2 to -1.8 • 95 % CI of upper limit:(2.6 ± 1.96×SE) = 1.9 to 3.3
S0°N-60°	0.1 (-0.4 to 0.6)	1.7	0.01	-3.3 to 3.5	0.03	• 95 % CI of lower limit: (-3.3±1.96×SE) = -4.2 to -2.4 • 95 % CI of upper limit:(3.5 ± 1.96×SE) = 2.6 to 4.4

$\overline{d}$= mean difference, **SD**= standard deviation, **SE**= standard error, **LoA**= limits of agreement.

To summarise, the results from the two statistical approaches used to investigate the concurrent validity of the new speech-in-noise tests were compatible with each other's which indicates that the S0°N0° and S0°N-60° tests developed by the Research Interface have good concurrent validity. Therefore, the other three new real-life tests developed by the Research Interface (SrN±60°, S0°N±60, and S+90°N-90°) would be assumed to have a similar level of validity.

4.3.4.3 Reference interval for real-life test battery:

Table 4.15 illustrates the reference interval and the 95% confidence limits for the newly developed tests in the real-life test battery. The Reference Interval was calculated using the following equation (Bland, 2015, p 330):

Equation 4.5 = mean ± 2 SD

To calculate the 95% confidence interval, the standard error (SE) of the limit of the reference interval was measured by the following equation (Bland, 2015, p 330):

Equation 4.6 = $\sqrt{SD^2\left(\frac{1}{n}+\frac{2}{n-1}\right)}$

Then the 95% CI of the reference interval was calculated as:

Equation 4.7 = (lower limit of the reference interval ± 1.95 × SE) to the (upper limit of the reference interval ± 1.95 × SE)

As the speech tests were administered in two sessions, the mean and SD (across the group) were calculated based on the averaged SRTs across the two sessions.

Table 4.15: Reference interval and the 95% confidence limits of the reference interval for the newly developed tests in the real-life test battery.

Test	Reference interval	SE	95% confidence interval of the lower limit	95% confidence interval of the upper limit
S0°N0° * (dB SNR)	-7.2 to -2.5	0.3	-7.8 to -6.6	-3.1 to -1.8
S0°N-60° * (dB SNR)	-11.6 to -5.8	0.4	-12.3 to -10.8	-6.5 to -5
SrN±60° * (dB SNR)	-9.2 to-3.5	0.4	-9.9 to -8.4	-4.3 to -2.8
S0°N±60° * (dB SNR)	-7.1 to -1.9	0.3	-7.8 to -6.4	-2.5 to - 1.2
S+90°N-90° * (dB SNR)	-20.2 to -13	0.5	-21.2 to -19.3	-14 to -12.1
Tracking (%)	100 -100	0	100	100
Telephone in quiet (%)	100- 100	0	100	100
Telephone in noise at +10 dB SNR (%)	96.1 to 100	0.4	95.2 to 96.9	100
Telephone in noise at +5 dB SNR (%)	91.5 to 100	0.9	89.8 to 93.3	100

*Reference interval has been calculated for average sessions of speech-in-noise tests.

4.3.5 Discussion

The present study aimed to assess the measurement precision of the newly developed tests included in the real-life test battery. The study also aimed to establish preliminary normative data (reference interval) for the newly developed tests. Therefore, NH participants were tested with the real-life test battery. The measurement precision has been assessed by measuring test-retest reliability and concurrent validity of the newly developed speech-in-noise tests.

The Research Interface in the AB-York Crescent of Sound was used to develop and administer the three newly developed speech-in-noise tests (SrN±60°, S0°N±60, and S+90°N-90°). Each newly developed test simulated a common listening situation in everyday environments. In addition, coding was written to present two further speech tests (S0°N0° and S0°N-60°) via the Research Interface. These two tests are considered typical tests commonly used in clinic and research settings. Moreover, the two tests (S0°N0° and S0°N-60°) tests were previously validated for use with patients (Lovett *et al*., 2010) and can be administered by the Clinical Controller in the AB Crescent of Sound. The purpose of developing coding for presenting these two tests by the Research Interface was to measure the concurrent validity of all tests developed by the Research Interface. This was done by comparing the scores of the participants for S0°N0° and S0°N-60° tests on the Research Interface and Clinical Controller.

4.3.5.1 Mean SRT of newly developed speech-in-noise tests

The results showed that there was a statistically significant difference in the mean SRTs among the five speech-in-noise tests that were presented by the Research Interface except between the S0°N0° and S0°N±60° tests. This is an important finding which suggests that the standard speech-in-noise test used in the clinic (speech and noise are presented from one loudspeaker placed at 0° azimuth) cannot reflect common listening situations, particularly when the speech was not fixed (such as in a group conversation) or when the speech was on one side, and the noise was on the opposite side (such as sitting in a car). This finding also indicates that the standard set-up might reflect the listening situation of fixed speech from the front in diffuse noise coming from both sides (such as with one-to-one where the conversation is in a noisy place) as there was no significant difference between these two tests. In other words, using fixed speech presented from the front in diffuse noise presented from both sides would give a similar effect as the speech and noise are presented concurrently from the front.

In addition, this finding showed that the SRTs of the five speech-in-noise tests administered by the Research Interface was improved as the speech and noise were spatially separated, such as in S0°N-60°, SrN±60°, and S+90°N-90° tests compared to S0°N0° and S0°N±60 tests. This improvement in the SRTs indicates the presence of spatial release from the masking effect that can be obtained when the noise and speech are spatially separated. The values of spatial release from masking, reported in the literature, typically range from 2 to 30 dB depending on test set-ups (Hawley *et al*., 1999, Marrone *et al.*, 2008, Litovsky, 2012). The spatial release from masking found in the current study ranged from 1.5 to 11.8 dB, which increased as the azimuth of separation increased. The largest improvement of 11.8 dB was found when speech and noise were presented at symmetrical opposite sides at 90°. This finding is in line with Marrone *et al.*

(2008) and Culling *et al*. (2012). A considerable amount of spatial release from masking was found, exceeding 12 dB, for larger separation between the target speech and noise (Marrone *et al.*, 2008). Similarly, Culling *et al*. (2012) found the largest spatial release from masking when the speech and noise were presented at symmetrically opposite sides at ± 60° compared to when the speech was presented at 0° and the noise at either +/- 90° for NH listeners. Moreover, the largest improvement in the SRT with the S+90°N-90° test indicates the advantage of the head-shadow effect where the SNR is increased in one ear due to noise attenuation from the head of the listeners (Litovsky, 2012).

These findings suggest that the newly developed speech-in-noise tests, particularly SrN±60° and S+90°N-90° tests, can provide additional information about the listener's performance in similar situations in real life that could not be obtained from the standard test (S0°N0°). Moreover, the spatial release from masking found in the two newly SrN±60° and S+90°N-90° tests indicate that these two tests are valid.

4.3.5.2 Reliability and validity of newly developed speech-in-noise tests

Test-retest reliability of the five speech-in-noise tests developed and administered by the Research Interface has been examined using different statistical approaches. There was a statistically significant difference between the average (across the five tests) SRTs for the first and second sessions. The performance, on average, was better in the second session than the first session by 0.5 dB. When looking at each test separately, the largest (0.9 dB) and smallest (0.2 dB) improvement in SRTs were for S0°N-60° and S0°N±60° respectively. There was no statistically significant difference between the SRTs in the two sessions for the three newly developed speech-in-noise tests (SrN±60°, S0°N±60, and S+90°N-90°). However, a significant difference between the SRTs in the two sessions was found for S0°N0° and S0°N-60° tests.

The statistically significant difference between the two sessions for the average speech tests and S0°N0° and S0°N-60° tests indicates there was a significant systematic difference. Since there was an improvement in the SRT scores for the second session, it could be excluding the fatigue effect as the two measurements were taken in two separate sessions with a minimum one-week interval and the time taken to administer all five speech tests was short (about 20-30 minutes). However, it is worth noting that the first session was longer than the second session because all four test categories (speech tests in Research Interface, speech tests in Clinical Controller, spatial-listening tests, and telephone tests) were administered in counterbalanced order in the first session whereas only speech tests in the Research Interface were administered in the second session. Thus, a possible fatigue effect may not be excluded. In addition, any change in hearing or physiological abilities which might cause variations were also excluded as when the participants returned for the second session, they were asked if they felt their hearing ability was changed since their first session.

Another possible reason for improving the scores in the second session is the learning effect. Learning effects are common in repeated measurements. For example, Boyle *et al*. (2013), Lovett *et al*. (2013) and Smits *et a*l. (2013) found a significant difference between the SRTs for the repeated measurements. Although the second session took place at least one week apart from the first session (two weeks on average) with randomisation of the order of the speech test conditions, learning effects may not be excluded. Yund and Woods (2010) argued that an improvement of SRT score could occur due to content learning. Even the sentence material is repeated at intervals of several months (3 to 6 months) after the original exposure. They found significant threshold improvements of 0.5 dB and 0.4 dB SNR for the HINT and the QuickSIN tests respectively. Nevertheless, the differences between sessions found in their study and the present study were considerably small (less than 1 dB), which might not be clinically important.

A significant difference between two measurements when the test is administered in two different listening conditions would be considered significant when the difference is greater than or equal to the repeatability coefficient (see Table 4.11). Smaller values of the variability and repeatability coefficient indicate better reliability (Lovett *et al*., 2013). However, no standard range defines what a small variability value is. Therefore, it would be helpful to compare the variability of these new speech tests with those of other speech-in-noise tests reported in the literature. Table 4.16 summarises the SDω of speech-in-noise tests reported in the literature for adult listeners with normal hearing. The smallest value for sentences for the test material was 0.4 dB (Hagerman, 1982), whereas the largest SDω was 2.1, reported in an unpublished PhD study (Semeraro, 2015). The SDω values of the newly developed speech-in-noise tests in the current study were comparable to those reported in the literature. The smallest SDω was 0.7 dB for the S0°N0° test, which is close to the values reported in (Plomp and Mimpen, 1979, Hagerman, 1982, Jansen *et al.*, 2012, Kaandorp *et al.*, 2015). The largest SDω found in the current study was 1.4 dB for the S+90°N-90° test, which also was close to those found in (Macleod and Summerfield, 1990, Nilsson et al., 1994, Summerfield et al., 1994, Jansen et al., 2012, Alkahtani, 2020). Therefore, the new speech-in-noise tests developed in this study have shown a good level of reliability as their variability values were comparable to variability values of other tests reported in the literature, particularly those that have been used extensively in clinical practice, such as the speech-in-noise test developed by Plomp and Mimpen (1979), IHR-McCormick automated toy discrimination test (Summerfield *et al.*, 1994) and Dutch TDT (Smits *et al.*, 2004).

Table 4.16: A summary of the variability values (SDω) of different speech-in -noise tests reported in the literature for NH adult listeners.

Study	N	Presentation	Language	Material	Variability (dB)
(Plomp and Mimpen, 1979)	10	Headphones	Dutch	Sentences	0.9
(Hagerman, 1982)	20	Headphones	Swedish	Sentences	0.4
(Macleod and Summerfield, 1990)	10	Loudspeakers	British English	Sentences	1.2
(Nilsson et al., 1994)	17	Headphones	American English	Sentences	1.1
(Summerfield *et al.*, 1994)	8	Headphones	British English	Sentences (6 reversals)	1.3
(Jansen *et al.*, 2012)	31	Headphones	French	Digits Sentences	0.4 1.2
(Smits *et al.*, 2004, Smits *et al.*, 2013)	10	Headphones	Dutch	Digits	0.7
(Boyle *et al.*, 2013)	25	Loudspeaker	British English	Sentences	0.9
(Kaandorp *et al.*, 2015)	12	Loudspeakers	Dutch	Digits Sentences	0.7 0.6
(Semeraro, 2015)	30	Headphones	British English	Sentences (CRM) Digits	1.9 to 2.1 2.6
(Alkahtani, 2020)	30	Headphones	Arabic	Sentences	1.6

The concurrent validity of the newly developed test has also been reviewed as a part of assessing the measurement precision of the newly developed tests. The scores of S0°N0° and S0°N-60° tests in the Research Interface were compared to scores when the Clinical Controller had administered these two tests. As mentioned earlier, tests available in the Clinical Controller, including these two tests, were previously validated for use with patients (Lovett *et al.*, 2010) and used in clinical practice. The results of the present study showed the measured SRTs on both interfaces not only displayed a significant good correlation (r= 0.5 and 0.6 for S0°N0° and S0°N-60° respectively), but the SRT scores for both tests were also similar across both interfaces. Based on this, it can be assumed that the three newly developed speech-in-noise tests (SrN±60°, S0°N±60, and S+90°N-90°) would have good concurrent validity.

To summarise, it can be concluded that the findings from the current study indicate that the newly developed speech-in-noise tests, particularly the SrN±60° and S+90°N-90° tests, demonstrate an acceptable measurement precision to justify its use to assess real-life speech perception in noise. This conclusion is based on three important findings in the current study as follows:

1. The newly developed speech-in-noise tests provided a piece of valuable additional information as the SRTs were significantly different across different tests
2. The newly developed speech-in-noise tests showed a good reliability level
3. The validity of the newly developed speech-in-noise tests can be assumed based on the good concurrent validity found between the tests presented by the Research Interface and those presented by the Clinical Controller. In addition, the presence of larger spatial release from masking in the new tests with larger separation between the target speech and noise is more evidence of the validity of the newly developed test.

Therefore, the implementation of the newly developed speech-in-noise tests in clinical practice could be considered particularly for adult CI users. This would help to better understand their performance in real-life listening environments and provide the most suitable device settings and rehabilitative strategies.

4.3.5.3 Evaluation of the real-life test battery and study recommendations

A real-life test battery was developed to assess the performance of adult CI users with a variety of tests that would provide more information about their hearing functions in real-life situations. New tests that simulate real-life situations (speech-in-noise, localisation, tracking and telephone tests) have been included. In addition, self-rated scales (SSQ and Telephone- Use questionnaires) were included in the test battery.

After developing the test battery, the next step was assessing the measurement precision of the newly developed tests before using the test battery with NH adults. The results show that the new speech-in-noise tests were reliable and valid. For the telephone test, the measurement precision was not assessed in the present study for several reasons. The telephone test developed is considered a rudimentary test and the purpose is to investigate the test's applicability and obtain an initial overview. In addition, the test has several limitations (as discussed in Section 4.2.2.5.5), requiring further work. The measurement precision of other tests included in the battery (localisation, tracking moving sounds, and SSQ questionnaire) were also not assessed because they are well-established and validated tests.

Another aspect considered in the evaluation of the test battery was practicality. The total duration required to administer all the tests included in the test battery for NH participants was roughly 45 minutes to a maximum of one hour. Administering the speech-in-noise tests via the Research Interface in the second session took approximately 20 to 30 minutes (five minutes for each test on average). In addition, all tests, except the telephone test, were feasible and easily administered by using the Crescent of Sound apparatus. The localisation test is already implemented in the Clinical Controller, whereas the three newly developed speech-in-noise tests and the modified version of the tracking test are only available in the Research Interface. Moreover, the reference interval of the newly developed speech-in-noise and modified version of tracking tests for NH listeners was established (as shown in Section 4.3.4.3) with an adequate sample size. On the other hand, the telephone test has substantial limitations in terms of test administration and applicability, as well as in terms of the procedure where participants' scores reached the ceiling effect (see Section 4.2.2.5.5).

However, the conclusions of the current study should be considered with caution for two reasons. First, the findings from this study only apply for young NH listeners as the mean age of the participants was 24.4 years. Therefore, the generalisability of the findings for elderly NH participants would not be possible, given the impact of ageing on hearing sensitivity and related cognitive functions (Jayakody *et al.*, 2018). It is also impossible to know whether the measurement precision and applicability of speech-in-noise and spatial-listening tests found in this study would be the same level as those used with adult CI users. Second, it should be noted that these findings would be limited to the test materials (BKB sentences in multi-talker babble noise) and measurement procedure (1-up/1-down procedure method) used in the present study. It is difficult to know whether the newly developed speech-in-noise tests would display the same level of validity and reliability if the test materials and procedure were altered, such as using a different type of noise (i.e. stationary noise) or using fixed SNRs.

Therefore, future studies should consider investigating the reliability and validity of the new speech-in-noise tests with different test materials and procedures. Moreover, it would be useful to assess the tests' reliability, validity, and applicability for elderly NH listeners in addition to adult CI users. Finally, it would be useful to consider extending the test battery by incorporating outcome measures for other important hearing functions in everyday life, such as music perception and also consider aspects such as listening effort.

4.3.6 Conclusion

The current study aimed to assess measurement precision, including the test-retest reliability and the concurrent validity, of the newly developed speech-in-noise tests and provide data about adult NH listeners' performance on the real-life test battery.

The following conclusions can be drawn:

- The mean SRTs of the new speech-in-noise test, specifically the SrN±60° and S+90°N-90° could provide additional information about the performance of NH listeners compared to the standard speech-in-noise tests (fixed speech and noise presented from the front)
- The new speech-in-noise tests showed a good reliability and validity level
- The new speech-in-noise, localisation, and modified tracking tests are feasible and easily administered using the AB- Crescent of Sound.

4.4 Chapter summary

Chapter 4 consisted of two sections. The first section reported the theoretical background and process of selecting and developing the real-life test battery. The real-life test battery comprised performance tests and subjective rating scales as follows:

1. Speech-perception-in-noise tests, including three test set-ups simulating common real-life situations with competing noise (speech):
    - group conversations
    - one-to-one conversations
    - a conversation while driving a car
2. Localisation
3. Tracking moving sounds
4. Telephone use in quiet and in noise
5. SSQ questionnaire
6. Telephone-Use questionnaire

The second section evaluated the measurement precision of the newly developed speech-in-noise tests. The new speech-in-noise tests display good test-retest reliability and concurrent validity. Furthermore, the applicability of the real-life test battery was discussed. It was shown that newly developed speech-in-noise, localisation, and the modified tracking tests would be considered practical tests for clinical use. In addition, reference data about the performance of adult NH listeners on the real-life test battery were provided in this section.

Chapter 5 Integrated bimodal listeners' outcomes on a real-life test battery

5.1 Introduction

Bimodal hearing has become the standard care for adult unilateral CI users having residual hearing in their non-implanted ear. However, as shown in the results of the international survey (Chapter 3), only 46% of unilateral CI users use a HA in the non-implanted ear. The survey also showed that protocols for introducing and continued use of HAs after the implantation were variable at most of CI services.

Standard HAs use a different processing strategy and physiological pathway, and thus sound different from CI. Many CI users find it challenging to integrate these different signals (Veugen et al., 2016a). Integrated bimodal devices with Binaural VoiceStream Technology have been developed in recent years to improve bimodal hearing and overcome the mismatch in the processing strategy between the HA and CI.

The aim of the present study was to compare the integrated bimodal hearing outcomes, including Advanced Bionic/Phonak's Binaural VoiceStream Technology with CI-only outcomes on the real-life test battery, outlined in Chapter 4.

As outlined in Figure 5.1, the current chapter includes a discussion of (1) the background of the integrated bimodal technology, including how it works and the benefits reported in the literature, (2) an overview of Binaural VoiceStream Technology, particularly StereoZoom, ZoomControl and DuoPhone, and (3) the outcome of integrated bimodal technology with/without using Binaural VoiceStream Technology on the real-life test battery.

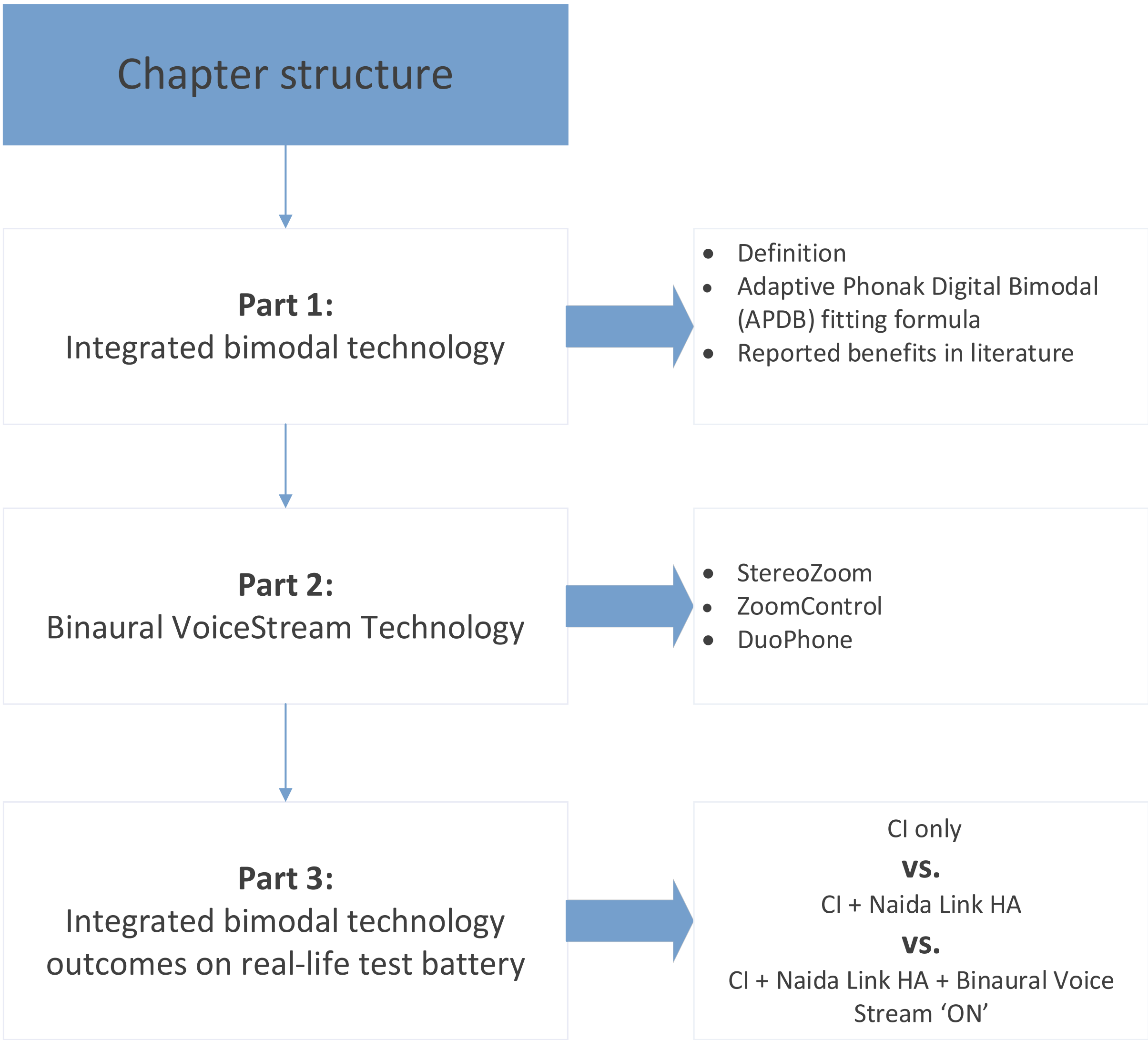

Figure 5.1: Flow chart illustrating the structure of Chapter 5.

5.2 Integrated bimodal technology

Phonak and Advanced Bionics (AB) have developed an integrated bimodal system known as the **Naida Link Bimodal system,** which consists of a Naida CI sound processor and a Naida Link HA. This technology has been designed to allow a CI and a HA to work on the same platform with the view of enabling greater synchrony and 'communication' between the two ears. The Phonak Naida Link HA is designed to work with the AB Naida CI Q70 or Q90 sound processor (Bionics, 2016c, Bionics, 2016d). The two devices provide matched compression algorithms and time constants. In addition, this technology also uses a dedicated fitting formula, adaptive Phonak digital bimodal (APDB), which adapts the AGC (automatic gain control) of the Naida Link HA to match the AGC in the Naida CI processor. Preliminary work has shown a benefit for speech understanding in noise and greater listening comfort with the matched AGC HA in comparison to using CI alone or with any standard HA (Veugen *et al*., 2016a). Furthermore, the Naida Link Bimodal system allows CI users to take advantage of Binaural VoiceStream Technology. This technology launched by Phonak allows the two devices (CI and HA) to be linked together wirelessly to stream full bandwidth audio signals from ear to ear simultaneously (Bionics, 2016a, Bionics, 2016b). The two devices communicate with each other and share automatic features and accessories. For example, audio signals are exchanged wirelessly between the Naida HA and CI processors to simultaneously direct important signals to both ears and reduce unwanted noise. Further details and discussion of these features are presented in Section 5.5. Additionally, the wireless-streaming feature allows the signal to be streamed to both the speech processor and a wide range of wireless devices (e.g. the Roger system or ComPilot).

5.3 Adaptive Phonak Digital Bimodal (APDB)-fitting formula

The Phonak prescriptive fitting formula has been developed for fitting the Naida CI processor and the Naida Link HA. The formula aligns the frequency response, loudness growth functions and AGC characteristics between the two devices (Bionics, 2016d). It has been argued that traditional HA-fitting formulae (e.g. NAL-NL2, DSLv5) do not align acoustic and electrical processing thus reducing the potential benefits of bimodal-hearing devices (Bionics, 2016d). Sheffield and Gifford (2014) suggested that the amplification-fitting formula, as per the APDB-fitting formula, should focus on the lower frequencies' regions (250 -750 Hz) to maximise the bimodal benefit as they carry temporal fine-structure information which is important for speech understanding in noise (Auletta *et al.*, 2021), whereas traditional formulae focus on maximising the amplification across the entire spectrum particularly in the frequency region required for speech understanding (1-4 kHz) (Cuda *et al.*, 2019). Moreover, the AGC system differs substantially between the HA and CI, as discussed in Chapter 2 section 2.4.3.2. Therefore, the APDB-fitting formula has been developed to optimise hearing for AB bimodal users and to facilitate the fitting process for the audiologist (Bionics, 2016d).

The main principle of the APBD-fitting formula is to align the HA toward the CI, rather than emphasising cues which are important to understand speech with the HA only, because the CI is the dominant provider for sound information to bimodal users (Warren *et al*., 2020). Three modifications are implemented to a standard HA prescription. First, frequency response is aligned to optimise low-frequency gain and bandwidth. Low-frequency gain is optimised by applying the model of effective audibility to ensure audibility of speech understanding in quiet environments (55 dB SPL) (Bionics, 2016d). According to the audiometric profile, the gain is often increased for frequencies below 1kHz. This gain increase is limited to ensure that speech (at 65 dB SPL) does not exceed the most comfortable level. However, for flatter hearing-loss configurations (i.e. flat, reversed, and mild-to-moderate sloping), this gain increase is not applied (Auletta *et al*., 2021). Frequency bandwidth is optimised by making bandwidth as wide as possible (Neuman and Svirsky, 2013), enhancing audibility of frequencies between 250 and 750 Hz, and the amplification does not extend into dead regions (Zhang *et al*., 2014, Auletta *et al*., 2021). The second modification is to align loudness growth between the two devices by implementing the input-output function of the CI sound processors (compression knee point of 63 dB SPL and ratio of 12:1) in the HA. The third modification is to align the AGC systems by porting the Naida CI dual loop AGC into the HA (Bionics, 2016d). The Naida CI processor has a single-channel dual-loop AGC system which includes both slow and fast attack-and-release time constants. To implement the latter compression system in the AGC of the HA, (1) the compression channels in the HA are coupled to mimic the single-channel compression, and (2) slow and fast time constants are applied in the HA (Vroegop *et al*., 2019). Figure 5.2 shows the calculation steps in the APDB-fitting formula.

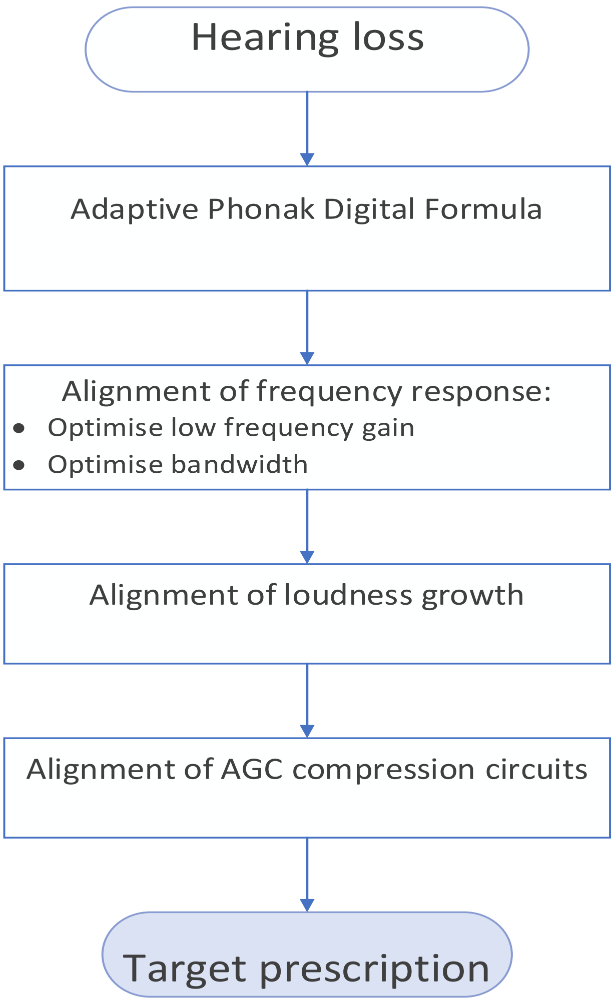

Figure 5.2: Calculation steps for the Adaptive Phonak Digital Bimodal (APBD)-fitting formula. Image adapted from (Bionics, 2016d).

Early studies were carried out to develop and verify the effectiveness of the APDB-fitting formula such as those by Chalupper *et al*. (2015) and Veugen *et al.* (2016a). Chalupper *et al*. (2015) assessed the effect of optimising frequency response for seven bimodal users. They increased gain to map speech (55 dB SPL) into effective audibility range and decreased gain in dead regions to optimise frequency response. The speech perception in noise was assessed under several conditions: CI alone, CI+HA (Phonak 1st Fit formula), CI+HA (NAL-RP) and CI+HA (Bimodal formula). The preliminary results showed that the optimised frequency response of the bimodal formula has a better starting point for HA fitting than standard prescriptions. Furthermore, Veugen et al. (2016a) showed that the alignment of AGC in CI and HA improved the bimodal benefit especially when the noise and speech are spatially separated, as mentioned in Chapter 2 section 2.4.3.2.

After the APDB-fitting formula had been established into clinical practice, several studies investigated the difference in the performance with the Naida Link HA when programmed with the integrated bimodal-fitting formula (APDB) and with the traditional HA-fitting formula (i.e. NAL-NL2 and DSLv5) (Cuda *et al.*, 2019, Vroegop *et al*., 2019, Warren *et al*., 2020, Auletta *et al*., 2021). All of the studies, except the one by Auletta *et al.* (2021), showed that there was no statistically significant difference between the integrated and traditional fitting formulae on speech perception in quiet and in noise. In addition, there were no significant differences on the SSQ between the APDB- and NAL-NL2-fitting formulae for the overall score and for the three subscale scores (Vroegop *et al*., 2019). However, differences in the individual performance of the participants were noted. For instance, two participants in the study by Warren *et al*. (2020) achieved significantly better scores with the APDB-fitting formula (approximately 18.9% and 21.7% improvement in speech perception scores compared to NAL-NL2). This finding underlines the importance of considering the individual differences when fitting the HA using different fitting formulae. In addition, Vroegop *et al*. (2019) found a significant difference between the APDB- and NAL-NL2-fitting formulae in the HA output for frequencies 2000Hz and above (less gain provided by the APDB compared with HAL-NL2), as well as a significant difference in the compression ratio for frequencies of 1000Hz and above (APDB had a higher compression ratio). Furthermore, the majority of participants in the study by Cuda *et al*.(seven out of nine) preferred the APDB over the DSL as it provided them with clearer hearing of speech. Similarly, seven out of ten participants in the study by Warren *et al*. indicated an overall preference for APDB over NAL-NL2 in the blind-acute sound-quality comparison test.

It should be mentioned that the measurements in the three studies mentioned above were conducted with a short acclimatisation period of 2-4 weeks after fitting the Naida Link HA. Holtmann *et al*. (2020) did not find a significant benefit in speech in noise with the Naida Link HA (fitted with APDB) over the standard HA after six weeks of fitting, but instead after 12 weeks.

Therefore, the short acclimatisation period of the Naida Link HA in the three studies (Cuda *et al*., 2019, Vroegop *et al*., 2019, Warren *et al*., 2020) might be the reason for not finding a significant difference when the Naida Link HA was adjusted with the APDB or with the traditional HA-fitting formulae.

Conversely, Auletta *et al.* (2021) found a significant difference between the APDB and the NAL-NL1 in speech perception tests in noisy conditions. The performance with APDB fitting was significantly better than the NAL-NL1 fitting by 20% at 0 dB SNR and -5 dB SNR. However, there were several limitations that might affect the generalisability of their findings. Firstly, the sample size is considerably small and heterogeneous. It only included six adults and five children. Secondly, the better performance with APDB fitting might result from a procedural bias found in the study protocol. Participants attended two sessions. In the first session, the Naida Link HA was fitted to each participant using the APDB formula. The second session was carried out after a seven-day acclimatisation period to the APDB, where speech perception in quiet and in noise was measured with a Naida Link HA using both formulae. Additionally, their findings might have been affected by the test order as the APDB was tested last for all the participants. Lastly, the signal audibility analysis indicated a difference of 8dB in audibility between the APDB and NAL-NL1 for frequencies below 1 kHz. Auletta *et al*. (2021) justified the reason for the discrepancy by explaining that a greater gain of APDB (more audibility benefit) was prescribed to the participants in their study because the average hearing loss was more severe than in the previous studies.

Although the preliminary work showed an advantage of applying the APDB formula over the traditional formula, the current evidence showed mixed findings that might relate to the difference in demographics of the participants or in methodological settings. However, it is worth noting that the coordination features of the Naida Link HA with the CI sound processor can still be used by the user even if any formula other than APDB is applied as the fitting formula (Warren *et al*., 2020). Therefore, using the APDB as the fitting formula or the Naida Link HA would be the starting point in standardising the fitting procedure for integrated bimodal technology.

5.4 Integrated bimodal technology benefits

As discussed above, preliminary work suggested a benefit for speech understanding in noise and greater listening comfort with the matched AGC HA in comparison to using CI alone or with any standard HA (Veugen *et al*., 2016a). Prior to commencing this study and to this researcher's knowledge, there were a few clinical studies (Bionics, 2016b, Bionics, 2016d, Bionics, 2017) that had assessed the benefits of integrated bimodal technology. The findings from these studies showed an improvement (10 to 15%) in speech perception in quiet. For a speech-in-noise condition, using the Naida Link HA significantly improved speech perception by 21 to 33% over the CI only, depending on the direction of the source of the speech and the masker noise. Furthermore, a significant additional benefit was obtained in noise when using Binaural VoiceStream Technology (21% with StereoZoom and 28% with ZoomControl), and further discussion about these features is presented in the next section (Section 5.5). This section focused on those studies that specifically investigated the potential benefits of integrated bimodal technology without using Binaural VoiceStream Technology.

Several studies have been published within the time span of the present study (Vroegop et al., 2018b, Cuda et al., 2019, Ernst et al., 2019, Vroegop et al., 2019, Holtmann et al., 2020, Warren et al., 2020, Auletta et al., 2021) that assessed the benefits of integrated bimodal technology (Naida Link Bimodal system), without using any features of Binaural VoiceStream Technology. All the studies, except Holtmann *et al.*, assessed the benefit of using the Naida Link HA with the CI in terms of speech perception. Holtmann *et al.* (2020) used a more comprehensive test protocol to assess the benefit of the Naida Link HA including speech perception, localisation, and self-reported questionnaires. Table 5.1 illustrates the methodological set-up of speech perception tests that were used in these studies.

Table 5.1: The set-ups of the speech tests used in the recent bimodal Naida Link hearing aid and CI studies.

Study	N	Sessions (duration between the sessions)	Speech target	Noise masker	Set-up	Procedure
Auletta *et al* (2021)	11 bimodal (6 adults & 5 children)	2 (7 days)	20 bisyllabic Italian words	10 talkers babble	S0°N±90°	Fixed (0 dB and -5 dB SNRs)
Warren *et al*. (2020)	10 bimodal	2 (3-5 weeks)	AzBio sentences	Multi-talker babble	S0°N0°	Fixed (Individual SNRs)
Holtmann *et al.* (2020)	12 bimodal	3 (4-6 weeks)	Oldenburg sentence (OLSA)	Not reported	• $S_{HA}N_{CI}$ • S0°N180°	Adaptive
Ernst *et al* (2019)	unilateral CI=10 bilateral CI=10 bimodal= 10	2-3 (One day - one month)	Oldenburg sentence test	Speech-shaped	• **Set up A:** S0° N (±60°, ±120°, & 180°) • **Set up B:** S0°N (±30° & ±60°)	Adaptive
Cuda *et al* (2019)	9 bimodal	2 (2 - 4 weeks)	Italian matrix sentences	International female fluctuating masker	S0°N0°	Adaptive
Vroegop *et al* (2019)	19 bimodal	3 (3 weeks)	• **In quiet:** Dutch speech test (monosyllabic words) presented at 45- & 55-dB SPL • **In noise:** Dutch speech test (sentences)	Steady state speech-shaped	• S0°N0° • S0°N90° • S0°N-90°	Adaptive

Vroegop *et al* (2018)	18 bimodal	1	Dutch speech material (sentences)	Babble noise	• **Static condition**: S0° N (±45° & ±135°) • **Dynamic condition:** S (45°or-45°) N (±45° & ±135°)	Adaptive

Vroegop et al. (2018b) measured the SRT in noise for 18 adult participants when using the CI only and also when using the integrated bimodal technology in both static and dynamic settings. All the participants used the AB Naida Q90 sound processor fitted with the Phonak Naida Link UP HA. The speech sentences were presented from the front loudspeaker placed at 0° for static conditions and randomly from a loudspeaker at -45° or 45° for the dynamic condition. Four uncorrelated babble noises were presented from the loudspeakers placed at -45°, 45°,-135°, and 135°. There was no significant difference between using the CI only and using the CI with the Naida Link HA in static conditions. In contrast, there was a significant improvement in the SRT of 3.1 dB with integrated bimodal listening compared to the CI only in dynamic conditions. In a later study, Vroegop *et al*. (2019) used a different testing set-up and noise masker to examine the benefits of the integrated bimodal technology compared to using the CI for 19 experienced bimodal CI users. The bimodal benefits were assessed in speech perception in quiet and in noise (see Table 5.1 for the test set-ups). A small significant bimodal benefit of 5% was found in speech perception in quiet at 45 dB SPL and 55 dB SPL. For speech perception in noise, a bimodal benefit of 1.6 dB and 2.5 dB was reported when the noise presented from the front and on the CI side respectively. There was no bimodal benefit when the noise presented from the HA side. Their findings were in line with findings of Spirrov *et al*. (2020) who found the largest bimodal benefit (4 .4 dB) with matched AGC between the CI and HA compared to using the CI only when the noise was presented on the CI side (as discussed in Chapter 2 section 2.4.3.2).

Similarly, Cuda *et al.* (2019) found a bimodal benefit of 3.9 dB for speech perception in noise when both the speech and noise presented from the front speaker. However, the benefit found in their study was considerably larger than the benefit found in the study by Vroegop *et al*. (2019). The discrepancy in the amount of benefit between the two studies might be related to several factors. Firstly, the sample size in the study by Cuda *et al*. (2019) was relatively small (n=9) compared to the Vroegop study (n=19). Additionally, a considerable inter-subject variability of 11.8 dB with the bimodal benefit was found in the study by Cuda *et al*. (2019). Another factor is the type of noise masker used; Cuda et al. used an international female fluctuating masker (IFFM) noise in their study, while a stationary noise masker was used in the study by Vroegop *et al.* (2019). The IFFM noise would be more difficult and distracting than the stationary noise which could increase the effect of informational masking (Spirrov *et al*., 2020). Furthermore, the average hearing threshold of the non-implanted ear for the participants in the study by Cuda *et al*. was slightly better than in the study by Vreogop *et al*. All these reasons would explain the difference in the amount of the bimodal benefit between the two studies. In line with previous studies, Warren *et al*. (2020) also found a significant bimodal benefit of integrated fitting (approximately 19.2%) compared to using the CI only when measuring speech perception scores in multi-talker babble noise for 10 participants. However, the amount of bimodal benefit was highly variable, ranging from 1.5% to 61.4%.

The difference between the Naida Link HA and the standard HA for unilateral CI users in speech perception has been investigated (Auletta *et al.*, 2021, Holtmann *et al*., 2020). Holtmann *et al.* (2020) compared the two HAs for 12 adults with unilateral CI in speech perception in quiet and in noise. They found an improvement in word perception in quiet at 65 dB with the Naida Link HA, but not significantly. For speech perception in noise, they found a significant improvement of 3.64 dB and 1.17 dB with the Naida Link HA over the standard HA at test set-ups S0°N180° and S_{HA} (90°) N_{CI} (90°) respectively. Auletta *et al*. (2021) found speech perception in quiet and in competing babble noise was measured for 11 unilateral CI participants (six adults and five children) when they used their own standard HA and with the Naida Link HA which was provided to them during the study. The results showed that the Naida Link HA using the APDB-fitting formula significantly improved speech intelligibility in the participants' own HA by 5% in quiet and by 20% to 30% in noise conditions (at 0 and -5 dB SNR respectively), with only a short acclimatisation period of seven days. However, the superiority of the Naida Link HA over the participant's own HA might be related to methodological bias. The Naida Link HA was fitted based on the current audiograms of the participants within the study protocol, whereas the participants' old HAs were fitted based on their less recent audiogram.

Only one study has assessed the benefit of Naida Link HAs for adult unilateral CI on localisation tasks as well as self-reported benefits using a subjective hearing-quality questionnaire (Holtmann *et al*., 2020). Four loudspeakers were placed at 0, 90, 180, and 270 degrees to assess the localisation performance using the Naida Link HA over the standard HA. There was no significant difference between the two HAs in localisation tests. The hearing implant sound quality index (HISQUI) 19 showed a significant improvement of sound quality only at the end of the study (at 8-12 weeks after the Naida HA fitting). The Oldenburg inventory did not show any statistically significant change from using the Naida Link HA. At the end of the study, seven participants (n=12) preferred to use the Naida HA.

To summarise, the results from these studies indicated that integrated bimodal technology can improve speech intelligibility in noise particularly compared to using CI only. However, the amount of benefit is highly dependent on the location of the target speech and the noise masker. In addition, only one study investigated the benefit of using this technology in localisation performance and self-reported benefits.

5.5 Binaural VoiceStream Technology features

Binaural VoiceStream Technology from Phonak is designed to allow two hearing devices to be linked wirelessly to stream full bandwidth audio signals for both ears in real time with short transmission delays by producing a third-order directional system via two-way communication between the dual-microphone systems on both devices that in turn create a four-microphone array. Unlike a telecoil, this technology is designed to transmit digital data with minimum power consumption (Latzel, 2012a). Different directional patterns are available with this technology. In addition, the technology introduced a variety of features that aimed to improve speech understanding in different challenging listening situations such as restaurants, classrooms or when using a phone in noisy situations. These features have been available in Phonak HAs for a number of years. Binaural VoiceStream Technology was introduced to the Naida CI Q70 and Q90 CI processors when Advanced Bionics was acquired by Sonova Holding AG and became a sister company to Phonak. The binaural features that can be enabled are as follows:

5.5.1 StereoZoom

StereoZoom is a third-order directional beamforming system (binaural beamformer) produced by wirelessly connecting the four omnidirectional microphones (two dual-microphone systems at each side, a Naida CI processor and a Naida Link HA). This feature can produce a much narrower fixed-target beam (±45°) than is provided by a monoaural two-microphone first-order beamformer (where the two microphones work independently) as illustrated in Figure 5.3. Buechner *et al*. (2014) measured the directionality of a binaural beamformer using polar plots obtained for an HA on a KEMAR artificial head in an anechoic room using a single noise source placed at different angles. They showed that the binaural beamformer attenuated sounds placed at -60° by approximately 5 dB compared to a monoaural beamformer.

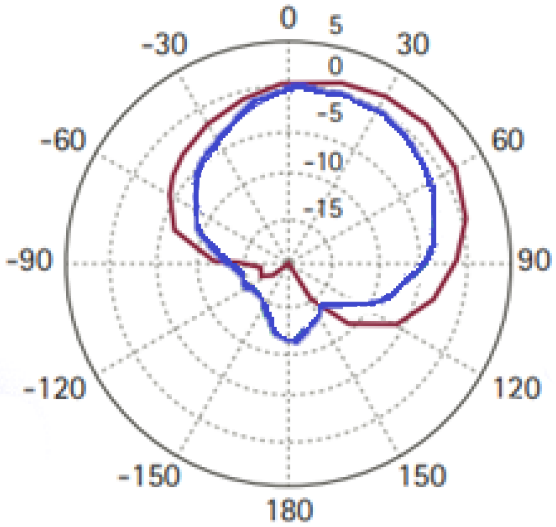

Figure 5.3: Polar diagram of a directional monoaural microphone (red) and StereoZoom (blue) for right KEMAR ear with broadband stimulation. The figure was adapted from Latzel (2012b) and Buechner *et al*. (2014).

The principles of the StereoZoom mechanism follow several steps (Best et al., 2015, Vroegop et al., 2018b). Firstly, the two microphones (on each side) are processed to produce a standard front dual cardioid-type polar pattern. Then, the directional signals are exchanged over the wireless link between the two devices (i.e. the HA and the CI). In the final step, the two devices then linearly combine the ipsilateral and contralateral directional signals to produce a binaural directivity by utilising a frequency-dependent weight function. The bandwidth of binaural directivity is controlled by the weighting function and is typically narrower than a simple monaural two-microphone beamformer can produce. The block diagram in Figure 5.4 shows the main principles of the StereoZoom mechanism.

StereoZoom allows listeners to focus on a single speaker standing directly in front of them while reducing interfering noise from the sides and back, as well as from near the front (Bionics, 2014). StereoZoom is only available for the Naida CI Q90 processor. It can be applied either across two AB CI sound processors, two Phonak Naida Link HAs, or across an AB CI sound processor and Naida Link HA.

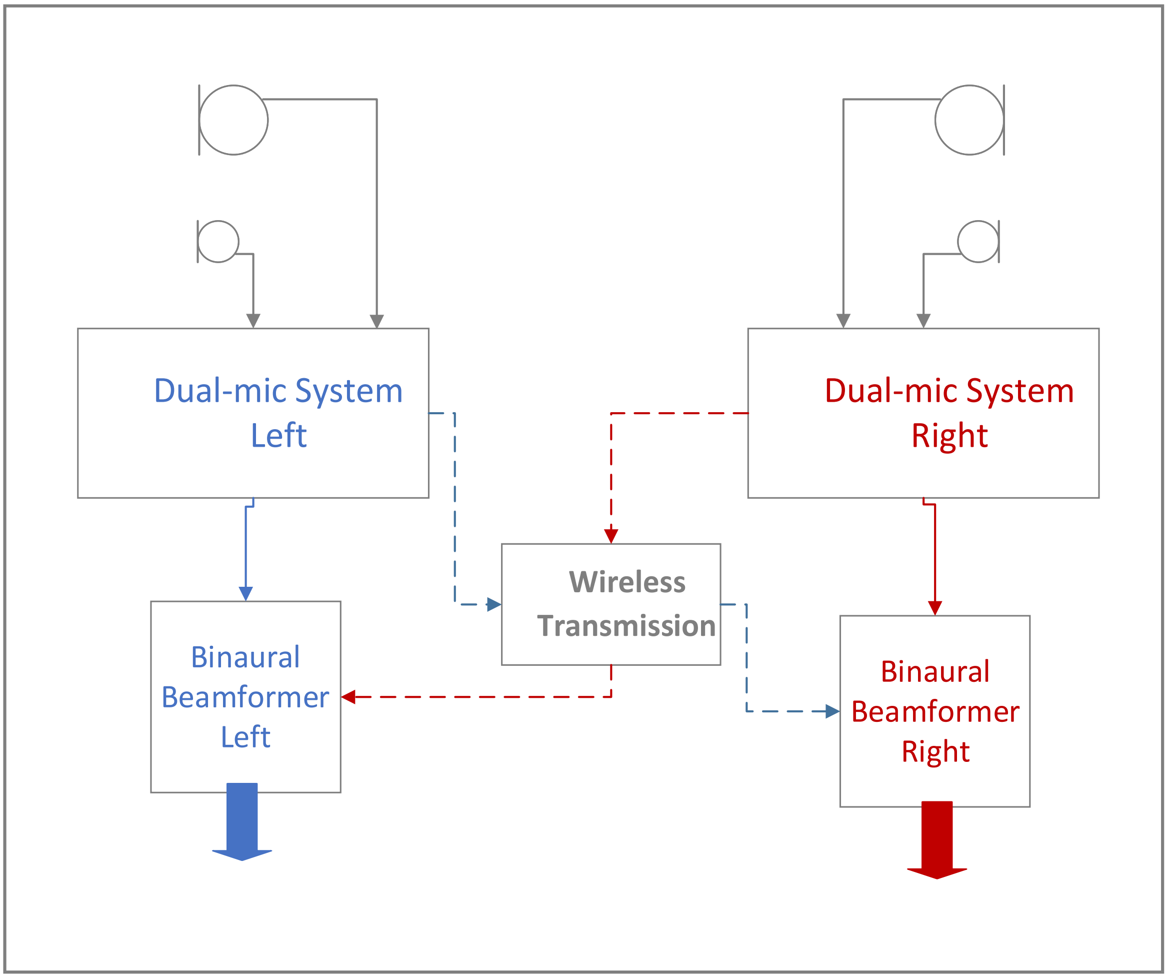

Figure 5.4: Flow chart of the technical implementation of StereoZoom. First, the dual microphone beamformer is calculated in the left and right device. Then the signal is wirelessly transmitted to the opposite side. The figure was adapted from Latzel (2012b).

In a clinical study (Bionics, 2016a), the benefit of StereoZoom was assessed in 19 experienced adult bimodal listeners using a Naida CI Q90 and a Naida link HA. A speech test was carried out in quiet and noise with three listening conditions: CI alone, CI + Naida Link HA and then CI + Naida Link HA with StereoZoom. For the noise condition, the sentences were presented from a loudspeaker located in front of the participants (0°) and in diffuse noise presented from five loudspeakers placed at ± 60°, ± 90°, ± 180°. A fixed procedure was used with custom SNRs (ranging from +2 to +15 dB for all the participants). The results showed that StereoZoom did not provide additional benefits in quiet compared to the CI-alone condition. In contrast, the speech test score was improved by an additional 21% when the StereoZoom was used in noise compared to the bimodal hearing condition (general settings without using StereoZoom). Compared to the CI-alone condition, the score was improved by 42% using the StereoZoom. In addition, the participants were asked to rate ease of listening on a five-point scale (ranging from 1= extremely difficult to 5= extremely easy). For the quiet condition, participants reported easier listening with StereoZoom over the CI-alone condition only; however listening with StereoZoom was reported to be the easiest over all experiment conditions. Thereafter, Vroegop et al. (2018b) also assessed the benefit of using StereoZoom on the SRTs for 18 bimodal participants. The measurements were carried out in two different set-ups: (1) a static condition where the speech was fixed at the front (0°), and (2) a dynamic condition where the speech was randomly presented from either loudspeaker placed at +45°or-45°. A significant improvement of 4.7 dB on the SRT was found by using the StereoZoom compared to using the general set-up of the integrated bimodal technology (everyday map) in the static condition. However, the StereoZoom did not provide any significant benefit in the dynamic condition. The results of the study by Vroegop *et al*. indicated that the benefit of using StereoZoom is relevant when the target speech is presented at the front. It also indicated that using the StereoZoom reduces the localisation performance as there was no improvement in the SRT in the dynamic listening condition.

Another study by Ernst *et al.* (2019) measured the benefit of using StereoZoom (binaural beamformer) over the UltraZoom (monaural beamformer) and T-Mic setting for bilateral and bimodal CI users. They used two loudspeaker set-ups (as shown in Table 5.1). For bimodal participants, StereoZoom provided a significant benefit over the T-Mic of 4.6 dB and 2.6 dB in test set-ups A and B respectively. In addition, the StereoZoom provided an advantage of 1.3 dB (set-up A) dB and 1.2 dB (set up B) over UltraZoom. Likewise, 5.2 dB and 3.4 dB benefits were obtained using StereoZoom over the T-Mic in set-ups A and B respectively for bilateral CI participants. It also provided a significant benefit of 0.9 dB (set-up A) and 1.4 dB (set-up B) over UltraZoom. Ernst *et al.* also compared the performance of bilateral and bimodal participants with StereoZoom active to a reference group (10 NH listeners). There was no difference between CI participants (both groups) and the NH group in the easier set-up (set-up A). For set-up B, there was a difference between the NH and bimodal groups, but not the bilateral group. However, there was no significant difference between the bimodal and bilateral groups in this test set-up.

The results from the previous studies suggest that using StereoZoom can provide a significant improvement for speech understanding in noise particularly when the speech is coming from in front of the listener. Although there was no significant difference in the StereoZoom benefits between the two loudspeaker set-ups for both groups in the Ernst *et al*. (2019) study, the amount of benefit seems largely dependent on the direction of the noise and the degree of separation between the target speech and the noise masker. A larger benefit could be obtained when the noise and speech are well separated. However, this is not the case in real-life situations where the noise could be moving rather than fixed, instead of in controlled conditions as in research set-ups.

Therefore, it is important to consider measuring the effectiveness of StereoZoom in real-life listening situations.

5.5.2 ZoomControl

The ZoomControl feature allows the listeners to select a preferred direction that they want to listen to. They can select to focus to the right, left or back, in situations where they cannot see the speaker's face. ZoomControl can switch the maximum sensitivity to the back when the listeners want to focus on speech from behind them. If the listeners want to focus on the right or left, the signal will be transmitted from one side to the other side where 75% of the direct microphone input in that side is suppressed to accommodate the transmitted signal (Bionics, 2014). ZoomControl is available with Naida CI Q70 and Q90 processors. This feature helps to improve speech understanding when the target signal is not in front of the listener (e.g. when driving a car). A clinical study by Bionics (2016b) was conducted to assess the benefit of using ZoomControl for 19 unilateral AB CI users fitted with a Naida Link HA. The speech perception was assessed in quiet and noise by using fixed procedures at custom SNRs (ranging from -7 to +15 dB) for the 19 participants in three listening conditions: CI alone, CI + Naida Link HA and CI + Naida Link HA with ZoomControl. In quiet, ZoomControl provided an additional 3% benefit to the bimodal benefit compared to CI alone. In noise, the sentences were presented to the side of the HA and the noise was presented on the CI side. The results showed that ZoomControl added an additional 28% benefit to the bimodal hearing and a total of 61% improvement over the CI alone. Furthermore, ZoomControl improved ease of listening especially in noise. The improvement of speech understanding was shown by the greatest number of participants (18 out of 19). One participant showed degradation in the performance with a bimodal hearing condition without the ZoomControl feature as well as with ZoomControl enabled.

A recent study has assessed the effectiveness of using the ZoomControl over the standard settings of the Naida Link HA when the speech was presented at the HA and the noise on the CI side (Holtmann *et al*., 2020). A significant improvement of 2.8 dB was found when enabling the ZoomControl. Additionally, a considerable significant benefit (3.9 dB) was obtained when using the ZoomControl compared to using the standard HA in the same test set-up.

These findings indicate that ZoomControl can enhance speech understanding when the signal of interest is on the poorer hearing side and can help to overcome the head shadow effect.

5.5.3 DuoPhone

DuoPhone improves speech understanding when using the phone via a binaural streaming technology (short-range wireless transmission with 8 kHz bandwidth and 2-ms transmission delay). DuoPhone delivers the signal picked up from the ear where the phone is located by the contralateral ear via digital nearfield magnetic induction (10.7 MHz) and CODEC (compression/decompression) without using any additional accessories (Miller *et al.*, 2021). The microphone input on the contralateral ear is reduced by 6 dB and is a 50% transmission wireless signal and 50% local microphone (Bionics, 2014, Miller *et al*., 2021). Thereby, the SNR at the contralateral ear is improved. In addition, the DuoPhone allows CI users to use the telephone naturally, holding the telephone next to the CI sound processor on the ear and the telephone signal is received in both ears simultaneously. Furthermore, it can be used with landline and mobile phones without any special interface equipment (Miller *et al*., 2021).

Preliminary studies showed an improvement in word recognition in both quiet and noise when DuoPhone was enabled for one participant with bilateral Naida CI Q 70 (Wolfe, 2013, Bionics, 2014). In a more recent study, Miller *et al*. (2021) assessed the benefit of using DuoPhone for nine AB bilateral CI users. They compared the telephone speech-perception outcomes in quiet and noise when the participants used the two CIs with DuoPhone compared to using only one CI. The CNC 50-item word list was presented to the participants via a mobile phone that was held next to the sound processor. In the noise condition, uncorrelated classroom noise was presented from four loudspeakers placed at 30°, 135°, 225° and 330° degrees. The results showed that word recognition over the phone was significantly better by approximately 20% in the DuoPhone condition relative to monaural condition (using one CI only) in both quiet and noise. Additional improvement (about 16%) in noise was obtained in the DuoPhone listening condition when the contralateral microphone was disabled relative to the standard settings of DuoPhone (6 dB attenuation on the contralateral microphone).

All in all, the preliminary data of these studies suggest that the DuoPhone might improve speech understanding over the telephone in background noise for CI users.

5.6 Interim summary of integrated bimodal and Binaural VoiceStream Technology

Integrated bimodal technology is one of the bimodal technologies available that might enhance binaural benefits for CI users. The main differences between integrated bimodal technology and using a standard HA with CI can be summarised by the following points:

- In integrated bimodal technology, both CI and the HA work together during sound processing on the same platform by using matched compression algorithms (AGC) and time constants (real-time synchronisation). In contrast, when using a standard HA, both devices (CI and the standard HA) work separately as they have different AGCs. As a result, different AGCs will cause unmatched binaural input that could lead to conflicting ILD cues and increase listening effort especially for conversational speech sounds as discussed in Chapter 2 section 2.4.3.2)
- Integrated bimodal technology enables Binaural VoiceStream Technology that would improve binaural benefits. A summary of each feature is shown in Table 5.2.

Table 5.2: Specific features of the Binaural VoiceStream Technology™.

Feature	Description
StereoZoom	1. Combines the signal inputs from the two microphones on the CI with the two mics on the HA to give a narrow directionality of approximately 90° 2. The talker should face the listener (recommended for one-on-one conversations in noisy environments)
ZoomControl	1. Stream the signal wirelessly from the ipsilateral side to the opposite side, so the signal is heard in both ears (the contralateral microphone is attenuated by 12 dB to reduce background noise) 2. This feature helps to change the direction of focus from right-left or front-back (e.g. listening to a passenger in the car)
DuoPhone	• The signal is streamed from the ipsilateral side to the contralateral side with attenuation of 6 dB to reduce background noise

5.7 Gap in knowledge and rationale for the study

As discussed earlier, integrated bimodal technology and Binaural VoiceStream Technology appear to be advantageous particularly for speech understanding in noise. However, further research is still needed for several reasons. Firstly, in most studies the speech target is fixed and presented from the front. In real-life situations this is often not the case, e.g. when seated at a table with others and other group situations or when travelling in a car. Secondly, to the best of the researcher's knowledge, no study has yet assessed the benefit of integrated bimodal technology for localisation and tracking, except one study (Holtmann *et al.*, 2020) assessed the localisation performance for only 12 participants. Thirdly, it would be interesting to further explore the potential benefits of this technology for telephone use. Fourthly, it is important to engage CI users regarding their perceptions and experiences of the technology. Fifthly, there is a need to compare CI users' outcomes with their standard settings (everyday map) to maps with the Binaural VoiceStream Technology, e.g. StereoZoom, ZoomControl and DuoPhone. Sixthly, participant numbers in previous studies have been relatively small (on average 10 participants) except for Vroegop et al. (2018b) and Vroegop *et al*. (2019) who included 19 participants. Finally, it would be of value to compare the outcomes of bimodal integrated technology users in relation to not only bilateral CI users but also individuals with normal hearing. This would be helpful in guiding clinical practice and also understanding the challenges faced by CI users in real-life listening situations where, for example, assistive listening devices could be used. To the best of the researcher's knowledge, only one study has compared the integrated bimodal users with bilateral CI users (Ernst *et al*., 2019). However, that study assessed the difference between the two groups with limited testing settings, specifically only using the StereoZoom. In addition, there is no study that has compared the performance of CI users when using this technology to the performance of NH listeners. It is important to understand the performance with the integrated bimodal technology to a reference base (NH listeners).

For these reasons this study was carried out to investigate the outcomes of the integrated bimodal technology compared to using the CI only, with a larger sample size using a real-life test battery that included performance tests (speech perception in noise, localisation, tracking of moving sounds and telephone use) and a subjective rating scale (SSQ questionnaire). In addition, the study was carried out to assess the benefit of using Binaural VoiceStream Technology compared to the standard settings of the integrated bimodal technology. Finally, the outcomes of the CI users with integrated bimodal technology were compared to bilateral CI users and NH listeners in a real-life test battery (as discussed in Chapter 7).

5.8 Aims and hypothesis

The aims of this study were as follows:

1. To compare the outcomes of adult CI users when using integrated bimodal technology (CI + Naida Link HA) versus the CI only on a real-life test battery that includes:
    - Speech-in-noise tests
    - Spatial-listening tests (localisation and tracking of moving sound tests)
2. To compare experiences of adult CI users when using the integrated bimodal technology (CI + Naida Link HA) versus standard bimodal technology (CI + standard HA) versus the CI only through self-reported measures (SSQ questionnaire)

3. To compare the outcomes of adult CI users when using the Binaural VoiceStream Technology (StereoZoom) versus using the standard settings (everyday map) of integrated bimodal technology on a speech-in-noise test
4. To compare the outcomes of adult CI users when using the Binaural VoiceStream Technology (ZoomControl) versus using the standard settings (everyday map) of integrated bimodal technology on a speech-in-noise test
5. To compare the outcomes of adult CI users when using the Binaural VoiceStream Technology (DuoPhone) versus using the standard settings (everyday map) of integrated bimodal technology on a telephone test (done both in quiet and noise)
6. To investigate the relationship between performance tests on the real-life test battery and the participants' perceptions on the SSQ when using the CI + Naida Link HA.

The hypotheses of this study were as follows:

- **Hypothesis 1**: adult CI unilateral users would show better outcomes using the integrated bimodal technology than using one CI in speech in noise, localisation, tracking and telephone use in quiet and in noise tests
- **Hypothesis 2:** using the Binaural VoiceStream Technology would improve the performance compared to the general settings of the integrated bimodal technology in the intended listening environment (testing set-up) that was designed for it
- **Hypothesis 3:** integrated bimodal technology would yield better rating scores on the SSQ questionnaire than by using the CI + standard HA and the CI only for adult unilateral CI users.

5.9 Method

Ethical approval was obtained for this study from the University of Southampton (ERGO ref: 45969).

5.9.1 Participants

26 users of a unilateral Advanced Bionics (AB) CI system participated in the study. Participants ranged in age from 19 to 87 years (group mean age = 62 years, SD = 20 years). They used the AB Naida Q70 or AB Q90 sound processor fitted with the Phonak Link UP HA in the non-implanted ear. All the participants were qualified to be invited based on the inclusion criteria: (1) aged over 18, (2) a minimum of six months of CI user experience, (3) a minimum of three months of integrated bimodal user experience, (4) BKB score in quiet of ≥ 50%, (5) participants had previously agreed to be contacted about research studies, and (6) no cognitive or learning difficulties that might affect the results. All the participants had StereoZoom, ZoomControl and

DuoPhone loaded on their CI sound processor for at least 3 months before the test session. Only one participant (Naida 5) had Ultrazoom instead of StereoZoom because the limitation of their sound processor (Naida Q70). The actual experiences with each program or map (everyday and the specific features maps) were not known as the participants were not asked whether or how much they used each configuration. The demographics are shown in Table 5.3. The participants' hearing thresholds of the non-implanted ears are summarised in Figure 5.5. The participants did not receive any payment for their participation in the study; however USAIS covered for the participants' travel expenses to the University of Southampton.

5.9.1.1 Sample size calculation

Prior to starting the present study, there were only a few published clinical studies that had assessed the benefits of the integrated bimodal technology (as discussed earlier in Section 5.4). As a result, the sample size was challenging to calculate for this study because there was not enough information about the difference between the integrated bimodal technology and the unilateral CI in speech perception (in dB SNR) and spatial listening tests. Also, new real-life speech-in-noise tests were developed for the purpose of the study. As a result, the effect size and test-retest reliability of these tests for adult CI users were unknown. Previous studies that used similar apparatus and set-ups were reviewed to estimate the appropriate sample size. Goman (2014) used the default tests of AB-York Crescent to assess the difference between using the CI only and using the CI with an HA for 12 bimodal users (standard HA technology) for speech-in-noise tests with different set-ups and spatial listening tests. The only significant difference noted between the two listening conditions was for the localisation test with 15° loudspeaker separation. The small sample size may have been the reason for not finding a significant difference. Looking at previous studies which investigated the bimodal benefits (standard technology) for speech-in-noise tests (Appendix D and E), a significant benefit was found in most of the studies that used a larger sample size (i.e. more than 15 participants). Therefore, it was decided to recruit 30 Naida Link bimodal users for the current study, with the assumption of a 25% dropout rate to compensate for any loss.

To review the sample size used in this study, a sample-size calculation was carried out afterwards, using the G*Power 3 (Faul *et al*., 2007). The minimum mean difference in the SRTs between the listening conditions (i.e. CI only versus CI+ Naida Link HA) that was decided to be considered as clinically significant and used in this calculation was 2 dB with an SD of 3 dB, a power of 0.8, and an alpha of 0.05. These parameters were based on a review of recent studies that have since been published. A statistically significant mean difference when speech and noise were spatially separated ranged from 2.5 to 3.1 dB (Vroegop *et al.*, 2018b, Vroegop *et al.*, 2019), with the SD of the difference not reported. When speech and noise were presented from the front, Cuda *et al.* (2019) reported a significant mean difference of 3.9 dB with an SD of 3.4 dB. The SD of the difference in SRTs between the listening conditions in the current study ranged from 2.5 to 5 dB depending on the target speech and noise location. Therefore, the parameters of a mean difference of 2 dB and an SD of 3 dB were chosen for the sample-size calculation. The G*Power 3, using a two-tailed paired t-test, indicated that 20 participants were enough (26 were recruited) to detect a mean difference of 2 dB with a power of 0.8 and an alpha (i.e. type-I error rate) of 0.05. It should be noted that the calculation was carried out with the assumption of no correlation being present between the two pairs.

Table 5.3: Demographic information of Naida Link bimodal participants.

Participant	Age (years)	Sex	Ear implanted	Aetiology	Age of HL onset	Duration of HL up till CI*	CI use (years)	Sound processors	PTA (dB HL) for non-implanted ear**
Naida 1	86	F	Left	Hereditary	35	44	7	Q90	94
Naida 2	74	M	Right	Hereditary	60	11	3	Q90	70
Naida 3	65	F	Left	Unknown	55	8	1.5	Q90	97
Naida 4	72	F	Right	Suspected Ménière's disease	40	30	2	Q90	97
Naida 5	74	M	Left	Infection	52	20	2	Q70	82
Naida 6	19	F	Left	Suspected maternal rubella	Congenital	9	10	Q90	92
Naida 7	58	M	Right	Hereditary	45	12	1	Q90	65
Naida 8	71	M	Left	Hereditary	33	32	6	Q90	90
Naida 9	79	M	Left	Unknown	63	12	4	Q90	74
Naida 10	84	M	Left	Noise exposure	59	20	5	Q90	84
Naida 11	40	M	Left	Unknown	6	33	1	Q90	108
Naida 12	84	F	Right	Unknown	62	20	2	Q90	92
Naida 13	65	M	Right	Unknown	20	34	11	Q90	104
Naida 14	81	M	Left	Unknown	69	10	2	Q90	84
Naida 15	86	M	Left	Unknown	72	13	1	Q90	81

Naida 16	87	M	Left	Unknown	66	20	1	Q90	97
Naida 17	74	M	Left	Hereditary	61	11	2	Q90	73
Naida 18	62	F	Right	Unknown	33	28	1	Q90	86
Naida 19	45	M	Left	Widened vestibular aqueduct	4	39	2	Q90	108
Naida 20	34	F	Left	Unknown	30	3	1	Q90	64
Naida 21	55	F	Left	Unknown	33	20	2	Q90	95
Naida 22	69	M	Left	Unknown	49	18	2	Q90	89
Naida 23	38	F	Left	Viral infection	34	2	2	Q90	65
Naida 24	40	M	Left	Maternal rubella	Congenital	38.5	1.5	Q90	87
Naida 25	45	M	Left	Hereditary	40	3	2	Q90	71
Naida 26	31	M	Left	Unknown	25	2	4	Q90	75

* All participants wore HAs consistently pre-implant and continued to in the non-implanted side after implantation.

** PTA= pure-tone average. The average of hearing thresholds was calculated based on the British Society of Audiology (BSA) recommended procedure for pure-tone audiometry (BSA, 2018), by the average of the pure-tone hearing threshold levels at 250, 500, 1000, 2000 and 4000 Hz. In the case of 'no response' at any frequency, the reading was given a value of 130 dB HL (BSA, 2018).

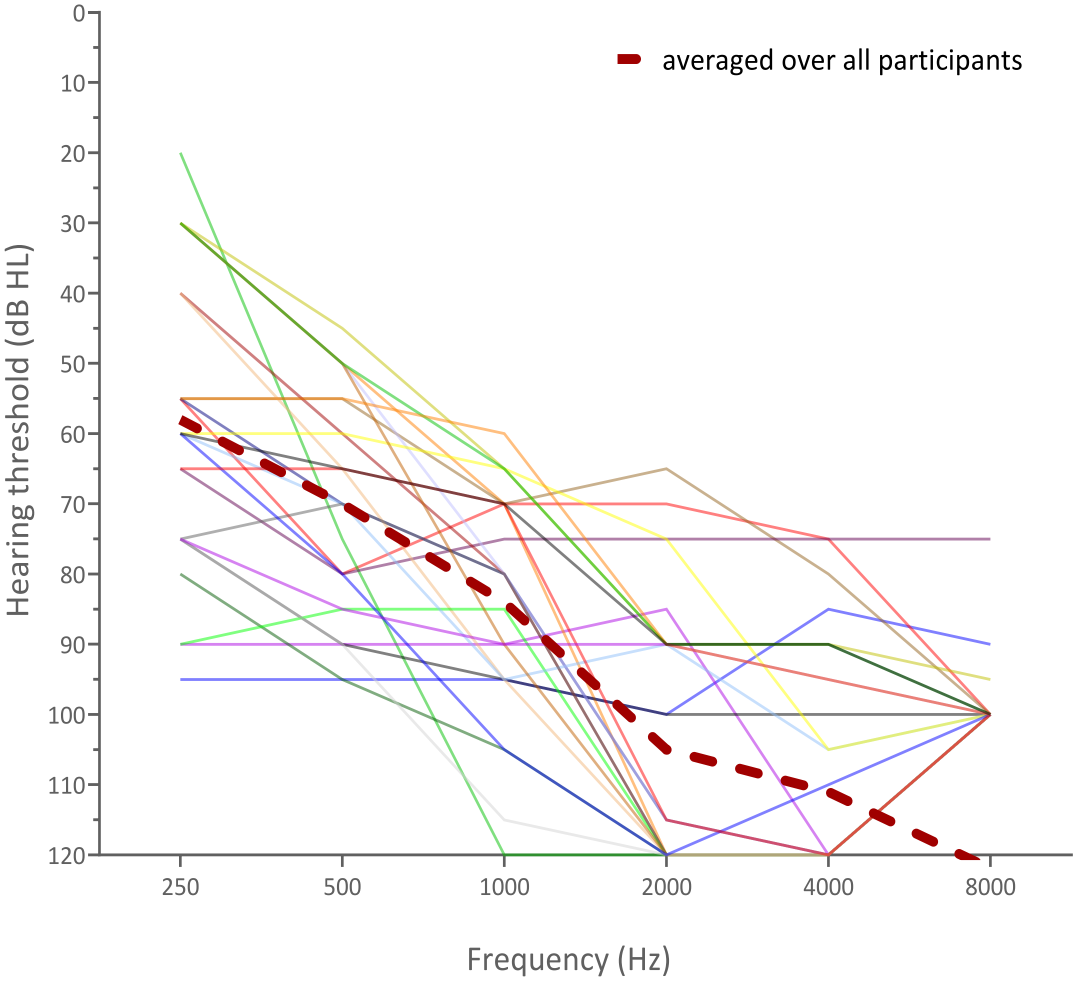

Figure 5.5: The unaided hearing thresholds of the individual participants for the non-implanted ear. The dashed red line displays the group mean threshold. For calculating the average, in case of 'no response', the reading was given a value of 130 dB HL based on (BSA, 2018).

5.9.2 Test battery

The real-life test battery that was developed as explained in Chapter 4 was used in this study. Figure 5.6 illustrates the performance tests and subjective rating scales included in the test battery.

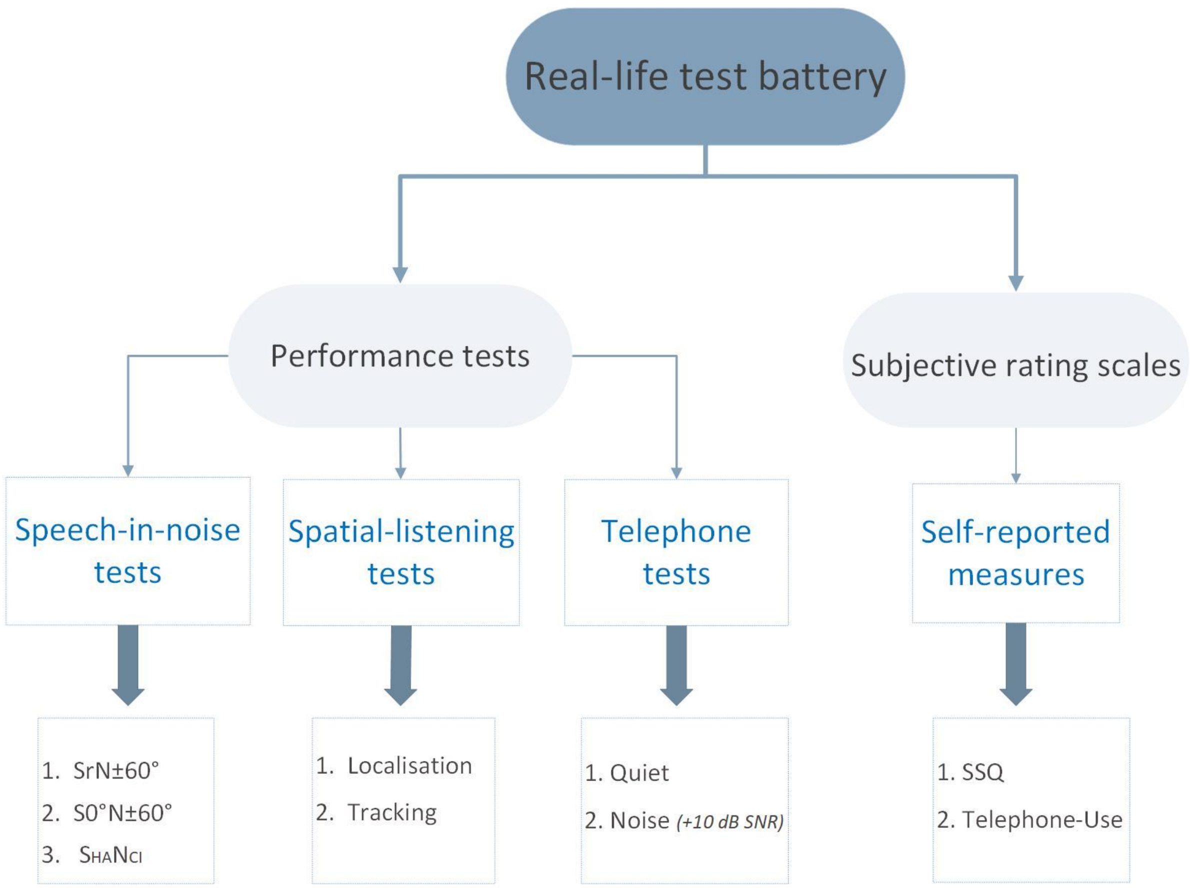

Figure 5.6: The performance tests and subjective rating scales included in the real-life test battery for CI participants.

The test battery was grouped into four categories where the first three categories included performance tests, and the fourth category included subjective rating scales.

The first category was the speech-in-noise tests that included three newly developed tests: (1) SrN±60°, (2) S0°N±60°, and (3) SHANCI where the speech was presented at the HA and the noise on the CI side at 90° azimuth. The benefit from StereoZoom was assessed in the speech test (S0°N±60°) because the optimal test settings to capture the benefit from StereoZoom would be by using a speech stimulus presented from a loudspeaker placed in front of the participants and diffuse noise sources presented from other loudspeakers placed at angles not less than 45° degree azimuth from the front loudspeaker (Bionics, 2016a). The benefit from ZoomControl was assessed in the speech test (SHANCI) because the optimal test settings to capture the benefit from ZoomControl would be by using a speech stimulus presented from a loudspeaker placed on one side (HA side) of the participant at 90° azimuth and a single noise source presented from a loudspeaker placed on the opposite side (at CI side).

The second category included spatial listening tests: (1) localisation using five loudspeakers with 30° separation and (2) tracking of moving sound. The third category comprised the telephone test in quiet and in noise (at +10 dB SNR). The AB-York Crescent of Sound was used to administer the tests in the first and second categories as well as to present the continuous loop of noise for telephone-in-noise tests in the third category. The detailed description of each test can be found in Chapter 4 section 4.2.2.

The fourth category included subjective rating scales (SSQ and Telephone- Use questionnaires). The SSQ questionnaire version 3.1.1 was used (Gatehouse and Noble, 2004, Noble and Gatehouse, 2004). However, a few modifications were made to allow for comparisons between using one CI versus the previous (standard) HA versus the Naida Link HA. Two questions were added at the beginning of the questionnaire to get snapshots about the duration of standard HA use and/or reasons for deciding not to wear a standard HA. In addition, participants were asked to answer each question for the following three listening conditions:

1. With their CI only
2. With their CI and standard HA in the other ear
3. With their CI and Naida Link HA in the other ear.

In addition, minor changes were made to a few questions to make them clearer to the participants. A summary of the modifications is provided in Appendix K.

A Telephone- Use questionnaire (Appendix L) was developed and included in the test battery of the study. The questionnaire consisted of seven questions to gauge the telephone use of the CI participants in their daily life.

5.9.3 Procedure

Testing took place within a double-walled sound-attenuated booth at the USAIS. All participants completed the listening tests in one session that lasted on average three hours, including short breaks of 10 minutes between the fourth test categories, and as requested by the participant. Information about the study and the participant information sheet were sent to participants via email at least one week prior to the testing session. In addition, the SSQ questionnaire was sent to them before the session to give them time to think about questions and to avoid the fatigue effect when answering the questionnaire at the end of the testing session.

At the beginning of the session, the participants were provided with a consent form to sign and were asked to complete the travel-expenses claim form. They were seated on a comfortable chair in the centre of the Crescent of Sound loudspeaker array one metre away from and facing the frontal loudspeaker which was placed at 0 degrees azimuth. A detailed illustration and instructions for each test were given to the participants. A summary of listening conditions, main procedure, and key points of the instructions for each test is given in Table 5.4.

Table 5.4: Summary of the main procedures and the listening conditions for CI participants using the Naida Link HA.

	Test	Listening conditions	Task	Head movement	Practice	Response required
Category 1 (Speech-in-noise tests)	SrN±60°	1. CI only 2. CI+ Naida Link HA	You are going to hear a man saying random sentences from one of these loudspeakers in front of you with a background noise masker coming from both sides	Allowed	No	Ignore the background noise and repeat any words you hear
	S0°N±60°	1. CI only 2. CI+ Naida Link HA 3. CI+ Naida Link HA + StereoZoom	You are going to hear a man saying random sentences from the front loudspeaker and a background noise masker coming from both sides	Fixed facing the front loudspeaker	No	Ignore the background noise and repeat any words you hear
	SHANCI	1. CI only 2. CI+ Naida Link HA 3. CI+ Naida Link HA + ZoomControl	You are going to hear a man saying random sentences from the loudspeaker placed on the HA side and background noise masker coming from the CI side	Fixed facing the front loudspeaker	No	Ignore the background noise and repeat any words you hear
Category 2 Spatial-listening tests	Localisation	1. CI only 2. CI+ Naida Link HA	You are going to hear a sentence of "Hello, what is this?" coming from one of these five loudspeakers in front of you	Fixed facing the front loudspeaker	No	Indicate the number of the loudspeaker from which the voice was presented
	Tracking	1. CI only 2. CI+ Naida Link HA	You are going to hear a moving sound. It may move from the right to the left, the left to the right, the right to the centre and back to the right, the left to the centre and back to the right or it may start at the centre and go to the right or left side and then back to the centre again	Allowed	No	Say or use your finger to show the direction in which you think the sound is moving

Category 3 Telephone test	in quiet	1. CI+ Naida Link HA 2. CI+ Naida Link HA+ DuoPhone	I am going to call you on this phone; once you pick up you are going to hear a list of digit sequences. Each sequence consists of 3 digits.	Fixed facing the front loudspeaker	Yes*	Repeat the digits you hear
	in noise (+10dB SNR)	1. CI+ Naida Link HA 2. CI+ Naida Link HA+ DuoPhone	I am going to call you on this phone; once you pick up you are going to hear a list of digit sequences. Each sequence consists of 3 digits. There are some background noises coming from the loudspeakers at the sides	Fixed facing the front loudspeaker	No	Ignore the background noise and repeat the digits you hear
Category 4 Subjective rating scales	SSQ questionnaire	1. CI only 2. CI+ standard HA 3. CI+ Naida Link HA	The participants were asked to read the questions and answer them for each listening condition	-	-	-

*Training was given for test-procedure familiarisation and finding the comfortable volume level of the sound processor and the mobile phone, and to the optimal placement of the mobile phone

The order of first (speech-in-noise tests) and second (spatial-listening tests) categories were counterbalanced across participants to minimise any possible order effect, whereas the third (telephone tests) and the fourth (subjective rating scales) categories were kept in the same order. This is because the speech-in-noise and spatial-listening tests were the primary-outcome measures whereas the telephone test is a rudimentary test (as discussed in Chapter 4 section 4.2.2.5) that was developed specifically for the current study. Moreover, the SSQ questionnaire was sent to the participants at least one week prior to the testing session. Therefore, it was decided to use this testing arrangement to avoid any order or fatigue effects on the primary-outcome measures. In other words, the test session for some participants started with a speech-in-noise test, then spatial-listening tests. For other participants, the test session started with spatial-listening tests followed by speech-in-noise tests. In addition, the listening conditions and order of the sub-tests within each category were also counterbalanced.

During the test session, the participant was provided and tested with a sound processor (Naida AB Q90) and a Naida Link HA dedicated to the study, rather than using the participants' own devices. The spare Naida Link HA was coupled with the participants' personal ear mould. Prior to testing, the SoundWave 3.0 clinical fitting software and Phonak Target 4.3 software were used to set the spare processor and the HA for each individual. The fitting was carried out according to clinical routine and guidelines of the USAIS centre using the APDB fitting prescription. Four maps were downloaded into the processor: (1) program 1: everyday setting (default) based on the participant's previous clinical program, (2) program 2: StereoZoom, (3) program 3: ZoomControl, and (4) program 4: DuoPhone. New batteries were provided at the beginning of the test session. Additionally, participants were instructed to use the volume settings that they were most accustomed to using. The noise-reduction algorithms on the CI and the HA (such as Clearvoice, Windblock and Soundrelax) were switched off during the testing.

For the telephone tests, the Telephone- Use questionnaire was always carried out prior to the testing. Then, a training trial was carried out to familiarise the participants with test procedures as well as to allow them to find the comfortable volume level of the sound processor and the mobile phone, and to find the optimal placement of the mobile phone as a designated mobile phone rather than their own was used to eliminate the influence of confounding variables. The participant was asked to hold the mobile phone next to the speech processor. The volume level for the sound processor and the mobile phone remained at the same level throughout testing.

In the last part of the test session, the participants were asked to answer the SSQ questionnaire if they did not complete it before the session. They were asked to answer each question based on their experience when using: (1) the CI only, (2) the CI + their old (standard) HA, and (3) the CI +their Naida Link HA. For the latter listening condition, the participants were asked to answer the questions based on their overall experiences with the integrated bimodal technology without any relation to specific settings or features (i.e., ZoomControl, DuoPhone, etc).

5.9.4 Analysis

Both descriptive and inferential statistical analyses were carried out and presented separately for each test within the category of the test battery. The descriptive analysis was achieved using GraphPad Prism software (version 9.1) and statistics were computed using IBM SPSS Statistical Analysis software (version 26).

Before computing the statistics, the normality distribution of the data was assessed using the Shapiro-Wilk test. Parametric statistical analysis tests were used, even if the assumption of normality was violated, since they are considered to be robust to non-normality (Maxwell and Delaney, 2004, Rasch and Guiard, 2004). Where there were multiple comparisons, post-hoc corrections were used. However, Bonferroni correction was not applied as it is generally conservative and overcorrects for Type I errors which affect the statistical power (Field, 2013, p.459). The least significant difference (LSD) was used instead in these statistics as it has greater power and is equivalent to performing multiple t-tests on the data. This increased the possibility of detecting differences between means that might, in reality, be meaningful.

The following sections explain the analysis that was carried out for the tests included in the test battery.

5.9.4.1 Speech-in-noise tests

The dependent variable was SRT in dB SNR. The SRT was obtained for each test with each listening condition. For each speech-in-noise test, the SRTs for the listening conditions were compared.

5.9.4.2 Spatial-listening tests

The analysis of localisation tests was carried out as a percentage of correct responses for each listening condition. Additionally, RMS error (the deviation in degree between the actual locations of sound source and locations identified) in the 30 trials per test run was calculated for each listening condition using the following equation:

$$RMS\ error = \sqrt{\frac{\sum_{i=1}^{n}(x-y)^2}{n}}$$

where x is the location of the source of the loudspeaker in degrees, y is the location of the response in degrees as indicated by the participant, and n is the number of the trials.

The chance range for randomly guessing was also calculated for both percentage correct and RMS metric using the "Monte-Carlo" simulation method in the MATLAB (version R2019a) software.

For the tracking-of-moving sounds test, there were six sequences of moving sound, as explained in Chapter 4 section 4.2.2.4 that were presented as a list of 12 sequences (where each sequence was repeated twice in a pseudo-random order). The percentage of correct responses for each listening condition was calculated. The chance range for randomly guessing was also calculated using binomial distribution with parameters of n=12 trials, each with a probability of success of p=0.167.

Furthermore, correlation between the localisation and tracking tests in the two listening conditions (CI only and CI+ Naida Link HA) was examined.

5.9.4.3 Telephone tests

One list of TDT consisting of 10 triplets was presented for each participant for each listening condition. The score was presented for each listening condition as the percentage of correct responses. A digit-scoring method was used where the scores are presented as a percentage correct out of 30 digits for one list.

5.9.4.4 The SSQ

Only completed questionnaires were included in the analysis. In addition, participants who answered 'not applicable' to the questions for any listening condition were treated as incomplete and were also excluded from the analysis.

The scores for each of the three main subscales of the SSQ (speech, spatial and qualities of hearing) were calculated for the three listening conditions (1) CI alone, (2) CI + standard HA, and (3) CI + Naida HA. In addition, an overall SSQ score was calculated for each listening condition by taking the average score across the three subscales.

In addition, the scores of two questions (13 and 14) in the speech subscale that related to telephone use were compared between the two listening conditions. Question 13 is about the ease of having a conversation on the telephone and question 14 is about the ability to understand the speech over the telephone in the presence of a background noise.

Furthermore, the difference on music perception between the three listening conditions was analysed by taking the average score of questions 5, 7 and 8 on the qualities-of-hearing subscale, and then compared with the listening conditions.

5.9.4.5 The relationship between performance tests and subjective rating scales

The relationship between the performance tests (speech in noise, spatial hearing and telephone use) and the subjective-rating scales (SSQ questionnaire) for the listening condition of using the Naida Link HA with CI has been examined. The correlation analysis has been conducted between:

1. The scores of SSQ on the speech subscale and the averaged scores of the three speech-in-noise tests of the best aided condition. The average scores of the speech-in-noise tests have been calculated by taking the average of scores of the three tests: (1) SrN±60 ° in CI+ Naida Link HA condition, (2) S0°N±60° in CI+ Naida Link HA+ StereoZoom condition, and (3) SHANCI in CI+ Naida Link HA + ZoomControl condition. If there was a significant correlation, then the correlation with each speech test (best aided) was examined.
2. The scores of SSQ on the spatial subscale and the average scores of the spatial-hearing tests (localisation and tracking) in percentage correct. If there was a significant correlation, then the correlation with each individual test was examined.
3. The question 13 scores of the SSQ on the speech subscale and the averaged scores of the telephone tests (in quiet and in noise) of the best-aided condition (using the DuoPhone). If there was a significant correlation, then the correlation with each test (best aided) was examined.
4. The question 14 scores of the SSQ on the speech subscale and the scores of the telephone test in noise when using the DuoPhone. This is because this SSQ question asked about the ability of using a telephone in noise.

5.9.4.6 The relationship between unaided hearing thresholds of the non-implanted ear and the integrated bimodal technology

The relationship between the unaided hearing thresholds of the non-implanted ear and the performance scores when using the Naida Link HA was examined by conducting a correlation analysis between the unaided hearing thresholds of the non-implanted ear and the following:

1. Average performance scores of the three speech-in-noise tests on the best-aided condition. The average scores of the speech-in-noise tests were calculated by taking the

average scores of the three tests: (1) SrN±60 ° in CI+ Naida Link HA condition, (2) S0°N±60° in CI+ Naida Link HA+ StereoZoom condition and (3) SHANCI in CI+ Naida Link HA + ZoomControl condition. If there was a significant correlation, then the correlation with each speech test (best-aided condition) was examined.

2. Average performance scores of the spatial-hearing tests (localisation and tracking) in percentage correct. If there was a significant correlation, then the correlation with each test was examined.
3. Average performance scores of the telephone tests (in quiet and in noise) on the best-aided condition (using the DuoPhone). If there was a significant correlation, then the correlation with each test (best-aided condition) was examined.
4. Rating scores of the overall SSQ.

In addition, the relationship between the unaided hearing thresholds of the non-implanted ear and the integrated bimodal benefit was examined by conducting correlation analysis between the unaided hearing thresholds of the non-implanted ear:

1. Average integrated bimodal benefit of the three speech-in-noise tests. If there was a significant correlation, then the correlation with benefit on each speech test was examined.
2. Average integrated bimodal benefit of the spatial-hearing tests (localisation and tracking) in percentage correct. If there was a significant correlation, then the correlation with the benefit on each test was examined.
3. The integrated bimodal benefit on the overall SSQ.

The integrated bimodal benefit was calculated as the difference between scores of the listening condition when using CI with a Naida Link HA and scores of the listening condition when using the CI only as:

Integrated bimodal benefit= (CI+ Naida Link HA) – CI only

Furthermore, correlation analysis was carried out between the unaided hearing thresholds of the non-implanted ear and the benefit of each feature of Binaural VoiceStream Technology (StereoZoom, ZoomControl, and DuoPhone). The benefit of Binaural VoiceStream Technology was calculated as the difference between scores of the listening condition when using Binaural VoiceStream Technology and scores of the listening condition when using the standard settings of Naida Link HA. Table 5.5 shows the calculation of the benefit for each Binaural VoiceStream Technology feature.

Table 5.5: Calculation of the benefit for Binaural VoiceStream Technology.

Binaural VoiceStream Technology	Benefit
StereoZoom	(CI+ Naida Link HA + StereoZoom ON) - (CI+ Naida Link HA + StereoZoom OFF)
ZoomControl	(CI+ Naida Link HA + ZoomControl ON) - (CI+ Naida Link HA + ZoomControl OFF)
DuoPhone	(CI+ Naida link HA + DuoPhone ON) - (CI+ Naida Link HA + DuoPhone OFF)

The unaided hearing thresholds of 250, 500 and 1000 Hz, the PTA of 250 and 500 Hz and the PTA of 500, 1000 and 2000 Hz of the non-implanted ear were examined in the correlation analysis.

5.10 Results

The results are presented in accordance with the test categories of the real-life test battery.

5.10.1 Speech perception in noise

This section presents the SRTs for the integrated bimodal users in the three speech-in-noise tests: SrN±60°, S0°N±60° and SHANCI. Lower SRTs indicate better performance in terms of the ability to tolerate a more adverse SNR. The left-hand panel of Figure 5.7 shows the SRTs of the integrated bimodal participants when listening with CI only and when listening with CI + Naida Link HA at SrN±60° test. The middle panel presents the SRTs of the participants for three listening conditions (Cl alone, CI + Naida Link HA, and CI + Naida Link HA + StereoZoom) of the S0°N±60° test. The SRTs of the participants of the SHANCI test for the three listening conditions (Cl alone, CI + Naida Link HA, and CI + Naida Link HA+ ZoomControl) are shown in the right-hand panel. The distributions of the SRTs for the listening condition of using CI alone as shown in Figure 5.7 indicate that the SRTs were somewhat skewed towards higher SRTs (i.e. positively skewed) in all three speech-in-noise tests. The individual scores for the participants are provided in Appendix M.

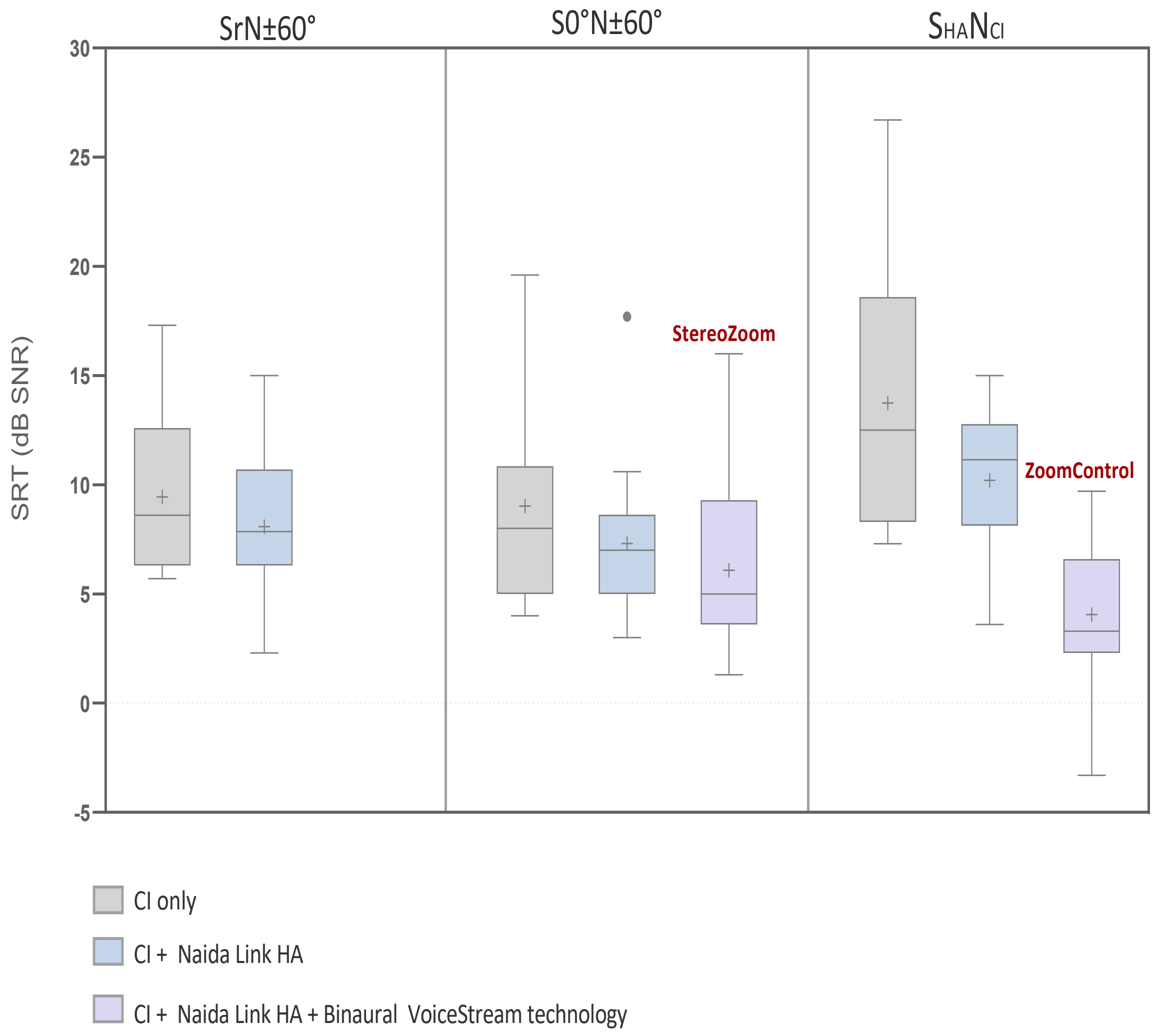

Figure 5.7: Box plots representing the SRTs in dB SNR for the three listening conditions: (1) CI only, (2) CI + Naida Link HA, and(3) CI + Naida Link HA+ Binaural VoiceStream technology (StereoZoom/ZoomControl) in SrN±60° (left), S0°N±60° (middle), and SHANCI (right) tests. The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The outliers are plotted as solid circles. Lower SRTs indicate better performance.

A paired-samples t-test was used to determine whether there was a statistically significant mean difference between the two listening conditions (CI only vs. CI+ Naida Link HA) in the SrN±60° test. Data are mean ± standard deviation unless otherwise stated. The SRT was lower (better) in the listening condition of using CI + Naida HA (8.1 dB SNR ± 2.9) as opposed to when using the CI only (9.4 dB SNR ± 3.1). The results showed a statistically significantly difference: t (25) = 2.7, p <.05, d=0.5. The mean difference and the 95% confidence intervals are shown in Table 5.6.

For the S0°N±60° and SHANCI tests, a one-way repeated measures ANOVA test was carried out for each test separately to determine whether there was a statistically significant mean difference between the three listening conditions: (1) Cl only, (2) CI + Naida Link HA, and (3) CI + Naida Link HA+ Binaural VoiceStream Technology (StereoZoom/ZoomControl). In the S0°N±60° test, Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated: $\chi^2(2) = 0.9$, $p = 0.6$. The SRT scores are statistically significant among the three listening conditions: F (2, 50) = 17.1, $p<.01$. The results of post hoc analysis are presented in Table 5.6. The results indicate that there was a statistically significant difference between the three listening conditions. In the SHANCI test, the assumption of sphericity was violated, as assessed by Mauchly's test of sphericity: $\chi^2(2) = 6.1$, $p = .05$. Therefore, a Greenhouse-Geisser correction was applied ($\varepsilon = 0.8$). SRTs were statistically significantly different for the three listening conditions, F (1.6,40.8) = 62.6, $p < .001$.

Table 5.6: Mean difference (95% confidence intervals) between the listening conditions for the SrN±60°, S0°N±60° and SHANCI tests. Results from post hoc analysis are also listed.

Test	Listening conditions	Mean difference (95% confidence interval)	p
SrN±60°	(CI+ Naida Link HA) - CI only	-1.4 (-2.4 to 0.3)	0.01
S0°N±60°	(CI+ Naida Link HA) - CI only	- 1.7 dB (-2.8 to -0.6)	0.004
	(CI+ Naida Link HA + StereoZoom) – Cl only	-2.9 dB (-3.9 to - 2)	< 0.001
	(CI+ Naida Link HA + StereoZoom) – (Cl + Naida Link HA)	-1.2 dB (-2.3 to - 0.2)	0.03
SHANCI	(CI+ Naida Link HA) - CI only	-3.5 dB (-5.5 to -1.5)	0.01
	(CI+ Naida Link HA + ZoomControl) - Cl only	-9.7 dB (-11.7 to - 7.7)	< 0.001
	(CI+ Naida Link HA + ZoomControl) – (Cl + Naida Link HA)	- 6.1 dB (-7.5 to - 4.8)	< 0.001

To provide an estimation of the population mean, mean benefit and the 96% confidence intervals for each speech test are presented in Figure 5.8. The values of these benefits are derived by comparing the SRTs for the two listening conditions.

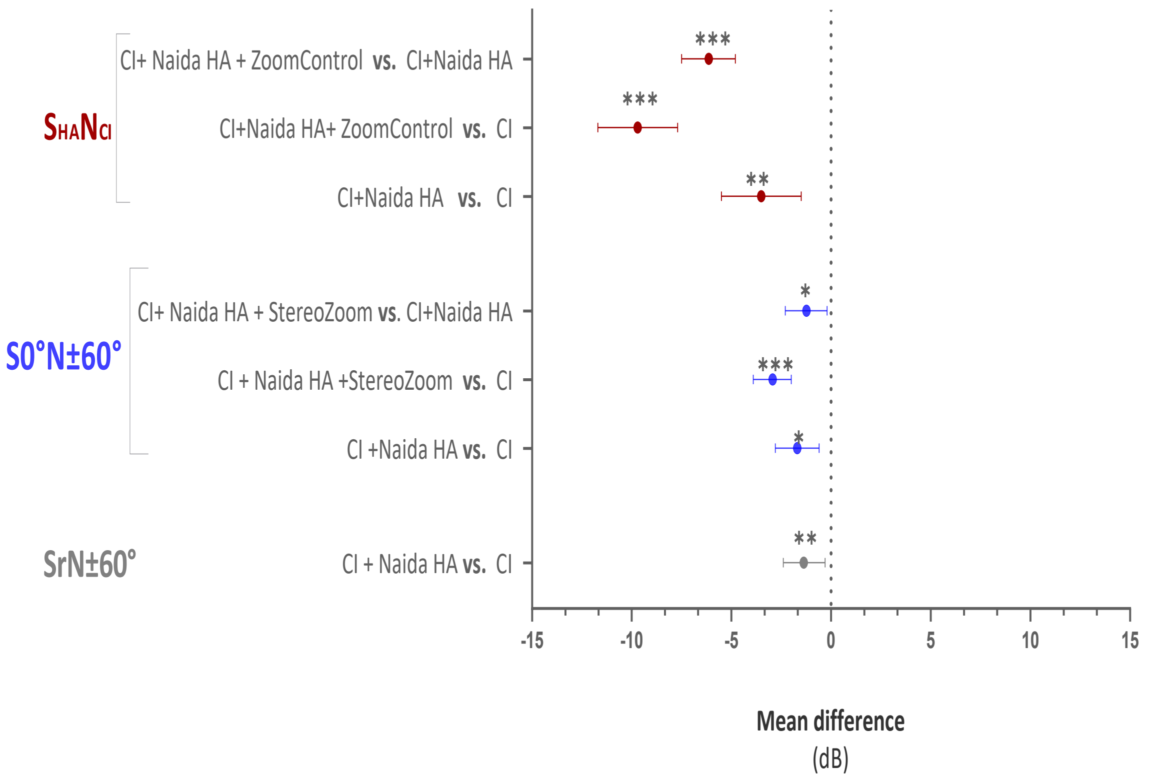

Figure 5.8: Mean bimodal benefit for the three-speech perception-in-noise tests, in dB, when using the Naida Link HA and when using the Binaural VoiceStream Technology (StereoZoom/ZoomControl). Error bars show 95% confidence intervals of the mean. The vertical dashed line indicates no benefit. Negative values indicate better performance. A significant benefit is indicated by asterisks (*** indicates p<.001, ** indicates p<.01, and * indicates p<.05).

5.10.2 Spatial-listening tests

Sound localisation

The mean performance on the sound-localisation test (30° separation) for the integrated bimodal participants in the two listening conditions, (1) CI only and (2) CI + Naida Link HA, is shown in Figure 5.9 (A). Mean performance when using the CI only was close to chance (mean=21.4 %, SD=7.8). However, the performance was higher than chance in the bimodal condition (mean=33.7 %, SD=10.1). Paired-sample t-tests showed that localisation accuracy was statistically significant higher in the bimodal condition by 12.3 % (95% CI, 7.6 to 17) compared to using the CI-only condition (t (25) = 5.4, p <.001).

The RMS errors were also calculated for both listening conditions. Figure 5.9 (B) shows that the mean RMS error when using the CI only was 57.3° (SD= 9.5°) which was within the guessing range, while the mean RMS error was 43.1° (SD=12.6°) for the listening condition of using CI and the Naida Link HA. Paired-sample t-tests revealed that the mean RMS error was statistically significantly lower in the bimodal condition by 14.2° (95% CI, 8.2 to 20.3) compared to using the CI-only condition (t (25) = 4.9, p <.001).

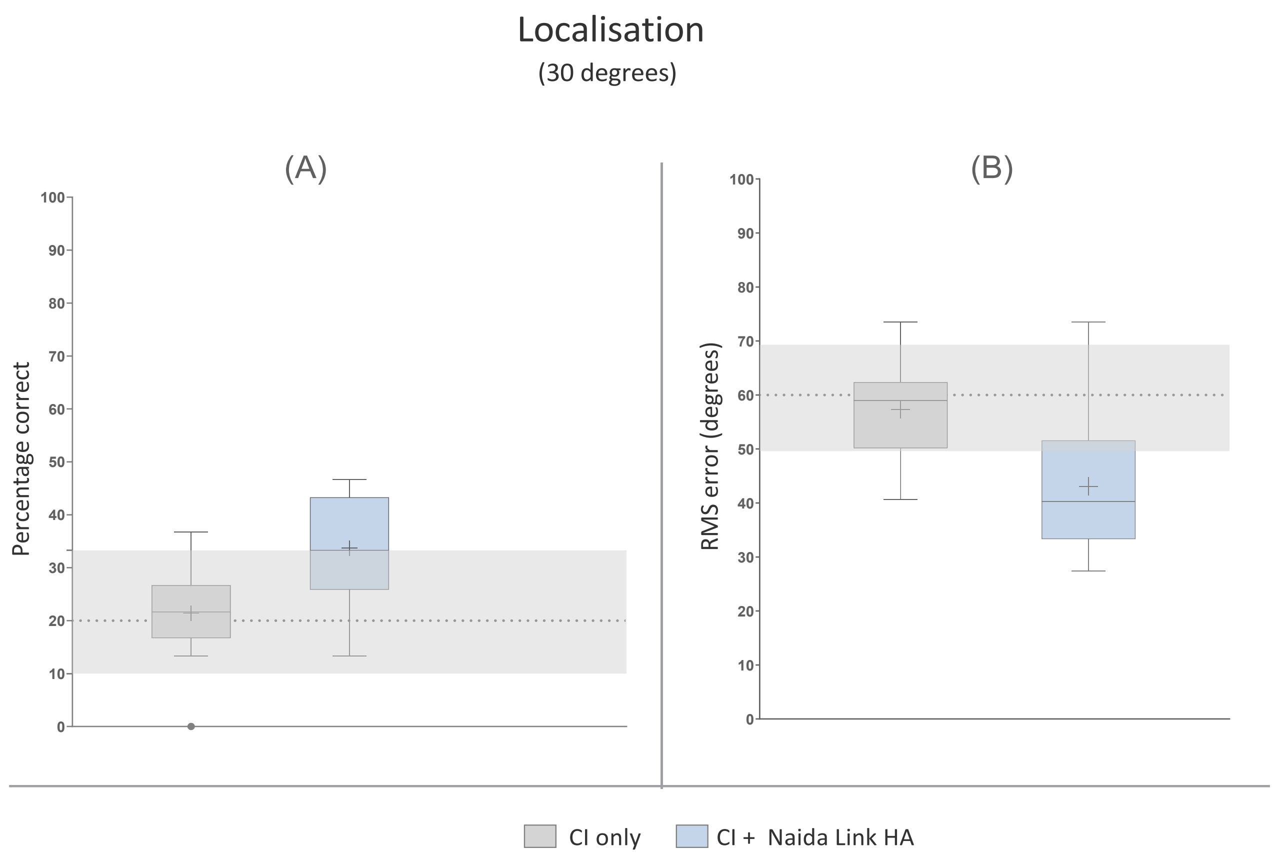

Figure 5.9: Results of the localisation test in percentage correct (left-hand panel) and in RMS error (right-hand panel) for the adult CI participants in the listening condition of using the CI only (grey box plots) and in the listening condition of CI+ Naida Link HA (blue box plots). The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The dashed horizontal line shows the level of performance expected by chance, with the grey shaded area showing the 5th and 95th percentiles of the chance range The outliers are plotted as solid circles.

Tracking

The mean performance on tracking moving sounds for the integrated bimodal participants in the two listening conditions, (1) CI only and (2) CI + Naida Link HA, is shown in Figure 5.10. The chance range was calculated using binomial distribution with n=12 and p=0.167 indicating the mean percentage correct of the chance range of random guessing is 16% with 33.3% and 0% as the 95th and 5th percentile respectively. Mean performance when using the CI only was within the chance range (mean=17.9 %, SD=15.4). Although there was a considerable variation in the performance among the participants when using the Naida Link HA with CI, the mean performance was higher than chance (mean=34.3 %, SD=15.6). Paired-sample t-tests showed that the difference between the two listening conditions was statistically significantly different ($t(25) = 4.5$, $p < .001$). The tracking of moving sounds was better in the bimodal condition than when using one CI by 16.4 % (95% CI, 8.9 to 23.9).

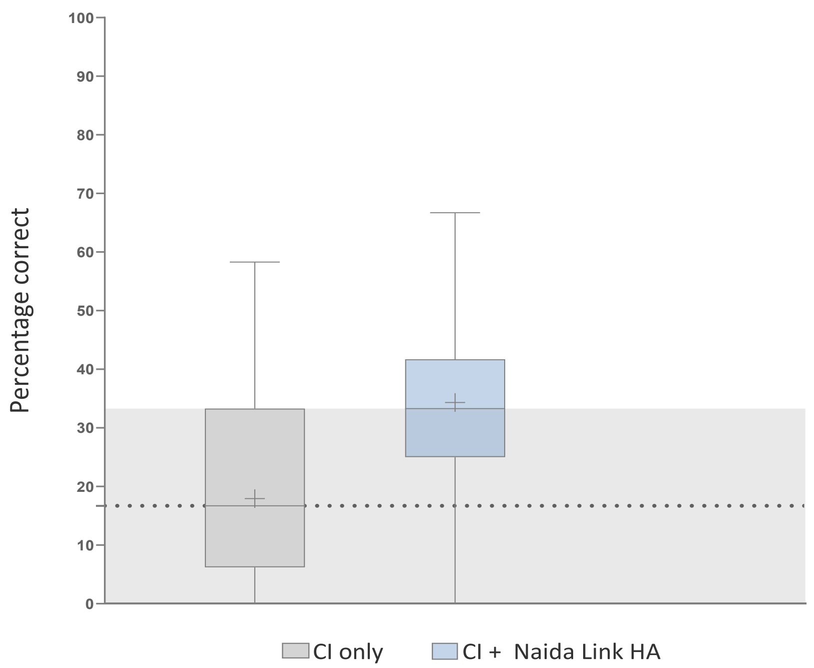

Figure 5.10: Results of the tracking test in percentage correct for the adult CI participants in the listening condition of using the CI only (grey box plots) and in the listening condition of CI+ Naida Link HA (blue box plots). The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The dashed horizontal line shows the level of performance expected by chance, with the grey shaded area showing the 5th and 95th percentiles of the change range.

Correlation between the localisation and tracking tests

The relationship between the localisation and tracking tests for integrated bimodal participants was examined for both listening conditions: (1) CI only and (2) CI+ Naida Link HA.

For the condition of CI only, there was no significant correlation between the two tests, r= 0.3 (95% CI -0.2 to 0.6), p=.2. For the bimodal listening condition, a significant correlation between the localisation and tracking tests was found, r= 0.6 (95% CI .3 to 0.8), p=.001.

5.10.3 Telephone test

The mean performance on the telephone test in quiet and in noise in the two listening conditions, (1) CI + Naida Link HA and (2) CI + Naida Link HA+ DuoPhone, is shown in Figure 5.11.

In quiet, the mean performance was 91.8% (SD= 7.8) and 91.1% (SD= 8.2) for CI + Naida Link HA and for CI + Naida Link HA+ DuoPhone conditions respectively. No clear difference between the two listening conditions can be seen.

In noise, the mean performance was 80.1% (SD= 13.9) and 84.3% (SD= 10.6) for CI + Naida Link HA and for CI + Naida Link HA+ DuoPhone conditions respectively. The mean difference between the two conditions was relatively small (mean= 4.2%, SD= 11). Paired-sample t-tests showed that the difference between the two conditions was not statistically significantly different ($t(25) = 1.96$, $p > 0.05$).

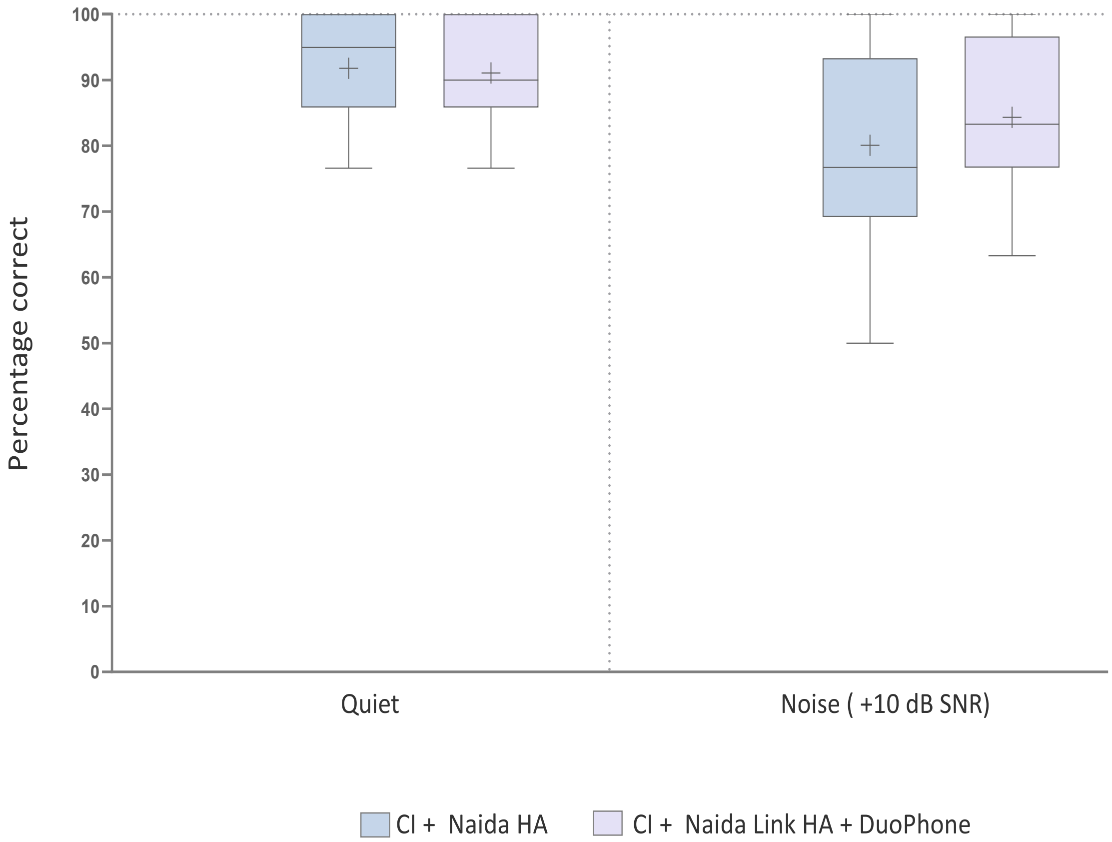

Figure 5.11: Results of the telephone test in quiet (left-hand panel) and in noise (right-hand panel) for the adult CI participants in the listening condition of CI+ Naida Link HA (blue box plots) and in the listening condition of using CI+ Naida Link HA+ DuoPhone. The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean.

Table 5.7. shows the responses from the integrated bimodal participants on the Telephone- Use questionnaire. Only 30.8 % of the participants were regular telephone users on a daily basis whereas 46.2% of the participants used the telephone 3-4 times a week. In addition, the questionnaire results indicate that the majority of the participants were somewhat confident when using the telephone (84.6%). All the participants used the telephone the standard way (relying on hearing only), particularly when they talked with familiar people. However, less than half of the participants (46.2%) talked with unfamiliar people when relying on hearing only. Approximately 69.2% of the participants preferred to use a mobile phone and use the special features, programs or any accessories. Bluetooth and DuoPhone were the most commonly used programs as reported by the participants (61.1% and 55.6 % respectively).

Table 5.7: Naida Link bimodal participants' responses on the Telephone- Use questionnaire (n=26).

Q1. How often do you use your mobile phone/telephone?	**Responses N (%)**	**Comments**
Every day	8 (30.8)	
3-4 times in the week	12 (46.2)	
From time to time (a couple of times in a year)	6 (23.1)	
Never	0	
Other	0	
Q2. How confident are you in using a telephone using the 'standard' way, i.e. relying on hearing only?	**Responses**	**Comments**
Not confident at all	1 (3.8)	
Somewhat confident	22 (84.6)	
Confident	2 (7.7)	
Very confident	1 (3.8)	
Q3. To whom do you speak when using the telephone the 'standard' way, i.e. relying on hearing only?	**Responses**	**Comments**
Familiar people	26 (100)	
Unfamiliar people	12 (46.2)	
Q4. How do you use the telephone?	**Responses**	**Comments**
Hearing only	26 (100)	Preferred way:

Using both hearing and seeing the face of speaker, e.g. Skype or WhatsApp call etc.	5 (19.2)	• Rely on both hearing and seeing the face of speaker: 4 • Text messages: 4
Text messages	7 (26.9)	
Q5. What telephone do you prefer to use (if applicable):	**Responses**	**Comments**
Landline	7 (26.9)	
Mobile	18 (69.2)	
DECT	8 (30.8)	
Q6. Do you use any special features, programs or any accessories e.g. Bluetooth, ComPilot, DuoPhone etc.	**Responses**	**Comments**
Yes	18 (69.2)	If yes, please specify: • Bluetooth: 11 • Roger: 1 • ComPilot: 7 • Connect: 1 • DuoPhone: 10
No	8 (30.8)	
Q7. Would you be interested in attending a telephone-training workshop at USAIS?	**Response**	**Comments**
Yes	14 (53.8)	
No	11 (42.3)	

5.10.4 SSQ

Only the complete questionnaires for the three listening conditions were included in the analysis (n=20; 77%). Five questionnaires were excluded due to being incomplete in at least one of the three listening conditions. One of the participants did not wish to complete the questionnaire. Informal feedback from the participants was that the questionnaire was lengthy and took a long time to complete.

Overall and the three subscales

The scores of the three main subscales of the SSQ, namely speech, spatial and qualities of hearing were calculated for each participant for the three listening conditions: CI only, CI + previous standard HA, and CI + Naida Link HA. In addition, the overall SSQ score was calculated by taking the average score across the three subscales. Figure 5.12 shows the self-rated scores on the overall SSQ and each of the three subscales for the integrated bimodal participants in the three listening conditions. A higher score indicates greater ability.

Several trends can be observed from Figure 5.12. First, there is no notable difference in the scores reported for the overall and the three subscales among the using CI alone condition and using CI with a standard HA. However, the scores were generally higher in the listening condition of using CI with a Naida Link HA than the other two listening conditions on the overall SSQ and the three subscales. Additionally, the mean score of the spatial subscale tends to be the lowest while the main score of the qualities of hearing tends to be highest (best) for the three listening conditions.

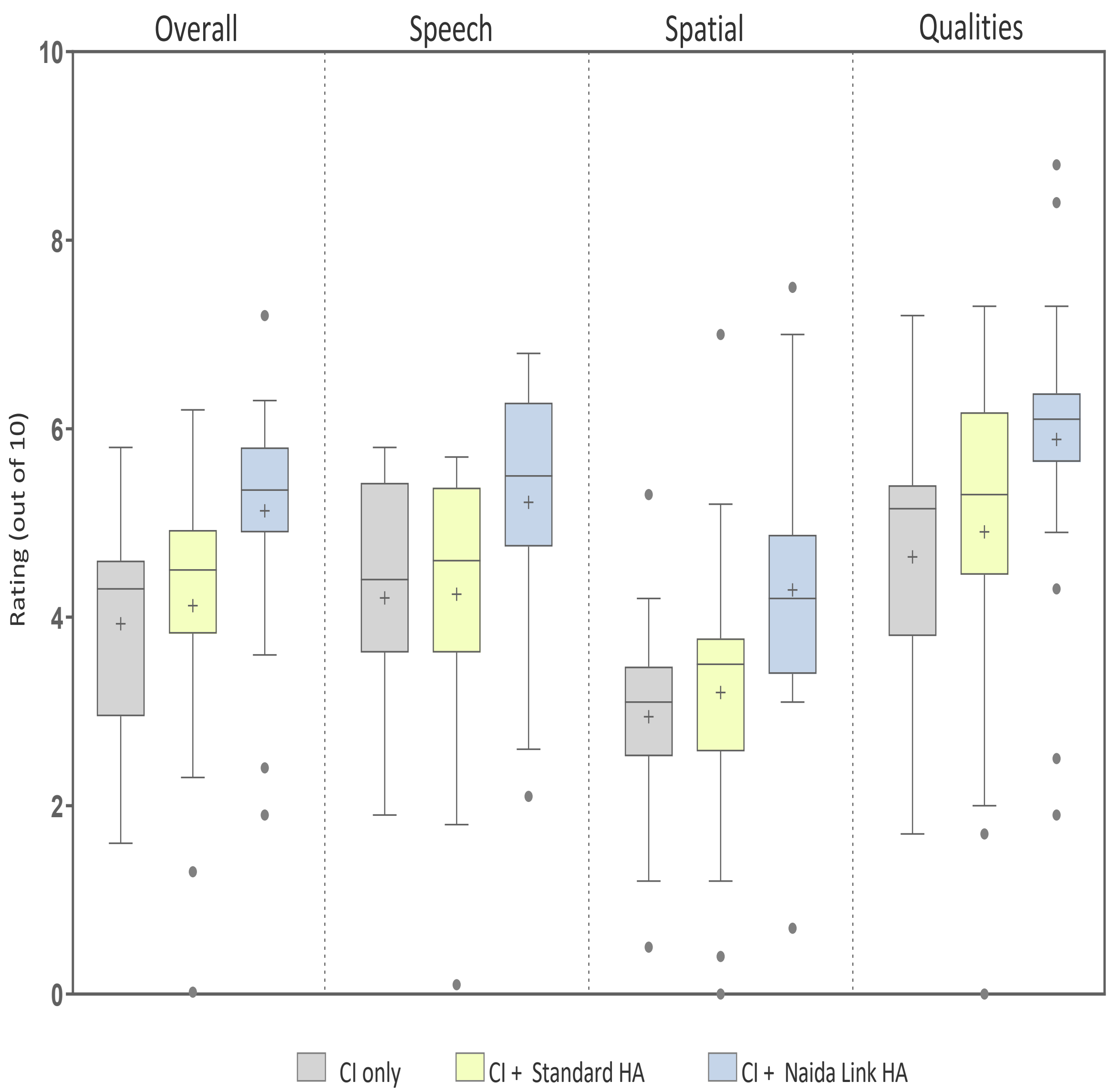

Figure 5.12: Scores on the overall SSQ and each of the three subscales: speech, spatial and qualities of the listening conditions: (1) the CI alone (grey box plots), (2) CI + previous standard HA (green box plots), and (3) CI+ Naida Link HA (blue box plots). The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The outliers are plotted as solid circles.

To examine the above trends, a two-way repeated measures ANOVA test with the listening condition and type of subscale as the independent variables was performed. Mauchly's test of sphericity indicated that the assumption of sphericity had been met for the listening condition and for the type of subscale, but it was violated for the two-way interaction, $\chi 2(9) = 20.2$, $p = .02$. Therefore, the two-way repeated measures ANOVA test with a Greenhouse-Geisser correction was used to find the main effect of the interaction. The main findings are:

- The main effect of the listening condition was statistically significant, indicating that the averaged SSQ scores across the subscales (overall scores) are statistically significantly different between the three listening conditions: F (2,38) = 19.6, p<.001.
- Post hoc tests revealed a significant difference between using CI with a Naida HA compared to using CI alone, and between using CI with a Naida HA compared to using CI with a standard HA. The results of post hoc tests for the overall SSQ are reported in Table 5.8.
- The main effect of the type of subscale was statistically significant, indicating the average scores across the listening conditions are significantly different between each subscale: F (2,38) = 22.4, p<.001.
- Post hoc tests revealed that the scores for spatial subscales were significantly lower than that for the speech (p= 0.001) and qualities subscale (p <0.001). The tests also showed that the scores for qualities of hearing was significantly higher than that for the speech (p= 0.021) and spatial subscale (p<0.001).
- The listening condition* type of subscale interaction was not statistically significant, F (2.9, 54.9) = 1.2, p= 0.3. This finding indicates that the differences between the subscales are the same for the listening conditions. In other words, the finding indicates that the difference between the three listening conditions is not statistically significantly different on the SSQ subscales.

To examine the difference between the listening conditions in greater depth for each subscale, a one-way repeated measures ANOVA test was carried out for the scores of the speech, spatial, and qualities-of-hearing subscales. Mauchly's test of sphericity indicated that the assumption of sphericity was met ($p > 0.05$) for each subscale. There were statistically significant differences between self-rated scores among the three listening conditions for the speech subscale (F (2,38)= 21.7, p<.001), spatial subscale (F (2,38)= 12.7, p<.001), and qualities subscale (F (2,38)= 19.8, p<.001). Then, post hoc tests were carried out to investigate the differences between the three listening conditions. The mean difference with a 95% confidence interval is reported in Table 5.8. There was a slight improvement in self-rated scores when using CI with the standard HA compared to using CI alone on all subscales; however the difference is not statistically significant. In contrast, the scores were statistically significantly higher when using CI with a Naida Link HA compared to using CI alone or CI with the standard HA for all subscales.

Table 5.8: Mean difference (in dB) between listening conditions (95% confidence of the mean difference) and p values on the overall SSQ and three subscales: speech, spatial and qualities of hearing.

	Overall	**Speech**	**Spatial**	**Qualities**
(CI + Standard HA) - CI only	0.2 (-0.2 to 0.6) *p*=.3	0.04 (-0.2 to 0.3) *p*=.8	0.3 (-0.2 to 0.8) *p*=.3	0 .3 (-0.1 to 0.6), *p*=.2
(CI + Naida Link HA) - CI only	1.2 (0.7 to 1.7) *p*<.001	1 (0.6 to 1.4) *p*<.001	1.3 (0.7 to 2) *p*<.001	1.2 (0.7 to 1.8) *p*<.001
(CI + Naida Link HA) - (CI + Standard HA)	1 (0.6 to 1.4) *p*<.001	1 (0.6 to 1.3) *p*<.001	1.1 (0.5 to 1.7) *p*=.002	1 (0.6 to 1.4) *p*<.001

Telephone use

A one-way repeated measures ANOVA test was carried out on the rated scores of questions 13 and 14 to assess the difference between the three listening conditions for each question separately.

For question 13, Mauchly's test of sphericity indicated that the assumption of sphericity was met: $\chi2(2) = 5.6$, $p = 0.06$. The results show that the self-reported scores were statistically significantly different across the three listening conditions, $F (2,38) = 25.1$, $p< 0.001$. Post hoc tests (paired-sample t-test) revealed significant differences between all three listening conditions as shown in Table 5.9.

For question 14, Mauchly's test of sphericity indicated that the assumption of sphericity had been violated $\chi2(2) = 24.7$, $p <0.001$. Therefore, the Greenhouse-Geisser correction was applied. The results show that the self-reported scores were statistically significantly different across the three listening conditions: $F (1.1, 21.8) = 14.8$, $p= 0.001$. Post hoc tests (paired-sample t-test) revealed a significant difference between the conditions of using CI with a Naida Link HA and using the CI only, and between the conditions of using CI with a Naida Link HA and using the CI with the standard HA as shown in Table 5.9.

Table 5.9: Mean difference between listening conditions (95% confidence of the mean difference) and p values on questions 13 and 14 on the speech subscales of the SSQ.

	Question 13	**Question 14**
(CI + Standard HA) **-** **CI only**	-0.8 (-1.4 to -0.2) *p*=0.008	-0.1 (-0.2 to 0.04) *p*= 0.2
(CI + Naida Link HA) **-** **CI only**	1.03 (0.6 to 1.4) *p*<.001	0.8 (0.4 to 1.3) *p*=.001
(CI + Naida Link HA) **-** **(CI + Standard HA)**	1.8 (1.2 to 2.5) *p*<.001	0.9 (0.5 to 1.4) *p*=.001

Music perception

To measure the difference in music perception between the three listening conditions, the scores on questions 5, 7, and 8 on the qualities subscale have been averaged and then compared between the listening conditions. A one-way repeated measures ANOVA test was carried out on the average score for the three listening conditions. Mauchly's test of sphericity indicated that the assumption of sphericity was met: $\chi2(2) = 4.03$, $p = 0.1$. The results showed that the average scores were statistically significantly different across the three listening conditions, $F (2,38) = 26.8$, $p< 0.001$. Post hoc tests (paired-sample t-test) followed which revealed a significant difference of 0.6 point (95% CI, 0.3 to 0.9), $p =0.001$ between the conditions of CI + standard HA and using CI only. Additionally, there was a significant difference of 1.3 point (95% CI, 0.8 to 1.7), $p < 0.001$ and of 0.7 (95% CI, 0.3 to 1.01), $p= 0.001$ between CI + Naida Link HA condition and CI only condition, and between CI + Naida HA condition and CI + standard HA condition respectively.

5.10.5 Correlation between performance tests and subjective rating scales

The relationship between the self-rated scores on the SSQ and scores of performance tests including the speech-in-noise, spatial-listening and telephone tests when using a Naida Link HA were examined. Only 24 participants completed the SSQ questionnaire in the listening condition of using the CI and the Naida Link HA. Therefore, correlation analysis has included the data of 24 participants.

The correlation between the average of the three speech tests and the SSQ scores of speech subscale was examined and the results are shown in Table 5.10. A significant correlation was found between the SSQ scores of speech subscale and the average of the speech tests. Thus, the correlation between each speech test and the SSQ speech subscale was investigated. A significant correlation was found only between SrN±60° test and the SSQ speech subscale.

Additionally, the correlation between the SSQ spatial subscale and the average of spatial tests in the listening condition for using the CI and Naida Link HA (including the localisation and tracking tests, in percentage correct for both tests) is presented in Table 5.10, showing no significant correlation.

The correlation between the SSQ scores and telephone test was examined by looking at the relationship between the scores of question 13 on the SSQ speech subscale and the average of telephone tests (including both quiet and noise conditions) in the listening condition of using DuoPhone. As a significant correlation was found, the correlation between the SSQ scores of question 13 and each telephone test was analysed. Table 5.10 also showed a significant correlation between each telephone test and the scores on SSQ question 13. In addition, the correlation between the scores on question 14 of the SSQ speech subscale and telephone-in-noise test at the listening condition of using DuoPhone is reported in Table 5.10, showing no significant correlation between them. It should be noted that the number of participants' data which was included in the correlation analysis between questions 13/14 on the SSQ speech subscale and the average of telephone tests was only 23. The data of a further participant were excluded due to incomplete answers on questions 13 and 14 on the SSQ speech subscale in the listening condition of using the CI and a Naida Link HA.

Table 5.10: Results of correlation analyses between SSQ-rated scores and the performance tests (speech- in-noise tests, spatial tests and telephone tests) in the listening condition of using CI + Naida Link HA. Significant correlations are highlighted in bold.

SSQ	Listening tests	Correlation r value (95% confidence interval)	P
SSQ- speech subscale	Average of speech tests (in the best-aided condition)	-0.49 (-0.75 to -0.11)	**0.02**
	SrN±60° test	-0.52 (-0.77 to -0.15)	**0.019**
	S0°N±60° (StereoZoom)	-0.34 (-0.66 to 0.07)	0.099
	SHANCI (ZoomControl)	-0.297 (-0.62 to 0.12)	0.2
SSQ- spatial subscale	Average of spatial tests (Both localisation and tracking in % correct)	0.13 (-0.29 to 0.50)	0.6
SSQ (Q13- speech subscale) *	Average of telephone tests (in DuoPhone condition)	0.6 (0.2 to 0.8)	**0.003**
	Telephone test-in-quiet with DuoPhone	0.51 (0.12 to 0.76)	**0.01**
	Telephone test-in-noise with DuoPhone	0.42 (0.01 to 0.71)	**0.04**
SSQ (Q14- speech subscale) *	Telephone test-in-noise with DuoPhone	0.2 (-0.3 to 0.6)	0.4

*n= 23 as one participant answered this question as N/A (not applicable).

5.10.6 Correlation between unaided hearing thresholds of the non-implanted ear and integrated bimodal technology

The relationship between the unaided hearing thresholds of the non-implanted ear and the performance scores of the participants when using the Naida Link HA was examined. In addition, the relationship between the unaided hearing thresholds of the non-implanted ear and the integrated bimodal benefit was examined. The data of all the 26 participants were included in the correlation analysis, except for the correlation between the thresholds and the SSQ questionnaire (only the scores of 24 participants on the SSQ and the data of the integrated bimodal benefit of 21 participants were included due to an incomplete questionnaire).

Pearson correlation analysis revealed that there was no significant correlation between unaided hearing thresholds of 250Hz, 500Hz, 1000 Hz, the PTA of 250-500 Hz or the PTA of 500-1000-2000 Hz of the non-implanted ear and the performance scores when using the Naida Link HA on any of the performance tests or on the SSQ questionnaire (the results of correlation analysis can be found in Appendix N). Similarly, there was no significant correlation between the unaided hearing thresholds of the non-implanted ear and the integrated bimodal benefit, as shown in Table 5.11.

Table 5.11: Results of correlation analyses, r values (95% confidence interval), between the unaided hearing thresholds of the non-implanted ear and the integrated bimodal benefit.

	PTA (500-1000-2000 Hz)	**PTA (250-500 Hz)**	**1000Hz**	**500Hz**	**250 Hz**
Average benefit in speech tests	-0.2 (-0.5 to 0.2)	0.1 (-0.3 to 0.5)	-0.1 (-0.5 to 0.3)	0.00 (-0.4 to 0.4)	0.2 (-0.2 to 0.5)
Average benefit in spatial tests	0.3 (-0.1 to 0.6)	0.3 (-0.1 to 0.6)	0.1 (-0.3 to 0.5)	0.2 (-0.2 to 0.6)	0.4 (-0.02 to 0.7)
SSQ overall*	-0.2 (-0.6 to 0.3)	0.1 (-0.4 to 0.5)	-0.1 (- 0.5 to 0.3)	0.1 (-0.3 to 0.5)	0.04 (-0.4 to 0.5)

*n=21

The results of the correlation analysis between the unaided hearing thresholds of the non-implanted ear and the benefit of each feature of Binaural VoiceStream Technology are shown in Table 5.12. There was a significant negative correlation between the ZoomControl benefit and the unaided threshold at 1000Hz in the non-implanted ear.

Table 5.12: Results of correlation analyses, r values (95% confidence interval), between the unaided hearing thresholds of the non-implanted ear and benefit of Binaural VoiceStream Technology (StereoZoom, ZoomControl, and DuoPhone). Significant correlations are highlighted in bold.

	PTA (500-1000-2000 Hz)	**PTA (250-500 Hz)**	**1000 Hz**	**500Hz**	**250 Hz**
StereoZoom benefit S0N ± 60	0.002 (-0.4 to 0.4)	-0.2 (-0.6 to 0.2)	0.1 (-0.3 to 0.4)	-0.1 (-0.5 to 0.3)	-0.3 (-0.6 to 0.1)
ZoomControl benefit SHANCI(±90)	-0.2 (-0.6 to 0.2)	-0.2 (-0.6 to 0.2)	**-0.4 (-0.7 to -0.1) p=0.03**	-0.3 (-0.6 to 0.1)	-0.1 (-0.5 to 0.3)
DuoPhone benefit Averaged telephone test (Quiet and noise)	0.1 (-0.3 to 0.4)	0.3 (-0.1 to 0.6)	-0.1 (-0.4 to 0.3)	0.1 (-0.3 to 0.5)	0.3 (-0.1 to 0.6)

5.11 Discussion

The aim of the present study was to assess the outcomes of the integrated bimodal technology (using Naida Link HA) compared to using the CI only and to the standard HA on a real-life test battery. The outcomes when using a Naida Link HA were compared to using the CI only in speech-in-noise and spatial-hearing tests. Additionally, these outcomes were compared to the standard HA in SSQ questionnaires. The second aim was to assess whether using Binaural VoiceStream Technology would add a further improvement compared to the standard settings (everyday map) of integrated bimodal technology. The main findings of this study are summarised as follows:

- There was a statistically significant improvement in the SRT when using CI + Naida Link HA compared to using the CI only in the three speech-in-noise tests
- There was a statistically significant improvement with StereoZoom compared to the standard settings (everyday map) of the Naida Link HA when the speech was fixed from the front and the uncorrelated multi-talker babble noise was presented from the loudspeakers placed at 60° on both sides

- There was a statistically significant improvement with ZoomControl compared to the standard settings of the Naida Link HA when the speech was presented on the HA side and the noise on the CI side
- There was a statistically significant improvement when using the CI + Naida HA compared to using the CI only in the localisation and tracking tests
- The overall self-reported scores of the SSQ, as well as the three subscales, were statistically significantly higher for the listening condition when using the CI +Naida HA compared to using the CI only or using the CI +standard HA. There was no significant difference for the listening condition when using the CI only compared to the CI+ standard HA on the overall score and three subscale scores of the SSQ
- Using the DuoPhone improved the performance of telephone use in noise in the sample. However, this improvement was not statistically significant. Similarly, there was no statistically significant difference between using the DuoPhone and using standard settings of the Naida Link HA in telephone use in quiet.

5.11.1 Speech in noise

In this section the overall results will be presented first followed by a more specific discussion of the effect of StereoZoom and ZoomControl.

The present study found a statistically significant bimodal benefit when using the integrated technology (CI +Naida Link HA) compared to using the CI only. The amount of benefit to the SRT in dB SNR ranged from 1.4 dB to 3.5 dB depending on the test set-up. This was consistent with findings from previous studies (Bionics, 2016a, Bionics, 2016b, Veugen *et al*., 2016a, Vroegop *et al*., 2018b, Cuda *et al.*, 2019, Ernst *et al.*, 2019, Vroegop *et al.*, 2019, Spirrov *et al.*, 2020, Warren *et al.*, 2020).

The largest benefit of 3.5 dB was found when the noise was presented on the CI side and the speech on the HA side. This is in line with Vroegop *et al.* (2019) as they found the largest bimodal benefit of 2.5 dB with using the Naida Link HA when the noise was presented at the CI and the speech from the front compared to other test set-ups in their study. Likewise, Spirrov *et al*. (2020) found the largest bimodal benefit of 4.4 dB with the matched AGC between the CI and HA when the noise was on the CI side compared to when the noise presented from the front or on the HA side. It should be noted that Spirrov *et al.* (2020) used a Nucleus 6 processor from Cochlear and an Enzo 3D HA from GN hearing in their study. However, they matched the AGCs between the CI sound processor and HA by using the same parameters used in the Veugen *et al.* (2016a) study which used an AB CI processor and the Phonak Naida IX UP HA. As discussed in Section 5.2, the study by Veugen *et al*. (2016) was the preliminary work for developing the Naida Link HA where the AGC parameters of the HA were changed to match the AGC parameters of the CI processor. Interestingly, the largest bimodal benefit (4.1 dB) in the study by Veugen *et al.* (2016a) was found in the test configuration of the noise on the HA side. When the noise was presented on the CI side, the bimodal benefit was 3.1 dB which was comparable to the benefit found in the present study. The difference in amount of the bimodal benefit when the noise was on the CI side between the present study and the previous study might be related to the slight difference in test set-up and the type of noise. The speech was presented on the HA side in the current study while it was presented from the front in the previous studies. In addition, Vroegop *et al*. (2019) used steady-state speech-shaped noise that would explain the smallest bimodal benefit of 2.5 dB found for this particular test set-up in their study, whereas a multi-talker babble noise was used in this study and a single talker masker in Veugen *et al.* (2016a) and Spirrov *et al*. (2020).

The smallest significant bimodal benefit in the present study was 1.4 dB in the test of roving speech in uncorrelated multi-talker noise presented from the two loudspeakers at 60°. This study used roving speech that can be presented randomly from one of the nine loudspeaker arrays placed at ±90°, ±60°, ±30°, ±15°, and 0° azimuth. This test set-up simulates one of the common listening situations in real life where the listener is sitting around a table with a group of speakers (i.e. friends, family, colleagues etc.) with background noise. Limited studies have used roving target speech set-ups with adult CI users. For instance, van Hoesel (2015) and Dorman *et al.* (2020) assess the performance of bilateral CI users using a dynamic spatial-visual paradigm where the target speech was presented randomly from different loudspeakers. One of the aims of the present study was to understand the performance of adult CI users with different listening conditions (CI only vs. CI+ Naida Link HA) in this listening situation. This task might have been challenging to the CI users as they needed first to identify where the speech was coming from and then spontaneously turn their heads and focus on the target sentence. Although the participants were not asked to identify the direction of the speech during the test trial, it was challenging to constantly need to adapt speech that was not fixed. Thus, this would explain the smallest bimodal benefit found in this test set-up. To the best of the researcher’s knowledge, there is only one study that used non-fixed speech when testing the CI users using the integrated bimodal technology. In the study by (Vroegop et al., 2018b), the speech was randomly presented from two loudspeakers placed at +45° and -45°, whereas a babble noise was presented from four loudspeakers placed at ± 45° and ± 135°. They found a bimodal benefit of 3.1 dB using the Naida Link HA which is better than the benefit found with roving speech in the current study. Again, this could be related to the number of loudspeakers used to present the speech in the Vroegop *et al*.

(2018b) study with only two loudspeakers which might be easier for the listeners compared to nine loudspeakers as has been used in the current study.

For the S0N± 60° test, the bimodal benefit was 1.7 dB which is comparable to the benefit found by Vroegop *et al*. (2019) of 1.6 dB when the speech and noise were presented from the front. It can be argued that this comparison is not relevant as the noise was presented from different directions. Nevertheless, the study carried out in Chapter 4 showed there was no significant difference in the SRTs between S0°N± 60° and S0°N0° for the NH participants. In a similar set-up but with the noise presented from ± 45° and ± 135° simultaneously and the target speech from the front, Vroegop *et al.* (2018b) did not find a bimodal benefit. The reason that there was no bimodal benefit might possibly be related to the set-up being more difficult than if the noise was presented from two loudspeakers. Cuda *et al*. (2019) also reported a significant bimodal benefit when the speech and noise were presented from the front; however the amount of the benefit (3.9 dB) was larger than those found in the current study and in the one by Vroegop *et al.* (2019). The discrepancy in the amount of bimodal benefit might be related to the differences in methodological settings among these studies. In addition, the finding in the current study is in line with Warren *et al.* (2020) who found a significant improvement in the speech perception score of 20% with using the CI and Naida Link HA compared to using the CI only when the speech and noise were presented from the front.

The above results show that using integrated bimodal technology significantly improved the speech perception in noise. The amount of bimodal benefit largely depends on the direction of the noise and speech. Only multi-talker babble noise was used in this study; therefore it would be interesting to know whether the bimodal benefit might be different with other type of noise using the same test battery.

StereoZoom

The benefit of using StereoZoom was assessed in the speech test S0°N± 60° only. As discussed in section 5.5.1, StereoZoom helps the listeners to focus on a single speaker standing directly in front of them while reducing the background noise, by producing a narrower fixed-target beam (± 45°). The present study found an additional bimodal benefit of 1.2 dB by enabling the StereoZoom feature, in total a 2.9 dB improvement over the CI only. This finding confirmed the significant benefit of the StereoZoom over the standard settings of the Naida Link HA and over the CI only shown in previous studies (Bionics, 2016a, Vroegop et al., 2018b, Ernst et al., 2019). However, the benefit found in this study was smaller than the benefit found in the literature. The StereoZoom benefit over the standard settings of a Naida Link HA found by Vroegop et al. (2018b) was 4.7 dB when the noise was fixed from the front and the noise from the loudspeakers was at ± 45° and ±

135°. Similarly, a StereoZoom benefit of 4.6 and 2.6 dB over the standard settings (using T mic) were found by Ernst *et al*. (2019) in test set-ups A (S0° N ±60°,±120°, & 180°) and B (S0°N±30° & ±60°) respectively. The StereoZoom benefit found in the present study compared to the standard settings of the Naida Link HA was only 1.2 dB. This small significant benefit was found without applying the Bonferroni correction. This benefit would not be considered significant with using Bonferroni correction. It would be arguable that there was a possibility of increasing the risk of type 1 (false positive) with results as a result of not using this type of correction. Nevertheless, Bonferroni correction has been avoided as it tends to be strict and affect the statistical power of the test. Using a conservative test, such as with Bonferroni, are likely to reject differences between two conditions that are, in reality, meaningful (Field, 2013)

In addition, set-up A in Ernst *et al*. (2019) study was similar to the set-up of this study in terms of the degree of separation between the noise and the target speech, the large discrepancy in the amount of the benefit is unclear.

The benefit in their study (Ernst *et al.*, 2019) was reduced, yet it was a significant benefit in the more challenging set-up (B) where the speech and noise were less separated. This test set-up more closely mimics real-life listening situations than the other controlled set-up where the noise can come from the front as well as from behind the listeners.

Vroegop et al. (2018b) did not find a StereoZoom benefit in the test set-up where the speech was randomly presented from one of the loudspeakers at ± 45° (not fixed) and the noise came from loudspeakers at ± 45° and ± 135°. The participants in their study were seated in front of the loudspeaker placed at 0°. As can be seen, the target speech overlapped with noise without any separation during the test presentation. Furthermore, the target speech was outside the spot of the beamformer (StereoZoom) as the participant's face was not turned toward the loudspeaker that the speech was coming from. Therefore, the effectiveness of StereoZoom is highly dependent on the degree of the separation between the target speech and noise as well as the presence of the target speech within the StereoZoom spot (± 45°). This is important to ensure that CI users have a good understanding of the situations where StereoZoom can be used and be beneficial. Yet, it would be interesting to know how much benefit the StereoZoom can provide in a real-life situation where the speech is not fixed from one direction.

ZoomControl

The ZoomControl benefit was assessed in the speech test SHANCI only. As discussed in section 5.5.2, ZoomControl allows the listeners to focus on a preferred direction that they want to listen to when they cannot see the talker's face (right, left, or back) such as when someone is seated behind the person in a car or walking alongside them.

For this test set-up, an additional significant benefit of 6.1 dB was found with using ZoomControl compared to the standard settings of a Naida link, in a total of 9.7 dB benefit over the CI only. This finding is in line with the results of the clinical study carried out by Advanced Bionics (Bionics, 2016b) which showed a statistically significant improvement in the speech scores (about 28%) when using the ZoomControl. To date, to the best of the researcher's knowledge, there is only one recent published study that assessed the benefit of ZoomControl for CI users with integrated bimodal technology (Naida Link HA) (Holtmann *et al*., 2020). They found a significant improvement with enabling the ZoomControl which was further improved at 12 weeks' acclimatisation from the fitting of a median SRT at + 0.97 dB with the standard settings of a Naida Link HA to a median at -1.8 using the ZoomControl. Although they used a similar test set-up (SHANCI) where the speech was presented on the HA side and the noise was on the CI side, the ZoomControl benefit found in the present study is relatively larger than the benefit found by Holtmann *et al.* (2020), Moreover, the participants in the Holtmann *et al.* (2020) study have a better residual hearing in the non-implanted ear than the participants in the current study. The PTA of 500, 1000, 2000, and 4000 Hz frequencies in the Holtmann *et al*. (2020) study was approximately 60 dB HL whereas the PTA for the same frequencies in the current study was 90 dB HL. One possible reason for this large discrepancy might be related to the noise masker. However, the type of noise used in the Holtmann *et al*. (2020) study was not explained. Therefore, whether the amount of benefit of ZoomControl would depend on the type of background noise is unknown. Additionally, the sample size in Holtmann *et al*. (2020) is relatively small (n=12) compared to the present study. It also worth noting that the intrasubject variability in the bimodal performance is commonly seen with CI users (Morera *et al.*, 2005, Blamey *et al.*, 2015). Nevertheless, in the current study, the large benefit that can be provided by the ZoomControl is clear. The SRTs for all the participants improved by at least 1.3 dB to 12.3 dB (Appendix M), except in one participant (ID=Naida16) where the SRT remained the same. For instance, one participant (ID= Naida 6) was able to obtain a lower SRT at a negative SNR at - 3.3 dB SNR compared to 9.3- and 5-dB SNR using CI only and CI+ Naida Link HA (general settings) respectively. The large benefit of ZoomControl probably resulted from the head-shadow effect that results in a level difference between the two ears (Veugen *et al*., 2017). Another reason is the 12 dB reduction at the microphone of the CI sound processor when ZoomControl is activated.

5.11.2 Spatial listening tests

For the localisation test, a significant improvement of the localisation performance was found using the CI+ Naida Link HA over the CI only. However, this improvement was relatively small (only 12.3%). Additionally, 14 participants (out of 26 participants) still performed close to or within the change range (33.3 % and less) with using the Naida Link HA. The single published study that assessed the localisation performance with integrated bimodal technology only compared the performance of CI users when using a Naida Link HA to the standard HA (Holtmann *et al.*, 2020). The test set-up consisted of four loudspeakers placed at 0°, ±90°, and 180°. Their results did not show a significant difference between the Naida Link HA and the standard HA in the localisation test. The number of participants included in the Holtmann *et al*. (2018) study was relatively small (only 12 participants). Therefore, it would be interesting to compare the two HAs (Naida Link HA vs. standard HA) for CI users in a localisation test with a larger number of participants. Although the sample of the current study was relatively larger (n=26), the comparison to the standard HA could not be carried out due to methodological applicability. The same test set-up using the AB Crescent of Sound has been used in previous work (Goman, 2014) to measure the localisation performance of CI participants with the CI only and with CI+ standard HA. There was no significant difference between the two listening conditions. Consequently, future studies might consider measuring the performance with standard HAs and Naida Link HAs by using the same apparatus and set-up.

In terms of RMS error in the localisation test, the present study showed a significant reduction in the error from 57.3° to 43.1° with using the Naida Link HA over the CI only. The mean RMS errors for the CI only was 57.3 which was within the range reported in the literature from 40° to 60° (Verschuur *et al.*, 2005, Ching *et al.*, 2007). Similarly, the mean RMS errors with using the Naida Link HA were close to the mean bimodal RMS errors reported in the literature when using the standard HA which ranged from 32° to 42.7° (Ching *et al*., 2004, Dunn *et al*., 2005, Potts *et al*., 2009). That would indicate that there is no large difference between the standard HA and the Naida Link HA on the localisation test. The chance range for random guessing in RMS error metric was calculated using the “Monte-Carlo” simulation in the MATLAB software. The mean of the chance range was 60° with 69.3° and 49.6° as the 95^{th} – and 5^{th}- percentile respectively. Looking at individual RMS errors of the participants enrolled in the present study showed that most of the participants (n=18, 69%) performed better than chance when using the Naida Link HA compared to the CI only. The single study that looked at the effect of using the integrated bimodal technology on the localisation test did not report its results in RMS errors. Again, it would be useful to carry out future studies that compare the CI alone vs. CI+ standard HA vs. CI+ Naida Link HA in terms of the reduction in the error and using more challenging set-ups to obtain a good understanding of the effectiveness of using the integrated bimodal system on localisation tasks.

The tracking of moving sound is an essential listening skill in real life particularly in tracking moving sound that would be life-threatening. The improvement of localisation skills is not clearly evident in the literature by using the standard bimodal technology as with the bilateral implantation. The effect of using the Naida Link HA, therefore, on tracking sounds has been considered in this study. The results showed a significant improvement in tracking performance by approximately 16.4% over the CI alone. However, the mean performance of CI +Naida HA (34.3%) was close to the chance range with the majority of participants (17 out of the 26) performing within the chance range for random guessing. To the best of the researcher‘s knowledge, only a single study (PhD study) by Goman (2014) assessed the movement tracking of the bimodal participants (standard HA) using the same apparatus as that used in the present study. Goman found an improvement in the performance by 14.6% compared to using the CI only; however the improvement was not significant. The tracking test used in this current study was harder than the test used in Goman’s study (2014) due to the modifications that were made (adding two further trajectories and making each one of the six trajectories presented twice (further details in Chapter 4 section 4.2.2.4). Yet, the current study found a significant improvement with using the Naida Link HA. Therefore, future studies might consider comparing the standard HA and the Naida Link HA on a similar test set-up to substantiate the effectiveness of integrated bimodal technology on tracking of moving sounds.

The correlation between the localisation and tracking tests was investigated in the present study. It would be useful to know whether CI users who tend to do better in localisation would do better in tracking. This would help to provide better understanding of the performance of CI users using different technology in daily-life activities. The present study found a significant correlation between the localisation and tracking in the listening condition of using CI with a Naida Link HA. This is reflected by the significant improvement seen with using a Naida Link HA in both tests. For listening using the CI alone, there was no significant correlation found between the localisation and tracking tests. This finding was expected as the scores in this listening condition were within the change range of random guessing for both tests; therefore they do not represent a real performance.

5.11.3 Telephone

There are no standardised tests that have been developed specifically to assess the performance of CI users in using and understanding speech over the telephone. Therefore, a new telephone test using a real-life set-up was designed and developed mainly to assess the effectiveness of using DuoPhone in quiet and noise relative to the use of the standard settings (everyday map) of the Naida Link HA for adult CI users. It should be noted that unlike the other tests included in the test battery, the telephone test in the present study is not directly relevant to assessing the binaural benefits of integrated bimodal technology compared to using the CI only. The results showed that there was no difference between the DuoPhone and the standard settings on speech perception in quiet. For noise conditions, using DuoPhone slightly improved the speech perception; however this small improvement was not statistically significant. This finding contradicts previous work that assessed the effectiveness of wireless-streaming hearing-assistance devices for CI users while using the telephone (Wolfe *et al*., 2016a, Wolfe *et al.*, 2016b). The device can be paired with the user's mobile phone or any personal electronic device via Bluetooth. Then, these devices transfer the audio signal from the user's device (i.e. mobile phone) to the HA or/and the CI sound processor using a digital radio frequency transmission or digital nearfield magnetic induction. Their results showed a significant improvement of word reception in quiet (18- to 28-%) and in noise (23-to 28-%) by using wireless streaming over acoustic coupling for bimodal and CI (both unilateral and bilateral) users. In addition, the finding from the present study was in contrast to a recent study that measured the benefit of using DuoPhone for bilateral CI participants which showed a significant improvement in quiet and in noise (Miller *et al*., 2021). There were few similarities in the test set-ups between the current study and the Miller *et al*. (2021) study in terms of using a fixed procedure to present the target speech in diffuse noise. In addition, one mobile phone (a study mobile) was used with all the participants to present the speech in both studies. However, there were few differences in test set-ups between the two studies which might be related to the discrepancy in the findings. Miller *et al*. (2021) used CNC words in uncorrelated classroom noise that was presented from four loudspeakers placed at 30°, 135°, 225° and 330°, whereas the current study used triple digits in multi-talker babble noise that was presented from two loudspeakers at ±60°. Moreover, the SNR level used in the Miller *et al*. study was unknown as they did not mention the personation level of CNC words.

To the best of the researcher's knowledge, the present study was the first that examined the effectiveness of using the DuoPhone to enhance speech perception over the telephone for CI participants using integrated bimodal technology (Naida Link HA). However, there were several limitations that affected the generalisability of this finding. The telephone test used in the current study was considered a rudimentary test that needs further development and standardisations (as discussed in Chapter 4 section 4.2.2.5.5). The majority of the participants' scores reached the ceiling particularly in quiet conditions. For instance, the lowest score found in the quiet test condition was 76.6% achieved by two participants whereas six participants were able to obtain a 100% correct score in the listening condition using everyday settings. Therefore, there was no improvement when the DuoPhone was enabled. Similarly, in noise, most participants achieved a score better than 70% using the standard settings of the Naida Link HA. The ceiling effect found in the present study might be related to the speech material used. The triple digits have been used as the target speech that may be easier to understand than using words or sentences for CI users. Additionally, a fixed procedure at a favourable SNR level (+10 dB SNR) has been used in noise conditions. It is well known that fixed procedures are more susceptible to floor and ceiling effects than adaptive procedures (Schafer *et al*., 2011). As a result, future studies should consider using more challenging SNR levels or using adaptive procedures. Therefore, the insignificant small benefit of DuoPhone found in the current study most probably related to methodological limitations rather than the efficiency of the DuoPhone.

Prior to carrying out the telephone test, the participants in the current study were asked to fill in a short questionnaire about their telephone use in daily life. The results of the questionnaire showed that nearly half of the participants (46%) were able to use the telephone to some extent (3-4 times in the week). Similar findings have previously been reported by Anderson *et al.* (2006) which found nearly 71% and 54% of CI users were able use a landline and a mobile phone to some extent respectively. Clinkard *et al*. (2011) reported a higher number where 87% of 252 adult CI users indicated they used a telephone to some extent. The higher percentage of CI users who using the telephone in the Clinkard *et al.* (2011) study would be related to the larger number of participants (252 CI users) compared to the participants that completed the telephone questionnaire in the present study (26 CI users).

No participant reported not using a telephone at all which contrasted to the previous studies. For instance, Adams *et al*. (2004) reported that 44% of the participants in their survey did not use the telephone at all. Likewise, some participants in the study by Anderson *et al*. (2006) reported not using a telephone, ranging from 15% to 40% according to the type of telephone (landline vs. mobile). In addition, 13% of the participants in the Clinkard *et al*. (2011) study indicated they did not use a telephone. Two possible explanations might be related to this discrepancy. First, the advanced improvement in telephone technology and hearing assistance devices in the last decade might have encouraged CI users to use the telephone. Another reason is that the sample size in the present study was relatively small (n=26 responses) compared to 86, 196 and 252 responses in the Adams *et al*. (2004), Anderson *et al*. (2006) and Clinkard *et al.* (2011) studies respectively. Nevertheless, many of the participants in the current study reported a lack the confidence to some extent when using the telephone. Nearly as many as 85% of them reported that they are only somewhat confident.

Talking to an unfamiliar speaker over the telephone was the most challenging for CI users. Approximately 46% of the participants in this study reported that they can use the telephone with an unfamiliar speaker whereas all participants reported that they can use the telephone to speak with a familiar speaker. These results are slightly better than reported in previous studies. For instance, only 7% of CI users (n=66) in a survey study conducted by Dorman *et al*. (1991) reported that they can use the telephone with an unfamiliar speaker. Anderson *et al*. (2006) showed only 25% and 38% of the CI participants in their international survey could use landline and mobile phones respectively to talk with an unfamiliar speaker. Similarly, Clinkard *et al.* (2011) showed that the ability of CI users to use the telephone was limited by the familiarity of the speaker as only 37% of the CI users using the telephone (n=217) were able to answer the telephone at any time regardless of the speaker familiarity. Moreover, a recent study (Rumeau *et al*., 2015) showed only 35% of the CI users (n=26) were able to use the telephone with an unfamiliar speaker. It seems that the recent advanced improvements in CI, telephone and hearing-assistance technology was associated with the increase in the number of CI users using the telephone with an unfamiliar speaker in the current study. However, it should be stressed that the sample size of the current study was smaller than these previous studies, except the Rumeau *et al.* (2015) study where the sample size was comparable. Approximately 69% of the participants in the current study reported using a hearing-assistance device or special features. Bluetooth and DuoPhone were the most reported features used, probably due to the ease of using them.

In short, the Telephone- Use questionnaire suggested that, although using a telephone is a challenging task for many CI users, the recent advances and improvements in the CI sound processor, HAs, hearing-assistance features, and telephone technology have helped to improve the use and speech understanding over the telephone. However, further studies are required to develop a standardised telephone test that can be used with CI users. The development of such a telephone test would be helpful in research and in clinical practice to accurately determine the performance of the CI users and to examine the effectiveness of assistance devices and features when using the telephone.

5.11.4 SSQ

One of the aims of the current study was to examine self-rated abilities of adult unilateral CI participants in real-life when using the CI only versus the CI with a standard HA versus the CI with a Naida Link HA. The results showed that the participants gave statistically significant higher ratings when using the CI with a Naida Link HA compared to using the CI only as well as to using the CI with their previous standard HA overall and the three subscales of the SSQ. The mean rating of the overall of the SSQ using the Naida Link HA was about 5.1 points which is at the mid-range of the scoring scale. Compared to the CI only (3.9 points) and to the CI with standard HA (4.1 points), this finding suggests that there is an improvement in the hearing skills needed for everyday functions with using the Naida Link HA; however there are still some difficulties which might be experienced. This finding was in line with previous studies that examined the subjective benefit of using integrated bimodal technology. Vroegop et al. (2018b) found an overall rating score of the SSQ of about 5.2 and 5.4 points for using the Naida Link HA when programmed with APDB and NAL-NL2 formulae respectively. A similar finding was found by Holtmann *et al*. (2020) where there was a significant improvement in using the Naida Link HA over the standard HA in the hearing implant sound quality index (HISQUI) – 19 at the 8-12 week assessment post-fitting. However, the finding of the superiority of using the Naida Link HA over the standard HA should be treated with considerable caution as the validity of rated scores for the listening condition of using the standard HA might be affected by the participants' memory. For instance, it could be some participants always use the Naida link HA which makes it hard for them to remember what the standard HA was like in the past. There was no question in the questionnaire asking about how well the participants remember their experience with standard HA.

Another finding of the present study is that there were statistically significant differences in the rating scores between the three subscales of the SSQ. The mean scores with the Naida Link HA plus the CI were 5.2 points on the speech subscale, 4.3 points on the spatial subscale, and 5.9 points on the qualities-of-hearing subscale. The participants rated their ability on the qualities-of-hearing subscale statistically significantly higher (better) than on the speech and the spatial subscales. It might be argued that the higher rating on the qualities of hearing associated with using the Naida Link HA could be due to some bias of the participants anticipating a better performance with the integrated technology. However, there was no statistically significant interaction between the listening conditions and the SSQ subscales which means a similar trend was found when using the CI only and using the CI with a standard HA. In addition, a similar trend was also reported in several studies for young and older NH adults where their scores were significantly higher on the qualities-of-hearing subscale than on the speech and spatial subscales (Banh *et al*., 2012, Demeester *et al*., 2012, Zahorik and Rothpletz, 2014, Moulin and Richard, 2016). Moreover, Vroegop et al. (2018b) reported similar rating scores on the speech subscale (5.1 points), on the spatial subscale (4.6 points), and on the qualities-of-hearing subscale (5.9 points) when using the Naida Link HA (fitted with the APDB formula).

There was no statistically significant difference found in the current study overall and on the three subscales of the SSQ between the listening condition of using the CI only and using the standard HA +CI. This finding is consistent with previous studies that used the SSQ questionnaire to assess the subject benefit for bimodal users (Noble *et al*., 2008, Farinetti *et al*., 2015). For instance, Noble *et al*. (2008) did not find a statistically significant difference on the rating scores of three of the SSQ between the bimodal users' group (n=39) and the unilateral CI users' group (n=70). Likewise, Farinetti *et al.* (2015) found better results on each subscale of the SSQ for the bimodal group (n=62) compared to the unilateral CI group (n=42), yet they were not statistically significant. However an unpublished single study (PhD study) found significantly higher ratings with the bimodal listening condition (using standard HA) compared to using the CI only on all three subscales of the SSQ (Goman, 2014). Their finding was most probably due to the relatively small sample size used (n=12).

For telephone use, the present study found that the participants rated their ability on understanding speech over the telephone statistically significantly better when using the Naida Link HA with the CI than when using the CI only and using the standard HA with the CI for both questions 13 and 14 on the speech subscale. This finding is in line with the study by Warren *et al*. (2020) in which the participants reported an improvement of the ease of speech understanding over the telephone when using the Naida Link HA compared to their pre-study HA (standard HA). However, it should be noted that it is unknown whether the positive rating found in the present study for telephone use when using the Naida Link HA was associated with use of the DuoPhone. Two questions (questions 13 and 14 on the SSQ speech subscale) were asked about telephone-use ability in general and in noise. No instructions or explanations were given to the participant to consider (or not) the DuoPhone when answering the two questions. The study also showed that there was no difference between the CI only and the standard HA with CI on speech understanding over the telephone, particularly in background noise. However, the participants rated their ability on how easily they could have a conversation on the telephone (question 13) as statistically significantly lower when using the standard HA with the CI than when using the CI only.

In short, the findings from the current study suggest that the Naida Link HA would improve speech understanding, spatial hearing, and qualities of hearing for adult unilateral CI users.

5.11.5 Relationship between performance tests and subjective rating scales

One of the findings of the current study is that there was a statistically significant negative correlation between the speech subscale of the SSQ and the average of the three speech-in-noise tests. When the relationship of each individual speech-in-noise test with the SSQ speech subscale was examined, the results revealed that the significant correlation was only present between the roving speech test (SrN±60°) and the SSQ-speech subscale. The roving speech-in-noise (SrN±60°) test was developed to mimic one of the common listening situations in real life: having a conversation with a group of people. With that in mind, the SSQ questionnaire included a wide spectrum of hearing functions in daily life whereas the traditional clinical and research tests provide a limited sample of hearing ability. Thus, these findings suggest that the roving speech-in-noise test (SrN±60°) and telephone test would reflect the listening experiences of adult CI users who use integrated bimodal technology in real life. It should be noted that the correlation between the SSQ and the performance tests was carried out with the best-aided condition on the performance test (as explained in section 5.9.4.5), for example, the listening condition of using the DuoPhone in the telephone test and the listening condition of using StereoZoom in the S0°N±60° test.

In addition, a statistically significant positive correlation was found in the present study between question 13 on the speech subscale of the SSQ and the average of telephone tests as well as the individual telephone test (in quiet and in noise). Question 13 on the speech subscale of the SSQ was about the ease of using the telephone to have a conversation. In contrast, there was no correlation between question 14 on the speech subscale of the SSQ and telephone-in-noise test. Again, the absence of the correlation may be related to the methodological limitations of the telephone test. As discussed in section 5.11.3, the ceiling effect found in the results limits drawing a conclusion about the ability of adult CI users fitted with a Naida Link HA in the non-implanted ear on understanding speech in noise over the telephone. Furthermore, using triple digits as the speech target may not be encountered in an everyday conversation over the telephone.

There was no correlation found in the current study between the spatial subscale of the SSQ and the average of the spatial tests (localisation and tracking tests) for the listening condition of using the CI and the Naida Link HA. It is worth noting that the participants' scores were considerably variable in localisation and tracking tests for the listening condition of using the CI and Naida Link HA, which might be expected to be corrrelated with the variability in their self-rated scores in the spatial subscale of the SSQ.

In summary, it is important to consider using the subjective rating scales when measuring the performance of adult CI users to encounter their performance in real-life listening situations. As discussed earlier, performance tests do not provide a wide picture of hearing functions and skills in real-life listening situations.

5.11.6 Relationship between the unaided-hearing thresholds of the non-implanted ear and integrated bimodal technology

The present study did not find any significant correlation between the unaided-hearing thresholds of the non-implanted ear and the scores of the listening condition of using the CI and Naida Link HA as well as with the integrated bimodal benefit on any performance test and the SSQ questionnaire. This finding is in line with Vroegop *et al*. (2019) and Warren *et al.* (2020) who showed no significant correlation between the unaided-hearing thresholds of the non-implanted ear and the integrated bimodal performance. However, the two latter studies did not provide any details of how they conducted the correlation analysis particularly for the hearing thresholds of the non-implanted ear (i.e. whether they looked at the correlation of the thresholds of each frequency, low-frequencies, or the PTA).

A number of studies, such as Zhang *et al.* (2010), Illg et al. (2014), Sheffield and Gifford (2014) demonstrated that the low-frequency thresholds (< 500Hz) in the non-implanted ear mainly contribute to the bimodal benefit. In contrast, other studies, such as in Ching *et al*. (2004), Gifford *et al*. (2007), Potts *et al.* (2009) and Hoppe *et al.* (2018), did not find a significant correlation between the unaided-hearing thresholds of the non-implanted ear and the bimodal benefit (the detailed discussion was provided in Chapter 2 section 2.4.3.1).

Despite the inconsistent findings in these previous studies, it can be noted that there is no consensus in the method used in examining the correlation of the unaided-hearing thresholds of the non-implanted ear with the bimodal benefit or performance. Some studies examined the correlation with the thresholds of each individual frequency while other studies examined the correlation with the PTA of different frequency ranges (see Table 5.13). For instance, Ching *et al*. (2004) examined the correlation of the bimodal benefit with thresholds of 250, 500, and 1000 Hz separately whereas Zhang *et al.* (2013) examined the correlation of bimodal benefit with the PTA of 125-250-500-750 Hz. As a result, the current study examined the correlation of the integrated bimodal benefit and performance with a wide range of thresholds to investigate any possible correlation which included the thresholds of 250 Hz, 500 Hz, 1000Hz, the PTA of 250 -500 Hz, and the PTA of 500-1000-2000 Hz. The threshold of 4000 Hz was not considered in the correlation analysis because approximately half of the participants (12 participants) reached the maximum limit of the audiogram with no response which might affect the accuracy of the analysis as there was not much variability in the data.

Table 5.13: The unaided hearing thresholds of the non-implanted ear that were used for the correlation analysis with bimodal benefit in previous studies.

Studies	Thresholds of non-implanted ear
(Ching *et al.*, 2004)	• 250 Hz • 500 Hz • 1000 Hz
(Gifford *et al.*, 2007)	• 250 Hz • 500 Hz • PTA (250-500 Hz) • PTA (250-500-1000Hz) • Difference between 250 and 1000 Hz (slop of hearing loss) • Difference between 500 and 1000 Hz
(Potts *et al.*, 2009)	• 1500 Hz • 2000 Hz • 3000 Hz • 4000 Hz • 6000 Hz
(Zhang *et al.*, 2013)	• PTA (125-250-500-750 Hz)
(Illg *et al.*, 2014)	• 125 Hz • 250 Hz • 1000 Hz • 4000 Hz
(Devocht *et al.*, 2015)	• 250 Hz • PTA (500-1000-2000 Hz)
Hoppe *et al.* (2018)	• Low frequencies (< 500Hz) • Mid frequencies (PTA of four frequencies) • High frequencies (4000 Hz)

In addition, the current study considered whether there is a correlation between the unaided-hearing thresholds of the non-implanted ear and benefits of Binaural VoiceStream Technology (StereoZoom, ZoomControl, and DuoPhone). Only a small significant correlation (r= -0.4) was found between the ZoomControl benefit and the unaided-hearing thresholds at 1000 Hz in the non-implanted ear. However, it should be noted that the Bonferroni correction was not applied in this analysis. As discussed in Section 5.11.1, to the best of the researcher's knowledge, there is only one study that assessed the benefit of ZoomControl for CI users with integrated bimodal technology (Holtmann *et al.*, 2020). However, this study did not examine the correlation between the unaided-hearing thresholds of the non-implanted ear and ZoomControl benefit. Interestingly, the mean threshold at 1000 Hz in the Holtmann *et al.* (2020) study was better than in the current study (48 dB HL versus 84 dB HL), yet the amount of ZoomControl benefit in their study was smaller than that found in the current study (2.8 dB versus 6.1 dB). Therefore, the finding of the significant correlation between ZoomControl benefits and the unaided-hearing thresholds at 1000 Hz which were found in the current study needs to be interpreted with caution.

5.12 General discussion and study limitations

The integrated bimodal technology particularly using the AB CI sound processor and Phonak Naida Link HA has been established into clinical practice in recent years. Prior to starting this study and to the best of researcher's knowledge, there were only a few clinical studies that had investigated the outcomes of adult CI users when using integrated bimodal technology (Bionics, 2016b, Bionics, 2016c, Bionics, 2017). In addition, the international survey study (see Chapter 3) showed nearly half of the CI professional respondents (52%) were not sure whether using the integrated bimodal technology could provide more benefits than the standard bimodal technology whereas 43% of the respondents felt that the integrated bimodal technology would provide more benefits than the standard one particularly in improving speech understanding in background noise. Due to the limited research evidence and clinical perspective about the integrated bimodal technology, the current study has been carried out. However, since the completion of the present study, seven studies examining the benefits of integrated bimodal technology have been published (Vroegop *et al*., 2018b, Cuda *et al*., 2019, Ernst *et al.*, 2019, Vroegop *et al*., 2019, Holtmann *et al*., 2020, Warren *et a*l., 2020, Auletta *et al.*, 2021). All of these studies reported an improvement of speech perception in noise for adult CI users when using the integrated bimodal technology compared to using the CI only or using the standard HA with the CI. However, the benefit was highly dependent on the direction of the target speech and the noise masker. The previous studies used typical research testing set-ups to assess speech perception where the speech was fixed from the front. However, this does not reflect real-life listening situations where the speech is not fixed in one direction. Moreover, the previous studies did not assess the other important hearing functions in daily life when using integrated bimodal technology such as direction identification, tracking of moving sounds, and using the telephone. Only a single study (Holtmann *et al*., 2020) assessed the sound localisation with using the integrated bimodal technology compared to standard bimodal technology, and they found no difference (Holtmann *et al*., 2020). The same study used standardised questionnaires to assess the subjective benefits. Therefore, the effectiveness of the integrated bimodal technology is still unclear, particularly in real-life environments, and further research is needed to substantiate the benefits of this technology for different hearing functions.

Therefore, the current study, most importantly, is the first study that provides insight on the listening abilities of adult CI users when using the Naida Link HA in real-life listening situations, by using a real-life test battery. This test battery included both performance tests and subjective rating scales which would help to provide an assessment for the most important hearing functions in real-life listening situations, such as of speech-in-noise perception, spatial listening and telephone use. Additionally, the current study included a larger sample size (n=26) which means that the findings of this study would have a higher external validity compared to previous studies. Moreover, the outcomes of integrated bimodal technology have been assessed in the current study with mixed research design. This chapter discussed the benefits of using the Naida Link HA with the CI compared to using the CI only, by using a within-subject comparison. The benefits of the integrated bimodal technology were also compared to the bilateral CI and to the NH listeners using a between-subject comparison (this will be discussed in Chapter 7).

The current study found statistically significant benefits with using the integrated bimodal technology over the CI only on the speech-in-noise, localisation, and tracking tests. In addition, it found a statistically significant better rating on the SSQ for the integrated bimodal technology over the standard bimodal technology and the CI alone. However, it should be stressed that the presence of the statistically significant benefits does not necessarily imply that benefit would be clinically important. Further work is needed to investigate whether the amount of the benefit found in the current study would be noticeable, clinically significant and important to the CI users. It has been suggested that a minimum 2 to 3 dB increase in the SNR would be required to perceive a noticeable difference between two listening conditions (Killion, 2004, McShefferty *et al*., 2015). However, this would vary according to the listening condition as well as to the type of speech and the noise masker. Moreover, McShefferty *et al*. (2016) argued that the minimum 2 to 3 dB SNR change does not indicate whether this difference is meaningful or not. Therefore, it is important to differentiate between the noticeable difference and meaningful difference (further discussion about the clinical significance will be presented in Chapter 8).

The test battery developed and used in this study is more representative of real-life listening situations than the typical research and clinical tests; however there are a considerable number of factors that limit its representation of real-life situations. One important factor is that there was no visual input in the speech-in-noise tests where the speech sentences were presented from loudspeakers. For instance, the roving-speech test (SrN±60°) simulates one of the common listening situations in real life, namely having a conversation with a group of people in background noise. The speech sentences were presented randomly from different loudspeakers during the test in a diffuse multi-talker babble noise. In addition, the participants were asked not to fix their heads toward the front in order to simulate a real-life listening situation. Although this test was significantly correlated with the speech subscale of the SSQ, the absence of visual input could limit the test representation of real life to some degree.

Despite that, it should be noted that statistical analysis for the current study has been carried out without applying the Bonferroni correction. It was decided to not use the Bonferroni correction as it tends to be strict (Field, 2013). Yet, there was a possibility of increasing the risk of type 1 (false positive) with results of the present study. Another important aspect that should be noted is that there was a considerable inter-subject variability among the participants, particularly on the spatial listening tests (including both the localisation and tracking tests). Therefore, a careful conclusion should be drawn regarding the benefits of integrated bimodal technology for spatial listening tests.

In addition, it might be arguable that the participants in the current study were not familiar with the listening condition of using the CI only which in turn might have inflated the amount of the benefit found with the listening condition of using the Naida Link HA with the CI. Consequently, in order to check whether this issue has an effect on the results, the results of performance tests and the SSQ questionnaire when using the CI only for participants in the current study (bimodal users) were compared with the results of the bilateral CI participants (for the study in Chapter 6) when they were tested with the CI only. As the two groups have different modalities for signal processing, that would suggest that the bimodal users might have a higher exposure (familiarity) to the listening condition of using the CI only than the bilateral CI users. If that is true, then a significant difference between the two groups would be seen on the listening condition of using one CI. Yet no significant differences on the listening condition of using the CI only between the two groups were found for any tests. In addition, the listening conditions were counterbalanced to avoid any learning effects related to the unfamiliarity with the listening condition. Therefore, the effect of the listening condition familiarity on the result is minimal.

The current study has some limitations. Firstly, it would be useful if the participants' performance with the Naida Link HA was compared to their previous standard HA. Conducting such a comparison would provide a better understanding of the benefits and the limitations of the integrated bimodal technology compared to the standard bimodal technology. However, this could not be done in the current study for practical reasons. One of the original aims of the study was comparing the outcomes of the Naida Link HA with the standard HA for adult unilateral CI users. The plan was to recruit AB adult unilateral CI patients who used a standard HA in their non-implanted ear from USAIS at the University of Southampton. However, the study preparation before starting the data collection took a considerable duration that included ethics applications, test battery development, and a material transferred agreement (getting Naida Link HAs from AB company). During this period, many AB CI patients in the USAIS had been upgraded and fitted with the Naida Link HAs. Therefore, the chance of recruiting the AB CI participants who had a standard HA has been reduced. In addition, it was not practical to ask the participants to bring their previous standard HAs especially as many of them had disposed of or placed these HAs for donation. Furthermore, it was also considered to test the participants with a 'spare' standard HA that would be provided during the testing session. However, this option was excluded for two reasons. Firstly, using the same type of HA with all the participants other than their own HAs would affect validity of the results and would produce unfair comparisons between the standard HA and the Naida Link HA. This is because the participants might not like the new standard HA as much as their own HA. Therefore, if the outcomes were better with the Naida Link HA than the standard HA, this would not be because the technology of the Naida Link HA is better than the standard one. Better outcomes with the Naida Link HA could result from the fact that the participants do not like the new standard HA and did not have enough time to acclimatise to it. Thus, this may introduce a kind of variation of adjusting to this new HA that could make the Naida Link HA better than the standard HA. Secondly, if all participants were fitted with the same standard HA, that would introduce a superficial similarity for the standard HAs used in the study. However, this is not the case in real life where standard HAs used by the CI users differ in their features and fitting strategies. Therefore, some revision in terms of the focus of the study was taken to avoid comparing the Naida Link HA with the standard HA for the current study. Future studies should consider examining the differences in the bimodal benefits when using integrated bimodal technology versus standard bimodal technology.

Another limitation was the telephone test used in the present study. This test was developed for this purpose of the study to assess the DuoPhone benefits for CI users. However, the test is still considered to be in the rudimentary stage and further work is needed (as discussed in Chapter 4 section 4.2.2.5.5). Additionally, there were ceiling effects in the results which thereby meant that drawing a conclusion was not possible.

5.13 Conclusion

Compared to using the CI only, using the integrated bimodal technology has been shown to improve performance on the real-life test battery. For speech understanding in noise, using the Naida Link HA provided significant improvement particularly when the target speech and noise masker were spatially separated. Additionally, using the Binaural VoiceStream Technology, specifically the StereoZoom and ZoomControl, has added a statistically significant additional improvement for speech understanding in noise. Furthermore, using the Naida Link HA has also significantly improved the subjective benefits over using the CI only and using the standard HA, especially of the qualities of hearing. For localisation and movement tracking, the Naida Link HA improved the performance, yet there was a considerable variation among the users. Lastly, the benefit of using DuoPhone with the Naida Link HA was still unclear.

In conclusion, this study has demonstrated that using integrated bimodal technology would provide greater benefits over using the CI only, especially on speech understanding in noise and on the subjective reported benefits.

Chapter 6 Bilateral cochlear implant outcomes with one versus two implants on a real-life test battery

6.1 Introduction

The benefits of bilateral CIs over unilateral CI for adults have been widely researched. As discussed in Chapter 2, there is evidence that bilateral CIs offer benefits over unilateral CI, particularly for speech understanding in noise and sound localisation (Gantz et al., 2002, van Hoesel and Tyler, 2003, Laszig et al., 2004, Nopp et al., 2004, Verschuur et al., 2005, Grantham et al., 2007, Neuman et al., 2007, Tyler et al., 2007, Dunn et al., 2008, Litovsky et al., 2009, Koch et al., 2010, Dunn et al., 2012, van Zon et al., 2017). The evidence also shows significant self-reported benefits with bilateral CIs compared to one CI (Summerfield *et al.*, 2006, Noble *et al.*, 2008, Laske *et al*., 2009, Smulders *et al*., 2016a, van Zon *et al*., 2017, Lee, 2018).

A recent assessment was conducted by Health Quality Ontario (Ontario, 2018) for the evidence of bilateral CI benefits compared with unilateral CI in adults and children. For adults, the review showed that the quality of the evidence was high for sound localisation, and moderate for improvement of speech perception in noise and subjective benefits of hearing (i.e. as perceived by CI users). In addition, the review assessed the evidence for the cost-effectiveness of bilateral CI versus unilateral CI. Researchers found a variation in the evidence of the bilateral CI cost-effectiveness, most likely linked to differences in study design, cost-utility measures, time span, funder perspective, and the analysis approach used in these studies. Therefore, providing adults with bilateral CI remains debatable as there is no consensus on the cost-effectiveness of bilateral CI for adults. An in-depth discussion of the evidence of bilateral CI benefits can be found in Chapter 2 section 2.3.2. This chapter compares the benefits of two CI versus one CI using tests that are more representative of real-life situations.

6.1.1 Bilateral CIs in real-life situations

Most of the previous studies that examined the benefits of bilateral CI have used standard testing set-ups, i.e. speech perception measured using fixed speech and noise, typically presented from one loudspeaker directly in front of the person. Yet this is not representative of many real-life environments where speech is not fixed, such as when having a conversation with a group of people in a noisy place (i.e. cafés, restaurants etc.) van Hoesel (2015) argued that using standard outcome measures may underestimate the benefit of the bilateral CI for speech perception. He justified that the improved localisation ability with bilateral CI may help CI users to better identify and use the location of the source, thereby improving the SNR performance.

van Hoesel (2015) used a dynamic spatial audiovisual paradigm to test his hypothesis. The speech was presented randomly from one of four loudspeakers placed at ± 34° and ± 90°. Eight interfering talkers were presented from eight loudspeakers that were placed spanning a full 360° circle; each interfering talker was presented from one loudspeaker. Four video screens were placed at the same radius and just above the loudspeakers where the speech sentences were presented from. The target speech consisted of audiovisual recordings of naturally spoken BKB sentences which were presented in audition-alone and audio-visual modes. An audio-only cueing phrase that consisted of one of four reserved BKB sentences at the same level of the target speech was presented prior to the speech sentence from the same loudspeaker to help the participants in attending to the correct direction. In audiovisual mode, video-only distracters were presented from the other three non-target screens to avoid the participants being able to respond to the location of the target it was based on as it contained only the active video screen.

The average benefit of using the two implants was 3 dB over the one CI (better ear) in the audition-alone mode (no visual information provided). The study also showed that the average performance with two CIs was improved by 5 dB when visual cues were used (audiovisual mode), whereas for listening with one CI, the performance was unaffected. The findings from van Hoesel (2015) study show the value of bilateral CI when the target speech varies by providing a larger benefit than using one CI due to improved localisation which in turn facilitates getting favourable SNRs and accessing visual cues.

The above findings were consistent with those reported by Dunn *et al*. (2010) and Dunn *et al.* (2012) who measured the SRTs of bilateral CI users using a roving speech set-up. They used an array of eight loudspeakers spanning a horizontal arc of 108° to compare the SRTs in the listening conditions of using one CI and two CIs. The test was composed of 12 spondee words that were presented randomly from one of the loudspeakers. A competing speech noise (two talkers) was presented from one loudspeaker that was ± 4 loudspeakers from the loudspeaker that played the target word. Prior to presenting the target word, a cueing phrase was presented to orient the participant to the direction of the loudspeaker that the spondee word would be played from. They found a significant bilateral benefit of 5dB.

More recently, Dorman *et al.* (2020) examined the potential benefit of bilateral CI using a test set-up similar to that used by van Hoesel (2015). The target speech was presented randomly from one of the loudspeakers at -90°, 0°, or +90° with video screens placed underneath these loudspeakers. The noise was presented from eight loudspeakers placed at 45° angles around the circle. Their findings were consistent with those of van Hoesel (2015) and showed that using two CIs improved speech intelligibility by 16.7% compared with one CI, with an additional larger benefit (24.1%) in visual cue conditions. In both studies, there was no improvement when the visual cues were added in the unilateral CI condition which emphasises the importance of bilateral CI in taking the advantages of visual cues.

In summary, consideration and testing using assessments that are more representative of real-life situations may offer a more effective way of assessing the benefit and cost-effectiveness of one versus two CIs in adults.

6.1.2 Independent versus linked AGCs

The benefits of bilateral CI might be limited due to uncoordinated AGCs in the two sound processors, given that bilateral CI users primarily depend on ILD cues rather than ITD cues particularly for sound localisation (van Hoesel and Tyler, 2003). However, Dorman *et al.* (2014) found that magnitudes of the ILD cues for bilateral CI users were smaller than those for NH listeners as a result of CI signal processing. Their results showed that the magnitude of ILD has reduced after CI sound processing from 15-17 dB to 3-4 dB for wideband signal and high-pass signals, and from 5.4 dB to 1.8 dB for low-pass signals. In addition, the independent operation of the AGCs for two devices (two ears) can adversely influence the ILD reduction especially when the compression at one sound processor is activated while not at the other processor (Seeber and Fastl, 2008, Dorman *et al.*, 2015, Potts *et al.*, 2019). This can be seen when the sound source is on one side of the listener, because the head is acting as an acoustic barrier; each sound processor will have received a signal that has different frequency components. This will cause the AGC in each processor to work differently. However, Bakal *et al*. (2021) argued that linking the two AGCs might have an adverse effect by reducing speech understanding in the ear opposite the sound source as the primary aim of the AGC is to reduce the signal level to be within the listener's dynamic range.

A few recent studies measured the effect of using linked AGCs compared with independent AGGs for bilateral CIs users (Potts *et al.*, 2019, Bakal *et al*., 2021, Gajecki and Nogueira, 2021). Potts *et al*. (2019) found a significant improvement of 8° to 19° on localisation errors when using linking AGCs for bilateral Nucleus CI users. They also found an improvement of 2.5 dB in speech perception in noise with linked AGCs over independent AGCs. Similarly, Gajecki and Nogueira (2021) found an improvement of the discrimination accuracy at large azimuths (i.e. 70° and 90°) with the linked AGCs for bilateral CI users. In contrast to the finding by Potts *et al*. (2019), Bakal *et al.* (2021) showed there was no significant improvement in speech perception in noise with linked AGCs. The discrepancy in the findings between the two studies might be related to the different noise maskers used in these studies. A multi-talker babble noise was used in the Potts *et al.* (2019) study while a single-talker masker was used in the Bakal *et al.* (2021) study. More consistent engagement of the linked AGCs would be produced with multi-talkers compared with single-talkers (Bakal *et al*., 2021). In addition, a larger benefit of the linked AGCs was found in continuous babble noise compared to intermittent babble (Potts *et al.*, 2019), which indeed demonstrates the effect of the noise masker on the functionality for AGCs. Another interesting finding by the Bakal *et al*. (2021) study is that there was no significant difference with linked AGCs between participants with symmetrical hearing loss and those with asymmetrical hearing loss. This finding suggests that there is no strong adverse effect of the linked AGCs on CI sound processors opposite the sound source which would be seen particularly for those with asymmetrical hearing loss.

Nevertheless, the technology improvement for linking the AGCs for bilateral CI users seems promising in terms of additional improvement of bilateral CI benefits. One of the technologies available on the market that can provide linking AGCs for bilateral CI users is offered by Advanced Bionics (AB). AB users can use Binaural VoiceStream Technology that allows two AGCs in the sound processors to be linked wirelessly to stream full bandwidth audio signals for both ears in real time with short transmission delays by producing a third-order directional system via two-way communication between the dual-microphone systems on both devices that in turn create a four-microphone array. Binaural VoiceStream Technology is available on Naida CI Q70/Q90 and Marvel CI processors from AB. A detailed description of this technology is provided in Chapter 5 section 5.5.

6.2 Gap in knowledge and rationale for the study

In light of the importance of using real-life tests to assess the bilateral CI benefits discussed earlier in Section 6.1.1, and the limited studies that used real-life testing set-ups to examine the benefits of bilateral CIs, the current study was carried out to assess the outcomes of adult bilateral CI users using the real-life test battery that was developed for the current PhD project and included performance tests of speech in noise, localisation and tracking of moving sounds, as well as a telephone tests and subjective rating scales (SSQ and Telephone- Use questionnaires).

In addition, the use of linked AGCs by the bilateral CI users appears to be advantageous. However, there is still a need to assess the effectiveness of this technology. Therefore, the benefits of using the linked AGCs were explored for bilateral CI participants who had AB devices.

6.3 Aims and hypothesis

The aims of this study were as follows:

1. To compare the outcomes of adult bilateral CI users when using one CI versus two CIs on the real-life test battery that included:
    a. Speech-in-noise tests
    b. Spatial-listening tests (localisation and tracking of moving sounds)
    c. A telephone test
    d. A questionnaire capturing CI user experience (SSQ)
2. To compare the outcomes of AB bilateral CI users when using the Binaural VoiceStream Technology (StereoZoom, ZoomControl, DuoPhone)
3. To investigate the relationship between performance tests on the real-life test battery and the participants' perceptions on the SSQ questionnaire.

The hypotheses of this study were as follows:

- **Hypothesis 1**: adult bilateral CI users would show better outcomes when using two CIs rather than one CI for speech in noise, localisation, tracking and telephone use in noise tests

- **Hypothesis 2:** using the Binaural VoiceStream Technology would improve the performance of AB bilateral CI users compared to the general settings (everyday map) when using the two CIs in the intended listening environment (testing setup) that was designed for it
- **Hypothesis 3:** the rating scores of adult bilateral CI users on the SSQ questionnaire would be better (higher) when using two CIs compared to using one CI.

6.4 Method

Ethical approval was obtained for this study from the University of Southampton (ERGO ref: 45969).

6.4.1 Participants

16 adult bilateral CI users participated in the study. Participants ranged in age from 23 to 82 years (group mean age= 47 years, SD= 20 years). The inclusion criteria were: (1) adults aged over 18 years, (2) a minimum of six months of CI use, (3) BKB score in quiet of ≥ 50%, (4) USAIS patients who had previously agreed to being invited to take part in research, and (5) no cognitive or learning difficulties (to ensure that the participant was able to do the testing reliably).

Nine participants were implanted with Cochlear devices; five participants were implanted with AB devices, and two participants were implanted with MED-EL devices. Five participants had simultaneous CI and eight participants had sequential CI. The remaining three participants had a mixed pattern in getting their bilateral CI. For instance, participant BiCI3 had a unilateral CI but then due to device failure, the CI company offered two simultaneous CIs. Participants BiCI7 and BiCI14 had simultaneous bilateral CI,s but then due to device failure on one side, they had a sequential CI. The time interval between the two implants for the participants with sequential bilateral CI ranged from 2 to 11 years with a mean interval of 4.9 years (SD= 3.1 years). Demographic information of the participants is presented in Table 6.1. The participants did not receive any payment for their participation in the study, but participants' travel expenses were reimbursed.

6.4.1.1 Sample size calculation

The sample-size calculation for the primary outcome measure of real-life speech-in-noise tests was considered but was challenging given that the new real-life speech-in-noise tests used had been developed for the purpose of the study. As a result, the effect size and test-retest reliability of these tests for adult CI users were unknown. Previous studies that used similar apparatus and set-ups were reviewed to estimate the appropriate sample size. Goman (2014) used the default speech-in-noise, localisation, and tracking tests of the AB-York Crescent to assess the difference between using one CI versus two CIs for 12 bilateral CI users. A significant bilateral CI benefit of 7.1 dB was only found when the noise was presented at the first implant. For the spatial-listening tests, a significant benefit of 37% and 49% was found in localisation (with 30° separation) and tracking tests respectively. The SDs of the difference between the two listening conditions in these tests were not reported. A further constraint was the low numbers of adults with bilateral implants as only 8% of the adult CI population in the UK have bilateral cochlear implants (BCIG, 2021). Given this low number it was also not possible to recruit participants with only one manufacturer's device as for the bimodal group (discussed in Chapter 5). It was decided to recruit

20 adult bilateral CI users for the current study, with the assumption of a 25% dropout rate to compensate for any loss.

To review the sample size used in this study, a sample-size calculation was carried out afterwards, using the G*Power 3 (Faul *et al*., 2007). Similar parameters used in the sample calculation of Naida Link bimodal group (Chapter 5) were also used for the bilateral CI group. A minimum mean difference of 2 dB in the SRTs between the listening conditions of one CI versus two CIs should be considered as clinically significant with an SD of 3 dB, a power of 0.8, an alpha of 0.05, and an assumption of no correlation present between the two pairs. The G*Power 3 using a two-tailed paired t-test indicated that 20 participants were enough (16 were recruited) to detect a mean difference of 2 dB with a power of 0.8 and an alpha (i.e. type-I error rate) of 0.05.

Table 6.1: Demographic information of study bilateral CI participants.

Participant	Age (years)	Sex	Aetiology	Age of HL onset	Duration of HL (diagnosis to 1st implant)	CI device	1st CI ear	Duration of use 1st CI	Duration of use 2nd CI	Simultaneous or sequential	Time interval	Reason for bilateral CI
BiCI 1	78	F	Hereditary	12	58	Cochlear	Simultaneous	6	6	Simultaneous	0	Visual impairment
BiCI 2	77	M	Hereditary	17	57	Cochlear	Right	3	1	Sequential	2	• Severe tinnitus in non-implanted ear • 2nd implant via self-funding
BiCI 3	51	F	Unknown	10	27	AB (Q70)	Left	14	12	One implant and then following failure simultaneous CI	2 (0)	• CI failure • Company offered 2 implants
BiCI 4	70	F	Usher Syndrome	8	60	Cochlear	Simultaneous	1.5	1.5	Simultaneous	0	Visual impairment
BiCI 5	82	M	Unknown	63	15	AB (Q90)	Left	4	1.5	Sequential	2.5	• CI failure • Self-funded

BiCI 6	37	F	Scarlet fever at age 2	2	22	Cochlear	Right	13	2	Sequential	11	2nd implant via self-funding
BiCI 7	55	F	Unknown	33	8	AB (Q90)	Left	14	11	• Sequential (left ear implanted first then right ear implanted 3 years later) • After 1st device started failing, left ear explant and re-implant	3 (0)	CI failure on one side
BiCI 8	50	F	Hereditary	19	19	MED-EL	Left	12	7	Sequential	5	Company offered a 2nd implant
BiCI 9	39	F	Usher Syndrome	10	17	Cochlear	Simultaneous	12	12	Simultaneous	0	Visual impairment
BiCI 10	44	F	Unknown	20	12	AB (Q90)	Simultaneous	12	12	Simultaneous	0	Visual impairment

BiCI 11	24	F	Unknown	6	9	Cochlear	Right	9	12	Sequential	4	Implanted as child
BiCI 12	49	M	Unknown	15	24	Cochlear	Right	10	7	Sequential	4	2nd implant via self-funding
BiCI 13	23	M	Unknown	2	2	MED-EL	Simultaneous	19	19	Simultaneous	0	Implanted as child
BiCI 14	24	M	Meningitis	4	0	AB (Q90)	Simultaneous	20	20	Simultaneous	0	• Implanted as child simultaneously • Reimplant age 12 (right)
BiCI 15	24	F	Unknown	4	2	Cochlear	Simultaneous	18	18	Simultaneous	0	Implanted as child
BiCI 16	32	F	Hereditary	5	2	Cochlear	Right	25	17	Sequential	8	Implanted as child

6.4.2 Test battery

The real-life test battery that developed as explained in Chapter 4 was used in this study. Figure 6.1 illustrates the performance tests and subjective rating scales included in the test battery. As explained in Chapter 5, the test battery was grouped into four categories where the first three categories included performance tests, and the fourth category included subjective rating scales.

The first category was the speech-in-noise tests that included three newly developed tests: (1) SrN±60°, (2) S0°N±60° and (3) S+90°N-90° where the speech was presented on the second CI side and the noise on the first CI side. For participants with simultaneous CI, the noise was presented on the preferred (dominant) CI side or on the right-hand side if the participants did not have a preferred side.

The second category included spatial-listening tests: (1) localisation using five loudspeakers with 30° separation and (2) tracking. The third category comprised the telephone test in quiet and in noise (at +10 dB SNR). The AB-York Crescent of Sound was used to administer the tests in the first and second categories as well as to present the continuous loop of noise for the telephone-in-noise test in the third category. A detailed description of each test can be found in Chapter 4, section 4.2.2. The fourth category included subjective rating scales (SSQ and Telephone- Use questionnaires). The SSQ questionnaire version 3.1.1 was used (Gatehouse and Noble, 2004, Noble and Gatehouse, 2004). However, minor modifications were made to a few questions in the questionnaire to make them clearer to the participants (a summary of the modifications is provided in Appendix O). A Telephone- Use questionnaire (Appendix L) was developed and included in the test battery of the study. The questionnaire consisted of seven questions to gauge the telephone use of the CI participants in their daily life.

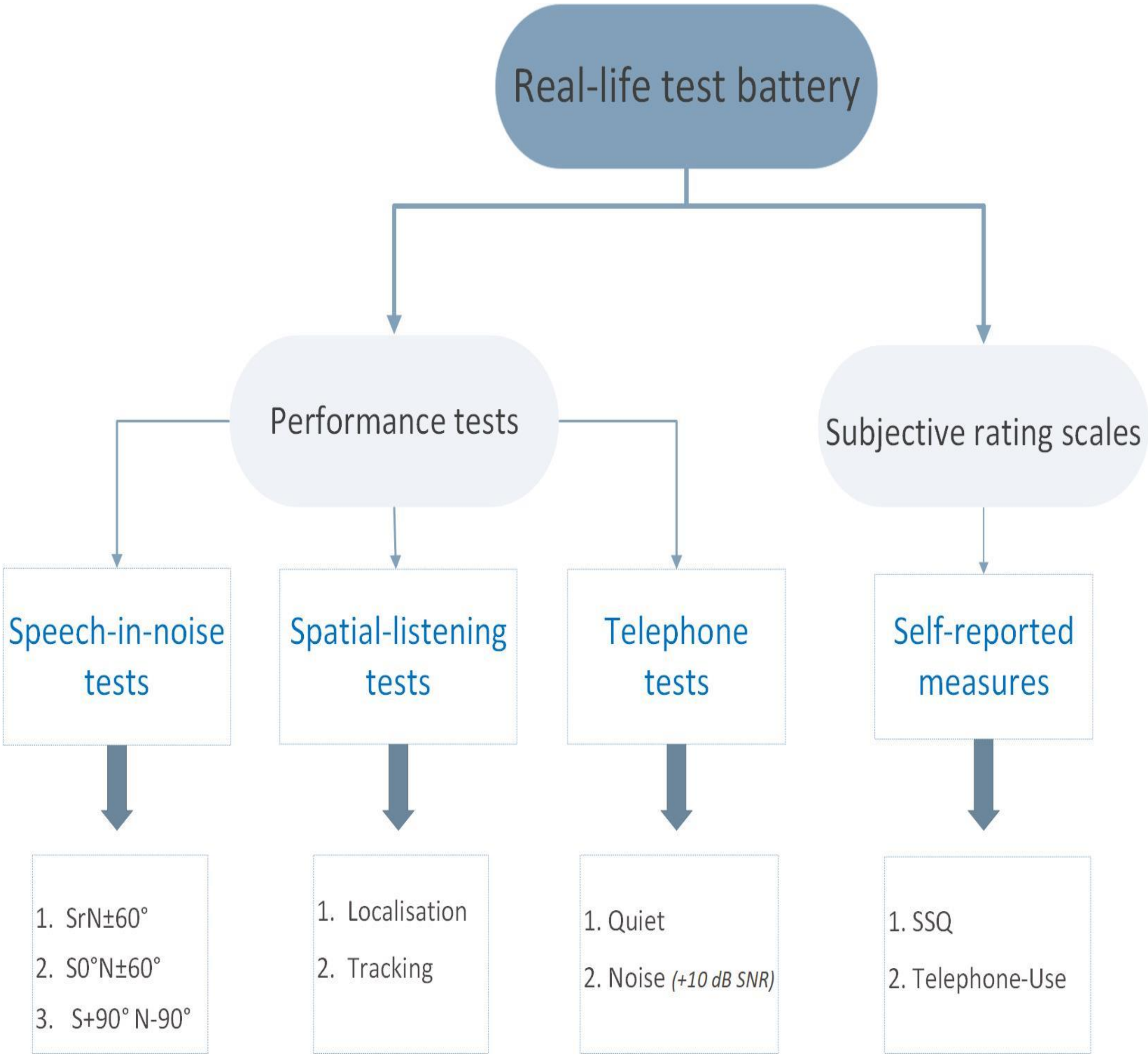

Figure 6.1: The real-life test battery for CI participants.

6.4.3 Procedure

Testing took place within a double-walled sound-attenuated booth at the USAIS. All participants completed the listening tests in one session that lasted on average three hours including short breaks of 10 minutes between the four test categories and as requested by the participant. Information about the study and the participant information sheet were sent to participants via email at least one week prior to the testing session. In addition, the SSQ questionnaire was sent to them before the session to give them time to think about questions and to avoid fatigue when answering the questionnaire at the end of the testing session.

At the beginning of the session, the participants were provided with a consent form to sign and were asked to complete the travel-expense claim form. They were seated on a comfortable chair in the centre of the Crescent of Sound loudspeaker array, one metre away from and facing the frontal loudspeaker which was placed at 0 degrees azimuth. Detailed illustrations and instructions of each test were given to the participants. A summary of listening conditions, the main procedure and key points of the instructions for each test is given in Table 6.2

Table 6.2: A summary of the main procedure and the listening conditions for bilateral CI participants.

	Test	Listening conditions	Task	Head movement	Practice	Response required
Category 1 (Speech-in-noises tests)	SrN±60°	1. One CI 2. Two CIs	You are going to hear a man saying random sentences from one of these loudspeakers in front of you with a background noise masker coming from both sides	Allowed	No	Ignore the background noise and repeat any words you hear
	S0°N±60°	1. One CI 2. Two CIs 3. Two CIs +StereoZoom *	You are going to hear a man saying random sentences from the front loudspeaker and a background noise masker coming from both sides	Fixed facing the front loudspeaker	No	Ignore the background noise and repeat any words you hear
	S+90°N-90°	1. One CI * 2. Two CIs * 3. Two CIs + ZoomControl*	You are going to hear a man saying random sentences from the loudspeaker placed on your 2nd implant side (or left) and a background noise masker coming from the opposite side	Fixed facing the front loudspeaker	No	Ignore the background noise and repeat any words you hear
Category 2 Spatial-listening tests	Localisation	1. One CI 2. Two CIs	You are going to hear a sentence of “Hello, what is this?” coming from one of these five loudspeakers in front of you	Fixed facing the front loudspeaker	No	Indicate the number of the loudspeaker from which the voice was presented
	Tracking	1. One CI 2. Two CIs	You are going to hear a moving sound. It may move from the right to the left, the left to the right, the right to the centre and back to the right, the left to the centre and back to the right or it may start at the centre	Allowed	No	Say or use your finger to show the direction in which you think the sound is moving

			and go to the right or left side and then back to the centre again			
Category 3 Telephone test	in quiet	One CI	I am going to call you on this phone; once you have picked up, you are going to hear a list of digit sequences. Each sequence consists of three digits.	Fixed facing the front loudspeaker	Yes	Repeat the digits you hear
	in noise (+10dB SNR)	1. One CI 2. Two CIs 3. Two CIs + DuoPhone *	I am going to call you on this phone; once you have picked up, you are going to hear a list of digit sequences. Each sequence consists of three digits. Some background noises will be coming from the loudspeakers at the sides	Fixed facing the front loudspeaker	No	Ignore the background noise and repeat the digits you hear
Category 4 Self-reported questionnaire	SSQ	1. One CI 2. Two CIs	The participants were asked to read the questions and answer them for each listening condition	-	-	-

* Only administered to the AB participants, i.e. those with the Binaural VoiceStream Technology (n=5).

The order of the first (speech-in-noise tests) and second (spatial-listening tests) categories was counterbalanced across participants to minimise any possible order effect, whereas the third (Telephone-Use tests) and the fourth (SSQ) categories were kept in the same order. This is because the speech-in-noise and spatial-listening tests were the primary-outcome measures whereas the telephone test is a rudimentary test (as discussed in Chapter 4 section 4.2.2.5.5) that was developed specifically for the current study. Moreover, the SSQ questionnaire was sent to the participants at least one week prior to the testing session. Therefore, it was decided to use this testing arrangement to avoid any order or fatigue effects on the primary-outcome measures. In another words, the test session for some participants started with a speech-in-noise tests, followed by spatial-listening tests. For other participants, the test session started with spatial-listening tests followed by speech-in-noise tests. In addition, the listening conditions and order of the subtests within each category were also counterbalanced.

All participants, except the AB CI users, were tested with their own speech processors. The AB participants were provided and tested with a speech processor (Naida AB Q90) dedicated to the study, rather than using their own devices in order to streamline testing and reduce the length of the test session for the participants. The study CI sound processors were programmed prior to the testing session using SoundWave 3.0 clinical fitting software. Four maps were downloaded into the processors: (1) program 1: everyday setting (default) based on the participant's previous clinical program, (2) program 2: StereoZoom, (3) program 3: ZoomControl, and (4) program 4: DuoPhone.

All the participants were provided with new batteries at the beginning of the test session. Additionally, participants were instructed to use the volume settings on the CI sound processors that they were most accustomed to using.

Prior to carrying out the training trial for the telephone test, the participants were asked to fill in the Telephone- Use questionnaire which was developed for this study. For the telephone test, participants were all required to use a designated mobile phone rather than their own to eliminate the influence of confounding variables. Participants were given the opportunity to find the optimal placement of the phone and adjust the volume setting on their speech processors.

In the last part of the test session, the participants were asked to answer the SSQ questionnaire if they did not complete it before the session. They were asked to answer each question based on their experience when using: (1) one CI and (2) two CIs. For AB participants, they were asked to answer the questions based on their overall experiences with bilateral CI without any relation to specific settings or features (i.e., ZoomControl, DuoPhone, etc).

6.4.4 Analysis

Both descriptive and inferential statistical analyses were carried out and presented separately for each test within the category of the test battery. The descriptive analysis was done using GraphPad Prism software (version 9.1) and statistics were computed using IBM SPSS Statistical Analysis software (version 26).

Before computing the statistics, the normality distribution of the data was assessed using the Shapiro-Wilk test. Parametric statistical analysis tests were used, even if the assumption of normality was violated, since they are considered to be robust to non-normality (Maxwell and Delaney, 2004, Rasch and Guiard, 2004). Where there were multiple comparisons, post-hoc corrections were used. However, Bonferroni correction was not applied as it is generally conservative and overcorrects for Type I errors which affect the statistical power (Field, 2013, p.459). The least significant difference (LSD) was used instead in these statistics as it has greater power and is equivalent to performing multiple t-tests on the data. This increased the possibility of detecting differences between means that might, in reality, be meaningful.

The following sections explain the analysis that was carried out for the tests included in the test battery.

6.4.4.1 Speech-in-noise tests

The dependent variable was SRT in dB SNR. The SRT was obtained for each test with each listening condition. For each speech-in-noise test, the SRTs for the listening conditions were compared.

6.4.4.2 Spatial-listening tests

The analysis of the localisation test was carried out as a percentage of correct responses for each listening condition. Additionally, RMS error (the deviation in degrees between the actual locations of the sound source and locations identified) in the 30 trials per test run was calculated for each listening condition using the following equation:

$$RMS\ error = \sqrt{\frac{\sum_{i=1}^{n}(x-y)^2}{n}}$$

where x is the location of the source of the loudspeaker in degrees, y is the location of the response in degrees as indicated by the participant, and n is the number of the trials.

The chance range for randomly guessing was also calculated for both percentage correct and RMS metrics using the “Monte-Carlo” simulation in MATLAB(v. R2019a) software.

For the tracking-of-moving-sounds test, there were six sequences of moving sound, as explained in Chapter 4 section 4.2.2.4, that were presented as a list of 12 sequences (where each sequence was repeated twice in a pseudo-random order). The percentage of correct responses for each listening condition was calculated. The chance range for randomly guessing was also calculated using the binomial distribution with parameters of n=12 trials, each with a probability of success of p=0.167.

Furthermore, the correlation between the localisation and tracking tests in the two listening conditions (one CI vs. two CIs) was examined.

6.4.4.3 Telephone test

One list of TDT that consisted of 10 triplets was presented for each participant for each listening condition. The score was presented for each listening condition as a percentage of correct responses. A digit-scoring method was used where the scores were presented as a percentage correct out of 30 digits for one list.

In quiet, the telephone test was only administered in the listening condition of using one CI for bilateral CI participants. For testing in noise, the test was administered in the two listening conditions of using one CI and two CIs. Only the results of 14 participants were included in the analysis. This is because the test was just administered with the condition of using one CI for participants (BiCI 1 and BiCI 2). Then, a decision was made to test the remaining bilateral CI participants in the listening conditions of using two CIs given that the test session had a sufficient time to carry out further testing. Therefore, the data of participants (BiCI 1 and BiCI 2) were excluded from the analysis.

6.4.4.4 The SSQ

Only complete questionnaires were included in the analysis. In addition, participants who answered the questions for any listening condition as ‘not applicable’ were treated as incomplete and were also excluded from the analysis.

The scores for each of the three main subscales of the SSQ (speech, spatial and qualities of hearing) were calculated for the two listening conditions (1) one CI and (2) two CIs. In addition, the overall SSQ score was calculated for each listening condition by taking the average score across the three subscales.

In addition, the scores of two questions (13 and 14) in the speech subscale that related to telephone use were compared between the two listening conditions (one CI versus two CIs). Question 13 was about the ease of having a conversation on the telephone and question 14 was about the ability to understand speech over the telephone in the presence of background noise. This was considered to obtain further information about the ability of participants to use the telephone as the telephone test used in the current study is a rudimentary test which needs further development.

Furthermore, the difference in music perception between the two listening conditions was analysed by taking the average score of questions 5, 7 and 8 on the qualities-of-hearing subscale, and then compared among the listening conditions. As discussed in Chapter 4, a music-perception test was considered to be included into the test battery for the current study. However, this could not be achieved because of the limited availability of standardised music-perception tests with appropriate duration and the time constraint of the test battery. Therefore, average scores of questions 5, 7 and 8 on the qualities-of-hearing subscale of the SSQ were assessed to obtain a general overview of music perception for the study's participants.

6.4.4.5 The relationship between performance tests and subjective-rating scales

The relationship between the listening tests (speech in noise, spatial hearing and telephone use) and the SSQ scores in the listening condition of using two CIs were examined. The correlation analysis was conducted between:

1. The scores of SSQ of the speech subscale and the averaged scores of the speech-in-noise tests. The average of the speech tests was calculated by averaging the scores for the two speech tests: SrN±60° test and S0°N±60° for the bilateral listening condition. If there was a significant correlation then the correlation between the SSQ and each speech test was examined to obtain additional information on how each speech-in-noise test would correlate with the reported benefit on subjective rating scales. The S+90° N-90° was not included in the average score as the test was only administered for five participants who had AB devices.
2. The scores of SSQ of the spatial subscale and the average scores of the spatial-hearing tests (localisation and tracking). If there was a significant correlation then the correlation with each test was examined.
3. Question 14 scores of the SSQ for the speech subscale and the scores of the telephone test in noise.

6.5 Results

The results are presented in accordance with the test categories of the real-life test battery, as outlined in Figure 6.1.

6.5.1 Speech perception in noise

This section presents the SRTs for the bilateral CI users in the two speech-in-noise tests: SrN±60° and S0°N±60. Figure 6.2 shows the SRTs of the bilateral CI participants when listening with one CI and when listening with two CIs in SrN±60° test (left panel) and S0°N±60° test (right panel).

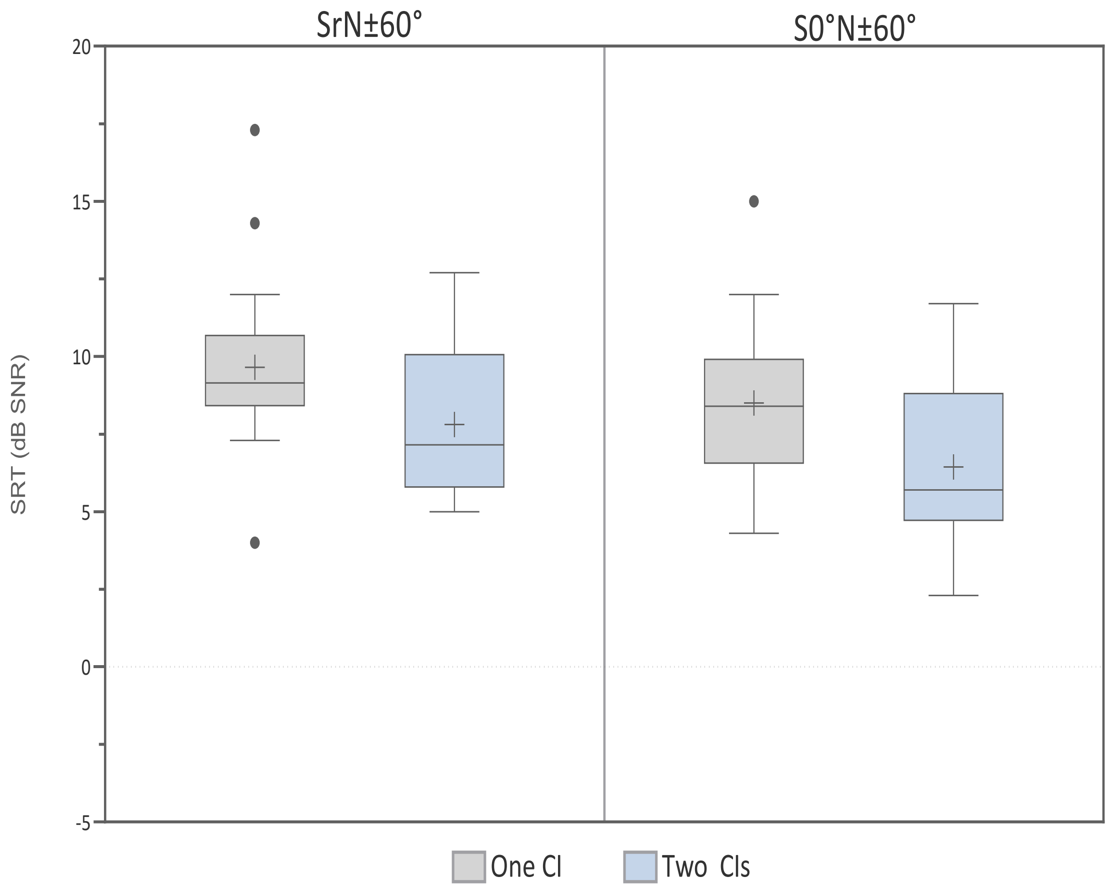

Figure 6.2: Box plots representing the SRTs in dB SNR (n=16) for the two listening conditions: (1) one CI and (2) two CIs in SrN±60° (left) and S0°N±60° (right) tests. The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The outliers are plotted as solid circles. Lower SRTs indicate better performance.

The results showed the SRT was lower (better) in the listening condition of using two CIs (7.8 dB SNR ± 2.6) and (6.4 dB SNR ± 2.7) as opposed to when using one CI only (9.7 dB SNR ± 3) and (8.5 dB SNR ± 2.7) in the SrN±60° and S0°N±60° tests respectively. The difference between the two listening conditions was statistically significant in the two speech-in-noise tests. Table 6.3 reports the mean difference between the two listening conditions and the results of the analysis for each speech test.

Table 6.3: Mean difference between the listening conditions of using two CIs versus one CI (95% confidence of the mean difference) and results of paired-samples t-test in speech-in-noise tests.

Test	t-test	p	Mean difference (95% confidence interval)
SrN±60°	t (15) = 3.8	0.002	1.8 (0.8 to 2.9)
S0°N±60°	t (15) = 3.9	0.001	2.1 (0.9 to 3.2)

To provide an estimation of the population mean, the mean benefit in the SRTs of using the two CIs over one CI and its 95% confidence intervals for SrN±60° and S0°N±60° tests are presented in Figure 6.3. The values of these benefits were derived from comparing the SRT for the two listening conditions.

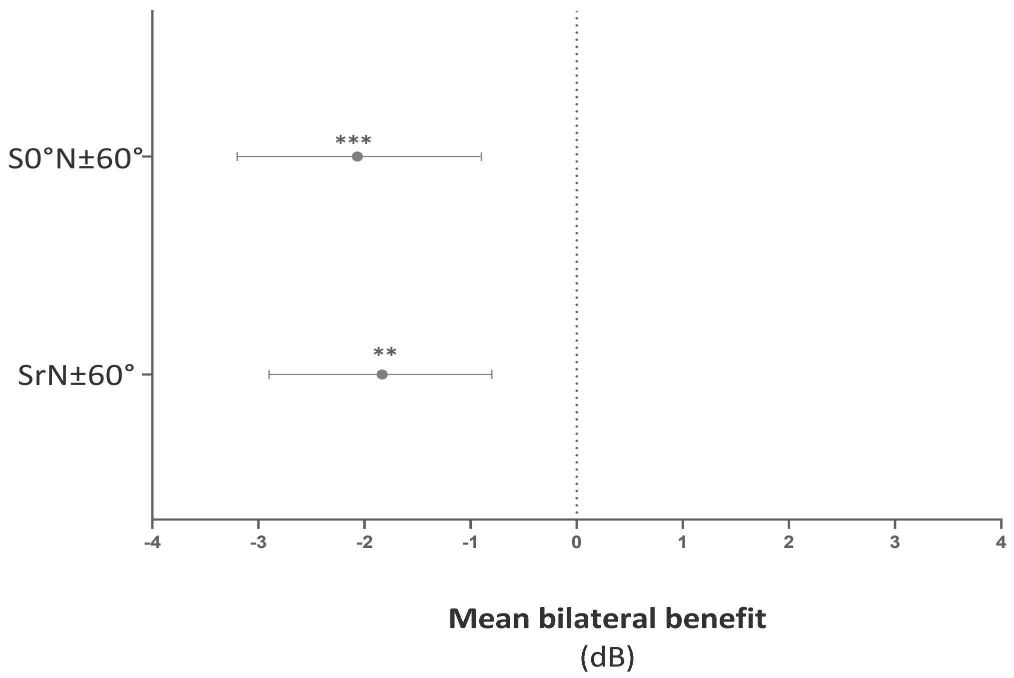

Figure 6.3: Mean bilateral benefit over using one CI for the two-speech perception-in-noise tests, in dB. Error bars show 95% confidence intervals of the mean. The vertical dashed line indicates no benefit. Negative values indicate better performance. A significant benefit is indicated by asterisks (*** indicates p<.001, ** indicates p<.01, and * indicates p<.05).

6.5.2 Spatial-listening tests

Sound localisation

The mean performance on the sound localisation test (30° separation) for the bilateral CI participants in the two listening conditions: (1) one CI and (2) two CIs are shown in Figure 6.4 (A). Mean performance when using one CI was close to the chance (mean=23.7 %, SD=6.8). However, the performance was noticeably higher than the chance when using the two CIs (mean=70 %, SD=21.9). Paired sample t-tests showed that localisation accuracy was statistically significantly higher when using the two CIs by 46.3 % (95% confidence interval, 34.3 to 58.2) compared to using one CI ($t(15) = 8.2$, $p < .001$).

The RMS errors were also calculated for the two listening conditions. Figure 6.4 (B) shows that the mean RMS error when using one CI was 57° (SD= 7.4°) which was within range of chance (due to guessing). The mean RMS error was 21.8° (SD=13.7°) for the two-CIs listening condition. A paired-samples t-test showed that the mean RMS error was statistically significantly lower in the two-CI condition by 35.2° (95% confidence interval, 25.9 to 44.4) compared to using the one-CI condition ($t(15) = 8.1$, $p < .001$).

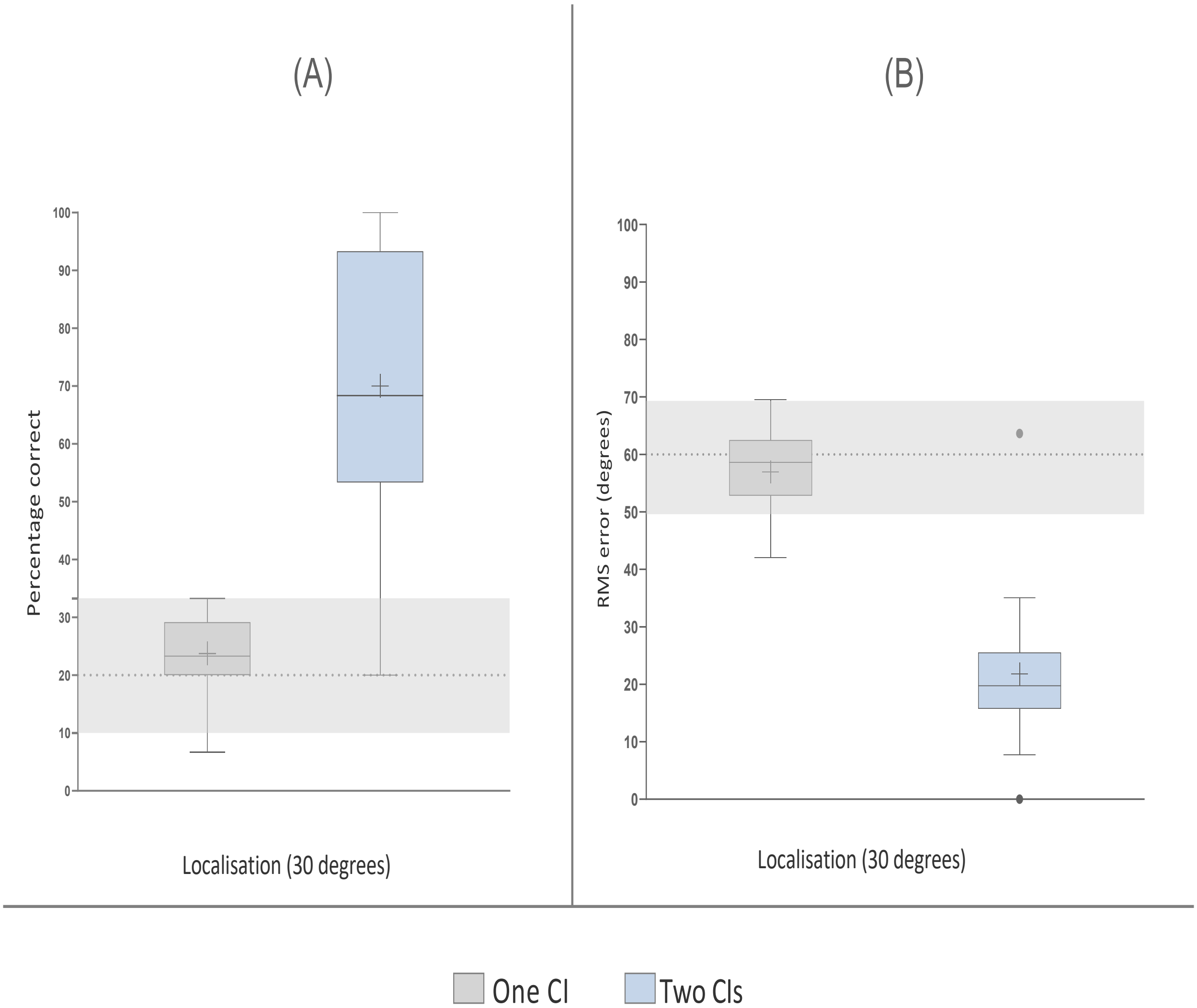

Figure 6.4: Results of the localisation test in percentage correct (left-hand panel) and RMS error (right-hand panel) for the adult CI participants in the listening condition of using one CI (grey box plots) and in the listening condition of using two CIs (blue box plots). The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The dashed horizontal line shows the level of performance expected by chance, with the grey shaded area showing the 5th and 95th percentiles of the change range. The outliers are plotted as solid circles.

Tracking

The mean performance for tracking moving sounds for the bilateral CI participants in the two listening conditions are shown in Figure 6.5. Mean performance when using one CI was close to the chance (mean=23.1 %, SD=12.2). Although there was a considerable variation in the performance among the participants when using the two CIs, the mean performance was markedly higher than chance (mean=78.5 %, SD=25.4). Paired-samples t-tests showed that the difference between the two conditions was statistically significantly different ($t(15) = 7.4$, $p < .001$). The tracking of moving sounds was better in the two-CIs condition than using one CI by 55.4% (95% confidence interval, 39.3 to 71.4).

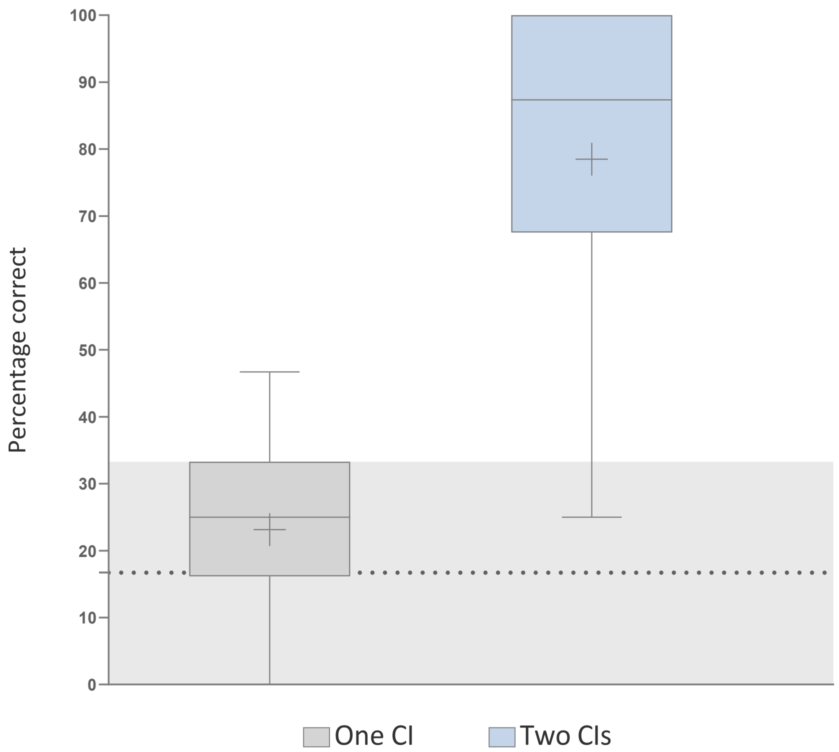

Figure 6.5: Results of the tracking test in percentage correct for the adult CI participants in the listening condition of using one CI (grey box plots) and in the listening condition of using two CIs (blue box plots). The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The dashed horizontal line shows the level of performance expected by chance, with the grey shaded area showing the 5th and 95th percentiles of the change range.

Correlation between the localisation and tracking tests

The relationship between the localisation and tracking tests for bilateral CI participants was examined for both listening conditions with one CI and with two CIs.

For the one-CI condition, Pearson correlation coefficients showed no significant correlation between the two tests ($r= 0.4$, 95% confidence interval -0.1 to 0.7, $p=.1$). For the listening condition of using two CIs, there was a significant correlation between the localisation and tracking tests (r= 0.7, 95% confidence interval 0.3 to 0.9, p=.0055).

6.5.3 Telephone test

The mean performance on the telephone test in quiet and in noise for the bilateral CI participants is shown in Figure 6.6. In quiet, the telephone test was only administered in the listening condition of using one CI. The mean performance was 96.2% (SD= 5.6).

For the telephone test in noise, the test was administered in the two listening conditions of using one CI and using two CIs. As explained in Section 6.4.4.3, only the results of 14 participants were included in the analysis. The mean performance was 78.1% (SD= 13.7) and 67.9% (SD= 26.6) in the one-CI condition and the two-CIs condition respectively. The score was worse in the bilateral condition by 10.2% (95% confidence interval, -24.6 to 4.2). Paired-samples t-tests showed that the difference between the two conditions was not statistically significantly different (t (13) = 1.5, p >0.05).

In the listening condition with one CI, the performance was 21.9 % (95% confidence interval, 30.6 to 13.1) worse in noise compared to testing in quiet. Paired-samples t-tests showed that the difference between the two tests was statistically significantly different (t (15) = 5.3, p <0.001).

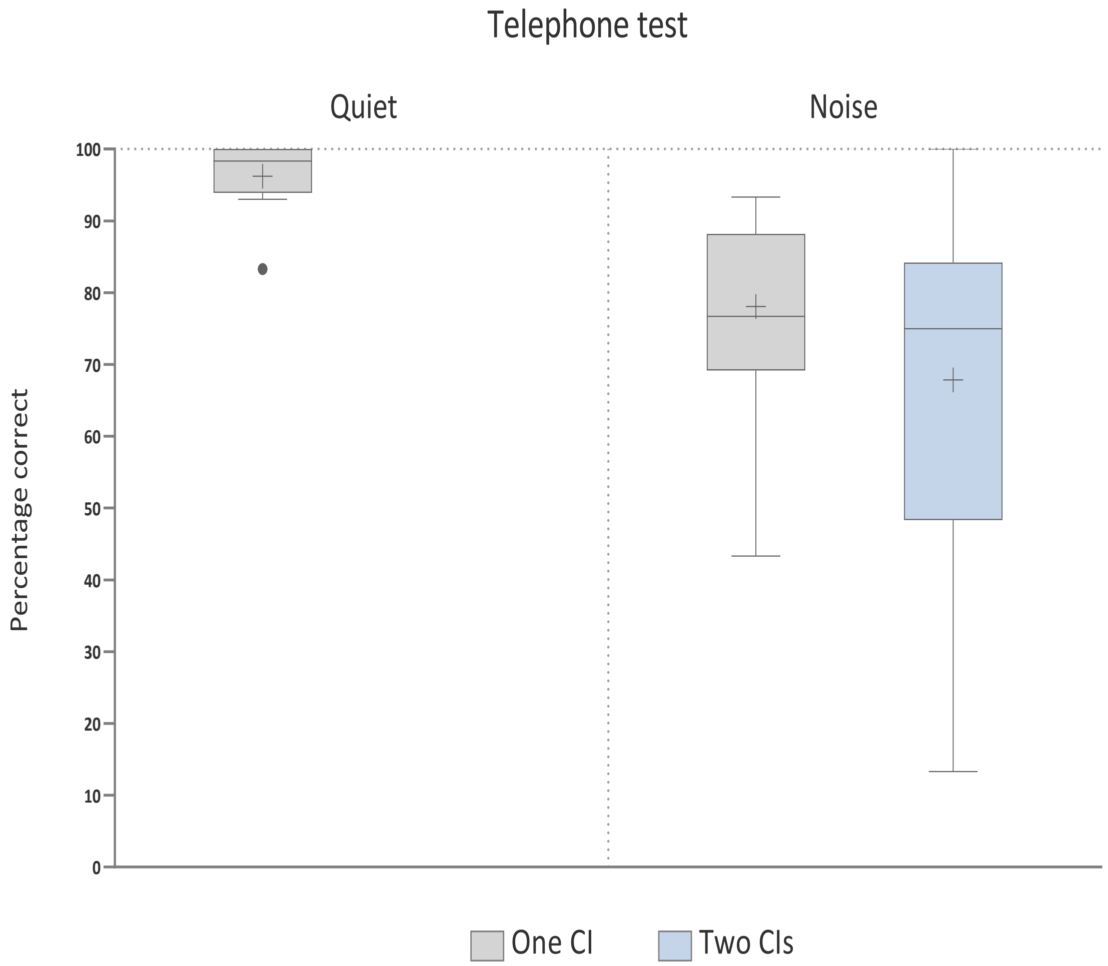

Figure 6.6: Results of the telephone test in quiet (left-hand panel) and in noise (right-hand panel) for the adult bilateral CI participants. In quiet (n=16), participants were only tested in the listening condition of one CI (grey box plots). In noise (n= 14), the results of the two listening conditions of one CI (grey box plots) and two CIs (blue box plots). The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean.

Table 6.4. shows the responses from the bilateral CI participants on the Telephone- Use questionnaire. The questionnaire indicated that more than half of the participants were regular daily telephone users (62.5%) with approximately half of them being somewhat confident (56.3%). Most of the participants could speak with both familiar and unfamiliar people (93.8% and 81.3% respectively) when using the telephone in the standard way (relying on hearing only). In addition, the questionnaire showed that half of the participants also used video calls and text messages. Most of the participants (93.8%) preferred to use a mobile phone rather than a landline or DECT phone. 62.5% used special features, programs and accessories with Bluetooth

being the most popular. Approximately 62.5% of the participants indicated an interest in attending a telephone-training workshop at USAIS.

Table 6.4: Bilateral CI participants' responses on the Telephone- Use questionnaire (n=16).

Q1. How often do you use your mobile phone/telephone?	**Responses N (%)**	**Comments**
Every day	10 (62.5)	
3-4 times in the week	2 (12.2)	
From time to time (a couple of times in a year)	4 (25)	
Never	0 (0)	
Other	1 (6.25)	
Q2. How confident are you in using a telephone the 'standard' way, i.e. relying on hearing only?	**Responses**	**Comments**
Not confident at all	2 (12.5)	
Somewhat confident	9 (56.25)	
Confident	3 (18.75)	
Very confident	2 (12.2)	
Q3. To whom do you speak when using the telephone the 'standard' way, i.e. relying on hearing only?	**Responses**	**Comments**
Familiar people	15 (93.75)	
Unfamiliar people	13 (81.25)	
Q4. How do you use the telephone?	**Responses**	**Comments**
Rely on hearing only (the standard way)	16 (100)	Preferred way: • Rely on hearing only (the standard way): 6 • Text messages: 4
Rely on both hearing and seeing the face of speaker e.g. Skype or WhatsApp call etc.	8 (50)	
Text messages	8 (50)	
Q5. What telephone do you prefer to use (if applicable):	**Responses**	**Comments**
Landline	2 (12.2)	
Mobile	15 (93.75)	

DECT	1 (6.25)	
Q6. Do you use any special features, programs or accessories e.g.. Bluetooth, ComPilot, DuoPhone etc.	**Responses**	**Comments**
Yes	10 (62.5)	If yes, please specify: • Bluetooth (11) • ComPilot (2) • DuoPhone (3) • Cochlear app. (1) • Special bilateral headset (1)
No	5 (31.25)	
Q7- Would you be interested in attending a telephone-training workshop at USAIS?	**Response**	**Comments**
Yes	10 (62.5)	
No	4 (25)	

6.5.4 SSQ

Only the complete questionnaires were included in the analysis (n=14). Two participants (BiCI1 and BiCI4) did not complete the questions which related to the condition of using one CI as they had simultaneous bilateral cochlear implants and did not wear only one implant at a time. Therefore, their scores on the condition of using two CIs were excluded from the analysis. Informal feedback from all the participants was that the questionnaire was lengthy and laborious to complete.

Overall and the three subscales

The scores of the three main subscales of the SSQ, including speech, spatial and qualities of hearing were calculated for each participant for the two listening conditions: (1) one CI and (2) two CIs. In addition, the overall SSQ score was calculated by taking the average score across the three subscales. Figure 6.7 shows the self-rated scores on the overall SSQ and each of the three subscales for the bilateral CI participants with the two listening conditions. A higher score indicates greater ability.

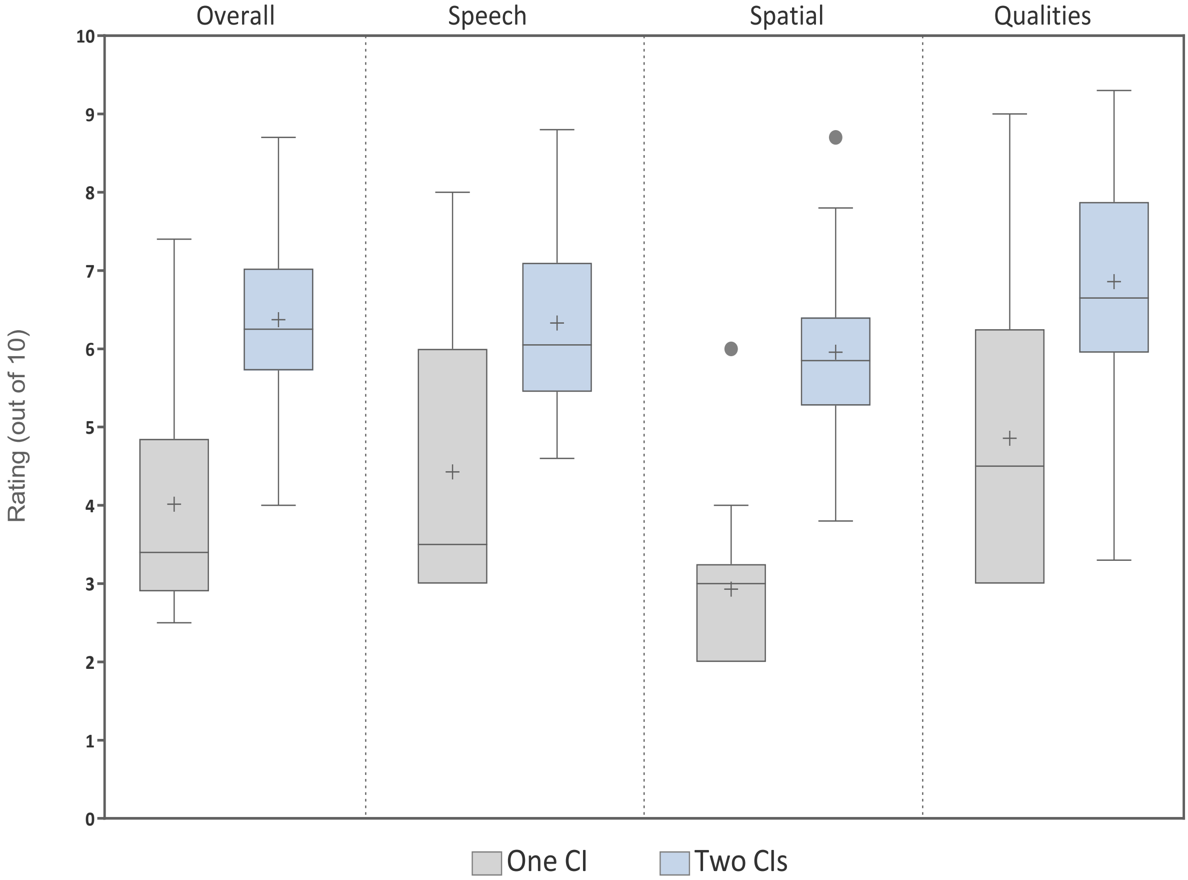

Figure 6.7: Scores on the overall SSQ and each of the three subscales: speech, spatial and qualities of the listening conditions: (1) one CI (grey box plots) and (2) two CIs (blue box plots). The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The outliers are plotted as solid circles.

Two trends can be seen in Figure 6.7. First, the self-rated scores were higher when using two implants compared to one implant. The second trend is that the difference between the two listening conditions is greater on the spatial subscale than for the other subscales. Two-way repeated-measures ANOVA test with the listening condition and type of subscale as the independent variables was performed to examine the above trends. Mauchly's test of sphericity indicated that the assumption of sphericity had been met for the type of subscale ($\chi2(2) = 2.6$, $p = 0.3$) and for the two-way interaction ($\chi2(9) = 5.97$, $p = .05$). The main findings were:

- The main effect of the listening condition was statistically significant which indicated that the average SSQ scores across the subscales (overall scores) are statistically significantly different between the two listening conditions by 2.4 points, $F(1,13) = 109.3$, $p<.001$

- The main effect of the type of subscale was statistically significant, indicating that the average scores across the listening conditions are significantly different between each subscale, $F(2,26) = 12.9$, $p<.001$
- Post hoc tests revealed that the scores for spatial subscales were significantly lower than those for the speech subscale by 0.9 point ($p= 0.004$) and for the qualities subscale by 1.4 points ($p=0.001$). It also showed that there is no statistical difference between the speech and qualities subscales (the mean difference was only 0.5 points), $p= 0.05$
- There was a statistically significant two-way interaction between the listening condition and type of subscale, $F(2, 26) = 9.3$, $p = 0.001$
- The interaction contrasts indicated the difference between the two listening conditions on the spatial subscale was statistically significantly larger than that on the speech subscale ($p=0.001$). Similarly, the difference between the two listening conditions on the spatial subscale was statistically significantly larger than the difference between the two listening conditions on the qualities subscale ($p=0.009$). It also revealed that the difference between the two listening conditions on the speech subscale was not statistically significantly different for the difference between the two listening conditions on the qualities of hearing subscale.

Figure 6.8 shows the mean rating score for the two listening conditions on the three subscale of the SSQ with 95% confidence intervals.

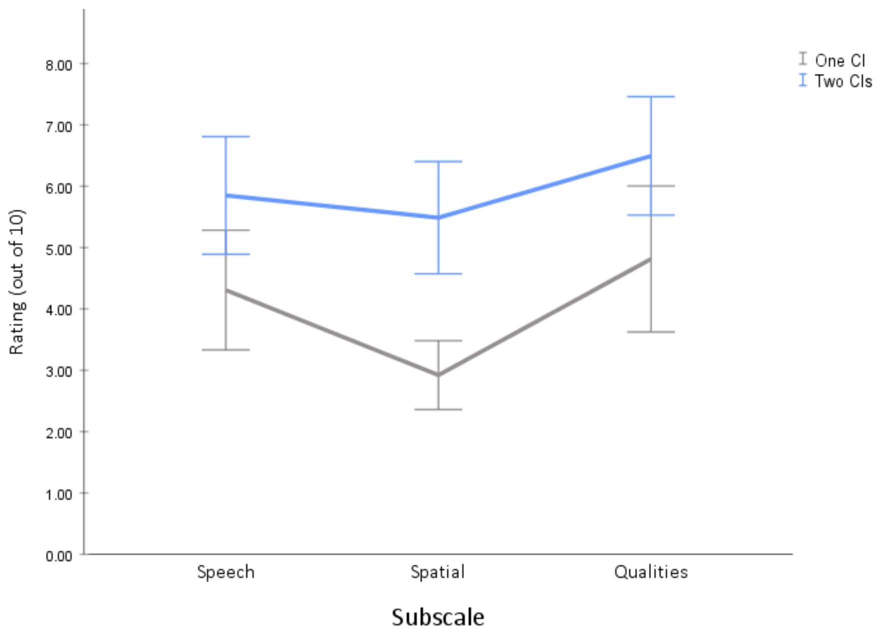

Figure 6.8: Mean rating scores on three subscales: speech, spatial and qualities of the two listening conditions: (1) one CI (grey line) and (2) two CIs (blue line). Error bars show 95% confidence intervals.

Telephone use

Only the data of 12 participants were included in the analysis. The four remaining participants answered the SSQ questions related to telephone use as 'not applicable'. Paired-samples t-tests were carried out on the rated scores of questions 13 and 14 to assess the difference between the two listening conditions for each question separately. There was no statistically significant difference between the two listening conditions on both questions. Table 6.5 shows the mean difference between the two listening conditions and the results of the analysis.

Table 6.5: Mean difference between the two listening conditions (95% confidence interval of the mean difference) and p values on questions 13 and 14 on the speech subscales of the SSQ.

	T-test	**p**	**Mean difference (95% confidence interval)**
Question 13	t (11)=0.5	0.6	0.3 (95%CI -0.8 to 1.3)
Question 14	t (11)=1.3	.2	0.5 (95% CI, -0.4 to 1.5)

Music perception

To measure the difference in music perception between the two listening conditions, the scores on questions 5, 7 and 8 on the qualities-of-hearing subscale were averaged and then compared among the listening conditions. Data of 14 participants were included in the analysis while the data of the two remaining participants were excluded due to incomplete answers to the questionnaire. The paired-samples t-test was carried out on the average score for the two listening conditions and the results revealed that the average score of the two-CIs condition was statistically significantly higher than the average score of one CI condition (mean difference=2 points, 95% confidence interval 1.2 to 2.8, $t(13)= 5.6$, $p< 0.001$).

6.5.5 Correlation between performance tests and subjective rating scales

The relationship between the self-rated scores on the SSQ and scores of performance tests including speech, spatial and telephone tests when using two CIs were examined to investigate whether the performance tests could reflect the ability of hearing functions in daily life as reported by the participants on the SSQ questionnaire. The correlation analysis included the data of all 16 participants.

The correlation between the average of the speech tests and the SSQ scores of the speech subscale was examined and the results are shown in Table 6.6. The average of the speech tests was calculated by averaging the scores for the two speech tests: SrN±60° test and S0°N±60°in the bilateral condition. The S+90° N-90° was not included in the average score as the test was only administered for the five participants who had AB devices (i.e. those with the Binaural VoiceStream Technology). No statistically significant correlation was found between the SSQ speech subscale and the average of the speech tests. In contrast, a significant correlation was found between SSQ scores of the spatial subscale and the average of the spatial-listening tests (including the localisation and tracking tests, in percentage correct for both tests). Thus, the correlation between each spatial- listening test and SSQ spatial subscale was investigated. A significant correlation was found for both the localisation and tracking tests with the spatial-speech subscale. Additionally, the relationship between the SSQ scores and the telephone test was examined by looking at the correlation between the scores of question14 on the SSQ speech subscale and the telephone-in-noise test. Table 6.6 shows no significant correlation between them. It should be noted that the telephone in quiet for the two-CIs condition had not been tested; therefore the correlation between the score of question 13 on the speech subscale and telephone test was not done.

Table 6.6: Results of correlation analysis between SSQ scores and the performance tests (speech tests, spatial tests, and telephone tests) in the listening condition of using two CIs. Significant correlations are in bold.

SSQ	Listening tests	Correlation (95% confidence interval)	p
SSQ- Speech subscale	Average of speech tests	-0.3 (-0.7 to 0.2)	0.2
SSQ- Spatial subscale	Average of spatial-listening tests (both localisation and tracking in % correct)	0.7(0.3 to 0.9)	**0.004**
	Localisation test (% correct)	0.6(0.1 to 0.8)	**0.02**
	Tracking test	0.6 (0.2 to 0.9)	**0.006**
SSQ (question 14- speech subscale) *	Telephone test in noise	0.3 (-0.3 to 0.7)	0.3

*The number of participants included in the analysis was 13 (two participants did not complete the SSQ while another participant answered the question as NA (not applicable). Therefore, their scores were excluded.

6.5.6 AB bilateral users and Binaural VoiceStream Technology

The five participants that were using the AB sound processor (BiCI3, BiCI5, BiCI7, BiCI10, and BiC14) were tested using Binaural VoiceStream Technology. This section presents the results for each of the five participants when they used StereoZoom, ZoomControl and DuoPhone compared to the condition of using one CI and the condition of two CIs (standard settings). It should be noted that statistical analysis tests could not be carried out due to the small sample size.

Figure 6.9 shows the SRTs for the five participants in the S0°N±60 test with the three listening conditions: (1) one CI, (2) two CIs, and (3) two CIs+ StereoZoom ON. For most of the participants, the SRTs were improved by using two CIs compared to using one CI, and a further improvement was obtained when they used the StereoZoom. One participant (BiCI7), however, found the SRTs were worse when the participant used two CIs, particularly with the StereoZoom compared to the one-CI condition.

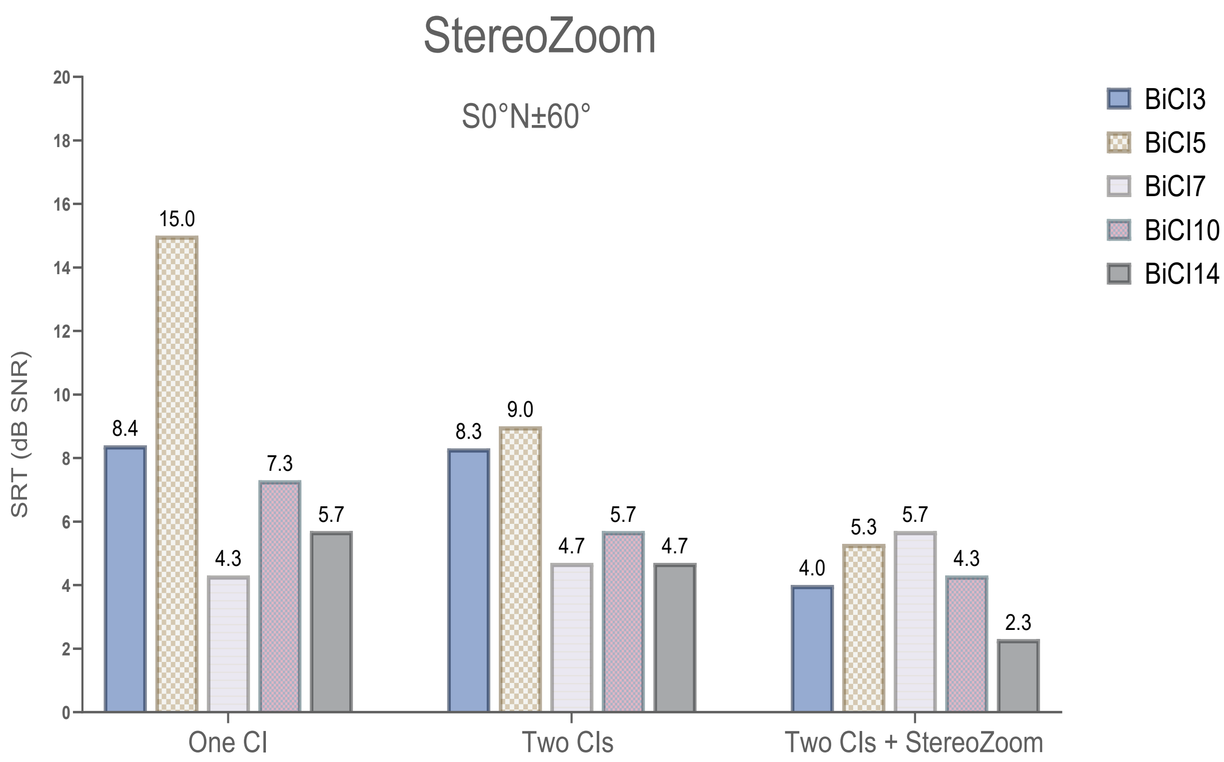

Figure 6.9: The SRTs on S0°N±60 test for each of the five AB bilateral CI participants in the three listening conditions: (1) one CI, (2) two CIs, and (3) two CIs+ StereoZoom. Lower SRTs indicate better performance.

The benefit of ZoomControl was assessed in the S+90°N-90° test as shown in Figure 6.10. The speech sentences were presented on the second CI side. For participants with simultaneous CIs, the noise was presented on the preferred (dominant) CI side or on the right-hand side if the participants did not have a preferred side. The SRTs improved when using ZoomControl for all five participants compared to the one-CI and two-CIs conditions with standard settings. The mean SRT in the listening condition of using two CIs and ZoomControl was 0.34 dB SNR while the mean SRT was 4.18 dB SNR and 11.52 dB SNR in the two- CIs condition (with standard settings) and the one-CI condition respectively.

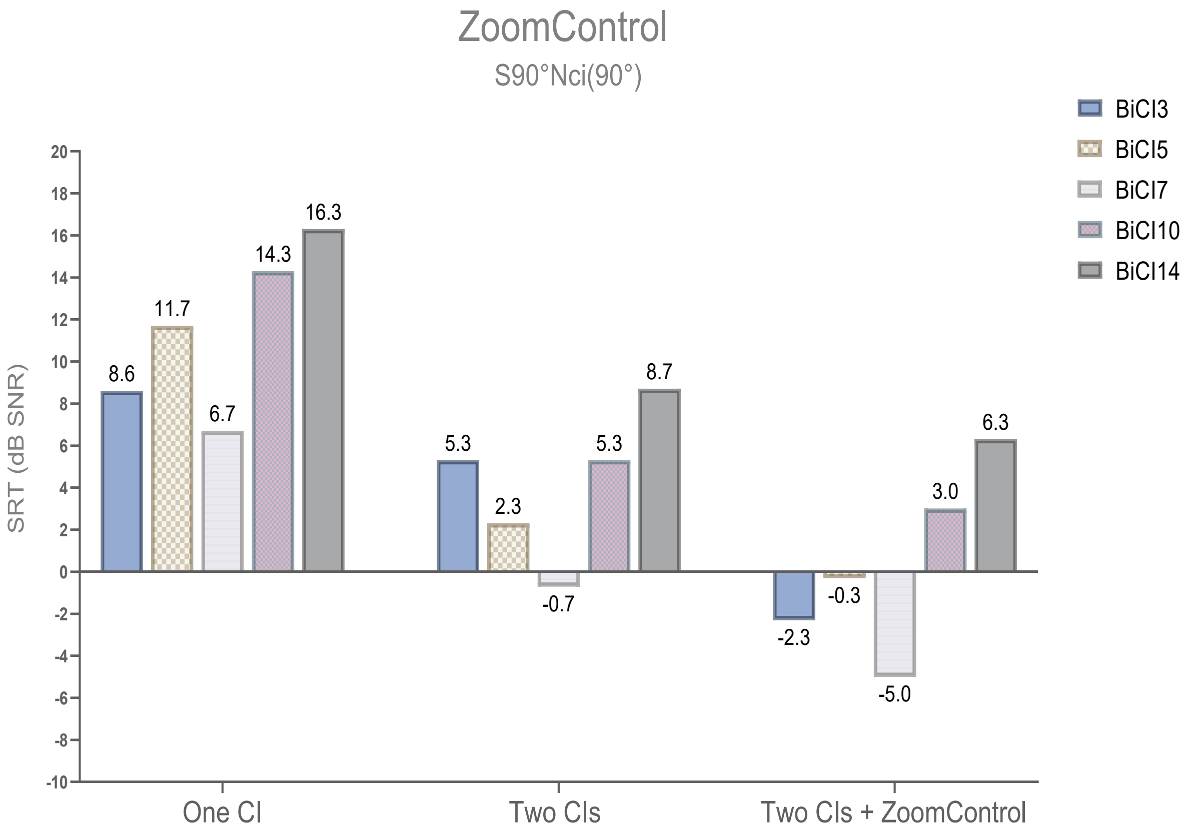

Figure 6.10: The SRTs on the S+90°N-90° test for each of the five AB bilateral participants in the three listening conditions: (1) one CI, (2) two CIs, and (3) two CIs+ ZoomControl. Lower SRTs indicate better performance.

Lastly, the benefit of DuoPhone for AB bilateral CI participants was examined. Figure 6.11 shows the scores of telephone tests in noise, in percentage correct, for each of the five AB participants in the two listening conditions: (1) two CIs with DuoPhone OFF and (2) two CIs with DuoPhone ON. There was no consistent performance pattern of the participants when using the DuoPhone. For instance, the performance was slightly decreased for participant BiCI3 with DuoPhone ON, whereas the scores were markedly improved with DuoPhone for participants BiCI10 and BiC14. The scores for the two remaining participants were unchanged with DuoPhone; however it should be noted that the scores reached the ceiling effect with standard settings of the two-CIs condition. Therefore, the benefit of DuoPhone for bilateral CI participants is unclear due to the test constraints.

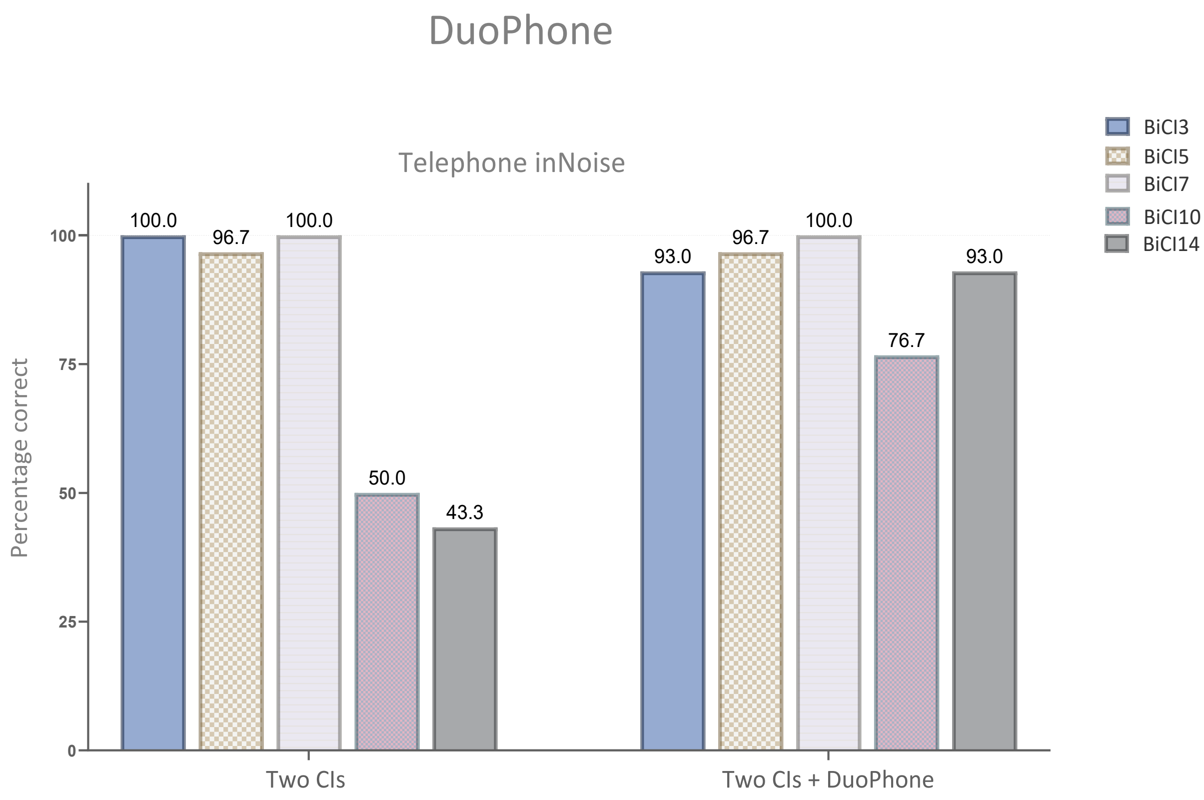

Figure 6.11: Mean scores on the telephone-in-noise test for each of the five AB bilateral participants in the two listening conditions: (1) two CIs and (2) two CIs+ DuoPhone.

6.6 Discussion

The current study compared the outcomes of bilateral CI users when using one CI versus two CIs on a real-life test battery which included both performance tests and subjective rating scales. The second aim was to assess whether using the Binaural VoiceStream Technology would add further improvement compared to the standard settings for the participants with AB devices.

The main finding of the current study is that outcomes with two CIs for adult bilateral CI users were statistically significantly better than with one CI in the following:

- Speech-in-noise tests
- Spatial-listening tests (localisation and tracking)
- Overall and three subscales of the SSQ questionnaire.

For the telephone test in noise, there was no statistically significant difference between using two CIs and one CI.

In addition, the current study found a significant correlation between the spatial subscale of the SSQ and the spatial-listening tests (both localisation and tracking tests).

For the five AB users, StereoZoom and ZoomControl seem to be advantageous in improving the SRT scores but the benefit of using DuoPhone was unclear due to test limitations.

6.6.1 Speech in noise

The results of the current study showed that two CIs were statistically significantly better than one CI for the SrN±60° and S0°N±60 tests, with SRT improvements of 1.8 and 2.1 dB respectively. This finding is in line with previous studies that used complex listening set-ups to assess speech perception for adult bilateral CI users (Dunn *et al*., 2010, Dunn *et al*., 2012, van Hoesel, 2015, Dorman and Gifford, 2017, Dorman *et al*., 2020). However, the bilateral benefit found in the present study in the roving-speech test was smaller than the bilateral benefit found in (Dunn *et al*., 2010, Dunn *et al*., 2012, van Hoesel, 2015). This can largely be explained by the differences in methodological settings between these studies and the current study. The roving speech in the van Hoesel (2015) study was presented randomly from four loudspeakers placed at ± 34° and ± 90 but presented randomly from nine loudspeakers of the Crescent of Sound which made the current study set-up more challenging than the one used by van Hoesel (2015).

Moreover, the previous studies used a cueing phrase prior to each speech sentence to help the participants in attending the correct direction, making the task less challenging than in the current study. Another methodological difference was the competing noise masker used by Dunn *et al.* (2010) and Dunn *et al*. (2012) who used a competing speech noise (a male or female talker repeating a different sentence from the target speech) which was presented from one loudspeaker that was ± 4 loudspeakers away from the loudspeaker presenting the target word. Similarly, van Hoesel (2015) used a different set-up to present the noise masker which was an interfering noise that was made using continuous dialogue from eight talkers. Each interfering talker was presented from one loudspeaker spanning a full 360° circle at 45° increments, whereas the current study used uncorrelated multi-talkers' babble noise presented from two loudspeakers placed ±60°. It should be noted that Dorman *et al*. (2020) found a significant bilateral benefit with using a roving-speech set-up. However, their findings could not be compared with the findings of the current study because they used fixed SNRs to measure speech perception.

The current study did not use any visual or auditory cues during the test. However, using visual cues during the measurement should be considered even though the test rig used in the current study did not have this option. As discussed in section 6.1, visual cues improved the SRT in the bilateral-CI listening condition by an additional 5 dB in the research of van Hoesel (2015) and 24.1% in the study by Dorman *et al.* (2020). In addition, a survey that included 131 responses from CI users showed that most CI users reported that in real life they can see the face of the speaker during the conversation in most situations (Dorman *et al*., 2016a). Therefore, using auditory information only in the assessment of bilateral-CI benefit may underestimate the effectiveness of the bilateral CI in real-life situations.

6.6.2 Linked AGCs

The current study also assessed the effectiveness of using two linked CI sound processors particularly using StereoZoom and ZoomControl for AB bilateral CI users. Although statistical analysis could not be carried out due to the limited number of participants, there was a trend of improved speech perception when using this Binaural VoiceStream Technology. The performance of most of the participants (80%) improved when StereoZoom was activated with an average improvement of 2.2 dB. The performance of one participant was degraded when the StereoZoom was used. It is not entirely clear whether there was any reason behind the performance declining for this participant. The trend found in the current study is in line with the finding of Ernst *et al*. (2019), whose study assessed the effectiveness of StereoZoom for ten bilateral CI users using two different test set-ups. The first set-up was similar to the test set-up used in the current study where speech was presented from the front loudspeaker and a speech-shaped noise was presented from loudspeakers placed at ±60°, ±120° and 180°. The average benefit of StereoZoom found in their study was 5.2 dB which was larger than found in the current study. The sample size and methodological differences (i.e. noise type and loudspeakers used to present the noise) could be possible reasons for this difference. The second test set-up in the study by Ernst *et al.* (2019) was more challenging as the noise was presented from narrower directions relative to the speech target. The speech was presented from the front while the noise from the loudspeakers was placed at ±30° and ±60°. The average StereoZoom benefit was smaller than the first test set-up (2 dB) which indicates that the effectiveness of StereoZoom is dependent on speech and noise separation.

Similarly, the performance of all five participants in the current study improved when ZoomControl was activated. The average ZoomControl benefit found in the current study was 3.8 dB. To the researcher’s knowledge, there are no other published studies that have assessed the effectiveness of ZoomControl for bilateral CI users. Future studies with a larger sample size are necessary.

6.6.3 Spatial-listening tests

For the localisation test, the current study found a statistically significant improvement for two implants compared to one CI. Although there was a noticeable inter-subject variability, nearly all of the participants performed above the level of chance for random guessing in the listening condition of using the two CIs. Only one participant performed within the chance range. The mean average improvement when using both implants was 46.3%. This finding is consistent with previous research that also used the AB Crescent of Sound and a localisation test with 30° loudspeaker separation (Goman, 2014, Smulders *et al.*, 2016a, van Zon *et al.*, 2017). Using a within-subject design, Goman (2014) tested 12 bilateral CI users and found an improvement of 34% with two implants versus one. He also found a significant improvement of 34% and 44% on 15° and 60° separation-test set-ups respectively. In a randomised clinical trial (Smulders *et al.*, 2016a, van Zon *et al*., 2017), the localisation performance of 19 adults who received bilateral CIs was compared to 19 adults who only received one CI (between-subject comparison) using the AB-York Crescent of Sound after 1- and 2-years' follow-up after the implantation. The performance of the bilateral CI group was significantly better than the unilateral CI group by 40.9% and 36.6 % on 30° separation set-up at the 1- and 2-years' follow-up respectively.

The mean RMS error in the current study was reduced by 35.2° when using the two CIs compared to using one CI. This finding is within the average RMS error reduction reported in the literature with bilateral CIs compared to a unilateral CI, which ranged from 13° to 43° (Gantz *et al*., 2002, van Hoesel and Tyler, 2003, Laszig *et al*., 2004, Nopp *et al*., 2004, Verschuur *et al.*, 2005, Grantham *et al.*, 2007, Neuman *et al.*, 2007, Tyler *et al.*, 2007, Dunn *et al.*, 2008, Litovsky *et al*., 2009, Koch *et al*., 2010, Dunn *et al*., 2012, Dorman *et al.*, 2016b, van Zon *et al*., 2017). In addition, the mean RMS error in the two-CIs condition (21.8°) in the current study was comparable to the mean absolute error (24°) in the two-CIs condition reported by Verschuur *et al*. (2005) and to the mean RMS error (29°) for bilateral CI users in the Dorman *et al*. (2016b) study.

The current study shows the advantage of using two CIs in improving sound localisation for stationary sound sources. However, this is not representative of real-life situations as many of the auditory stimuli are in motion, either because the listener moves, or the sound source does. As discussed in Chapter 4 section 4.2.1.3, the tracking of moving sounds is an important listening skill in daily life, especially for safety. Therefore, tracking of moving sound was assessed for bilateral CI participants. The current study found a statistically significant improvement in the tracking test from 23.1% with one CI to 78.5% with two CIs. This finding confirmed the results from previous work that used a similar test set-up (Goman, 2014). Although the task in the current study was more challenging than with Goman (2014) given that two additional motion trajectories were included, a slightly larger improvement with two implants (about 55.4%) was found compared to the benefit found in Goman's study (48.96%). The current study used six trajectories where each trajectory was presented twice in a pseudorandom order whereas Goman used only four trajectories where each trajectory was presented as one.

Furthermore, the current study found a significant correlation between the localisation and tracking in the two-CIs condition. For the one-CI condition, there was no significant correlation found between the localisation and tracking tests. This finding was expected as the scores in this listening condition were within the chance range of random guessing for both tests, thereby, they do not represent a real performance.

In short, the findings for the current study show that two CIs offer more advantages than one CI for sound localisation and tracking.

6.6.4 Telephone test

As discussed in Chapter 4 section 4.2.1.4, there are no standardised tests that have been developed specifically to assess performance of CI users in using and understanding speech over the telephone. A new telephone test was designed and developed mainly for the present study to assess the benefits of using DuoPhone for adult CI users in more representative of real-life testing set ups. Therefore, the telephone test is not directly relevant to assessing the binaural benefits. However, the difference in the performance when using two CIs and one CI has been examined.

As discussed earlier, this test is still considered a rudimentary test and has several limitations (see Chapter 4 section 4.2.2.5.5) for detailed discussion). One of these limitations is the ceiling effect being reached. This can be seen in the quiet condition of the telephone test where the mean performance reached 96% using one CI. The ceiling effect found in the quiet condition is most likely related to the test material. Triple digits have been used which are simple words usually presented in a closed-set paradigm. The ceiling effect would be reduced if other materials are used, such as sentences.

In the noise condition, there was no statistically significant difference between using one CI and two CIs. However, the performance with two CIs was lower than with one CI by approximately 10%. Although this reduction was small, this finding suggests that using two CIs over the telephone might be more distracting than using one CI. Therefore, bilateral CI users would be advised to use one CI during the phone call if there is any background noise.

The benefit of using the DuoPhone for AB CI users was examined. Statistical analysis was not conducted due to the small sample size. Only five participants were tested with DuoPhone as they had AB devices. As discussed earlier, only 8% of the adult CI population in the UK receive bilateral cochlear implants (BCIG, 2021). Given that the recruitment of bilateral CI participants has been carried out at one CI service (USAIS at the University of Southampton) and the limited number of adults with the bilateral CI in the UK, it was difficult to recruit a larger number of participants especially those with AB devices. In addition, the results of the five participants in the current study indicated a considerable inter-subject variability for DuoPhone benefits. Therefore, the benefit of DuoPhone for bilateral CI users was inconclusive based on the results of the current study.

A recently published study that assessed DuoPhone effectiveness for nine bilateral CI users found a significant improvement on average by approximately 20% in both quiet and noise (Miller *et al*., 2021). The study also showed an additional improvement (approximately 16%) was obtained when the microphone of the contralateral sound processor to the telephone was disabled. As a result, it would be recommended for future studies to use a large sample size in assessing the benefit of DuoPhone for bilateral CI users to substantiate the findings of Miller *et al*. (2021). In addition, future studies should consider using standardised telephone tests for measuring the DuoPhone benefits.

It seems that recent advances and improvements in CI, telephone and hearing-assistance technology have facilitated telephone use for CI users. For instance, most of the bilateral CI participants in the current study (approximately 81.3%) reported they could use the telephone with an unfamiliar speaker. This finding was relatively greater than those reported in previous studies, such as only 38% in Anderson *et al*. (2006) and 35% in Rumeau *et al.* (2015). Although the sample size of the current study (n=16) was relatively smaller than those included in Anderson *et al.* (2006) with 196 responses and Rumeau *et al.* (2015) with 26 responses, it is worth noting that more than half the participants in the current study (62.5%) reported using a hearing-assistance device or special features.

6.6.5 SSQ

The self-rated abilities of bilateral CI participants were examined in the current study when using one CI versus two CIs. The results showed that participants gave statistically significantly higher ratings when using two CIs over one CI on the overall and the three subscales of the SSQ. This finding is consistent with previous studies that assessed the subjective benefit of using bilateral CIs (Summerfield *et al*., 2006, Goman, 2014, Härkönen *et al.*, 2015, Smulders *et al*., 2016a, van Zon *et al*., 2017). It is worth noting that previous studies used different designs. For example, Summerfield *et al*. (2006) and Goman (2014) used a within-subjects comparison, while Smulders *et al*. (2016a) and van Zon *et al*. (2017) used a between-subjects comparison. All these studies found a significant improvement in the three subscales of the SSQ except for the quality-of-hearing subscale in the study by van Zon *et al*. (2017) where the improvement was not significant. The participants in that study were the same participants as in Smulders *et al.* (2016a) and tested with the same test battery after one year's follow-up after the implantation. The reason for this is unclear. A similar finding was reported by Noble *et al.* (2008) who used a between-groups comparison on the ten subsections of the SSQ (the ten subsections of the SSQ are illustrated in Table 4.2 in Chapter 4). The results of their study showed a significantly higher rating on the subsections of the spatial subscale and three out of four of the quality-of-hearing subsections. However, there was no significant difference in most speech subsections between the bilateral and unilateral CI groups. The mean listening experiences of the bilateral group was 22.9 months. It seems that for between-group comparisons, the time at which the rating took place might have had an effect on self-rated benefits. Table 6.7 shows the mean bilateral benefit on the three subscales in the current study and previous studies discussed earlier.

Table 6.7: Bilateral benefit on the three subscales of the SSQ found in the current study and previous research. The bilateral benefit was reported as a mean increase in the scores except in the studies by Smulders *et al*. (2016a) and van Zon *et al*. (2017) where the benefit was reported as a median increase in scores. The benefits in Summerfield *et al*. (2006) and Smulders *et al*. (2016a) were inferred from a figure showing the comparison between unilateral vs. bilateral. The benefits from Noble *et al*. (2008) were averaged across the 10 subsections of the SSQ.

		Mean bilateral benefit			**Study design**
		Speech	**Spatial**	**Qualities**	
Current study		2	3	2	Within -group
van Zon *et al*. (2017)		2.8	4.2	1.7 *	Between-groups
Smulders *et al*. (2016a)		3.4	3.6	1.2	Between-groups
Härkönen *et al.* (2015)	6 months	1	2.2	0.4	Within-group
	12 months	0.6	2.2	0.4	
Reeder *et al*. (2014)		2.05	2.9	1.8	Within-group

Goman (2014)		2.4	4.1	2.5	Within-group
Noble *et al*. (2008)		.8	1.7	1.1	Between-groups
Summerfield *et al*. (2006)	3 months	0.7	1.7	0.9	Within-group
	9 months	0.8	2	1.1	

*Reported as not significant

One of the main findings of the current study is that the mean rating of the overall of the SSQ using the two-CIs condition was about 6.4 points which is at the mid to high range of the scoring scale. This result was found to be broadly consistent with previous studies. For instance, Noble *et al.* (2008) reported a mean score of 6 points on the overall SSQ for 36 bilateral CI participants. Similarly, the reported mean overall SSQ in the Goman study (2014) was 6.6 points for 12 bilateral CI participants. In addition, Smulders *et al*. (2016a) and van Zon *et al*. (2017) found a median overall SSQ score of 6 and 6.2 points, respectively. Nevertheless, the finding in the current study suggests that, compared to the mean overall SSQ score with one CI (4 points), there is a substantial improvement in the hearing skills needed for everyday functions with two CIs; however there are struggles which might be experienced. Demeester *et al*. (2012) measured the SSQ-hearing disability cut-off points 2 SDs from the mean SSQ scores of NH listeners. The results from their study showed that scores below 7.25 indicate a significant degree of overall disability.

Another finding of the current study is that the largest bilateral benefit was found on the spatial subscale of the SSQ which was about 3 points compared to 2 points for speech and qualities-of-hearing subscales. This finding is also in line with the previous studies, outlined in Table 7.8, that showed the largest bilateral benefit was on the spatial subscale compared to speech and qualities-of-hearing subscales. In addition, this finding fits within strong evidence (such as Verschuur *et al*. (2005), Litovsky *et al*. (2009), Dunn *et al.* (2012) and van Zon *et al*. (2017)) for improved sound localisation with bilateral CIs over unilateral CIs.

The present study did not find significant differences between the one-CI and two-CIs conditions on the rating scores of understanding speech over the telephone questions (questions 13 and 14 on the speech subscale). Interestingly, this finding is in line with the results of the telephone test of the current study which showed no significant difference between using one CI and two CIs (section 6.4.3).

The participants' rating scores on the SSQ questions related to music perception (the average of questions 5, 7 and 8 scores on the qualities-of-hearing subscale) which were considered because the main aim of this PhD thesis was to assess the performance of bilateral CI and Naida Link bimodal users and the differences between them on a real-life test battery which comprises a variety of assessments for the important listening skills in real-life listening situations including music perception. However, a standardised music test was not included in the test battery because of the limited availability of standardised music-perception tests and the time constraint of the test battery. To compensate, it was decided to assess the SSQ questions which related to music perception in order to obtain a baseline for performance of the participants' study. The present study found a statistically significant higher rating when using two CIs over one CI on the average of questions 5, 7 and 8 scores on the qualities-of-hearing subscale.

In summary, the findings of the current study on the SSQ questionnaire showed the advantage of two CIs over one CI on hearing function in everyday life.

6.6.6 Relationship between the SSQ questionnaire and performance tests

The relationship between the SSQ questionnaire and the listening tests for the bilateral CI condition was also examined for bilateral CI participants. The main finding is that there was a significant correlation only between the spatial subscale of the SSQ and the average of the spatial-listening tests. The results also showed that there was a significant correlation between the SSQ spatial subscale and localisation test, and between the SSQ spatial subscale and tracking test. A similar finding was reported by Noble *et al*. (2008) and Laske *et al.* (2009) who found a significant correlation between the spatial subscale of the SSQ and the localisation test. Additionally, Goman (2014) reported a similar correlation coefficient to that found in the present study (r=0.6). Another point that should be stressed is that the data included in correlation analysis in the studies by Nobel *et al*. (2008) and Goman (2014) were composed of the data across three CI groups (bilateral CI, unilateral CI, and bimodal users), whereas the data included in the current study represent only the data for bilateral CI participants.

The present study did not find any significant correlation between the speech subscale of the SSQ and the average speech test. This finding contrasts with that of Noble *et al*. (2008) who found a significant correlation between all subsections of the speech subscale of the SSQ and speech-perception test. However, this discrepancy could be related to the data included in the analysis. The data in the current study represent only data of bilateral CI participants while the data in the research by Noble *et al*. (2008) were more diverse as it comprised three different CI groups (bilateral CI, unilateral CI, and bimodal users). This justification would be supported by the findings from Goman's (2014) study who found a significant correlation between the speech subscale of the SSQ and the speech-perception test when the speech and noise were presented from the front (0°) azimuth and when the noise was presented to first (or only) CI. She did not find any correlation between the speech subscale of the SSQ and the other speech tests (speech in quiet, speech in speech, speech in noise with noise opposite to first CI). Similarly, the data in Goman's (2014) study were more diverse than the data of the current study as it included the data of the three CI groups.

The current study also did not find a correlation between question 14 on the speech subscale of the SSQ and telephone-in noise test. The absence of the correlation may be related to the methodological limitations of the telephone test (as discussed in Chapter 4 section 4.2.2.5.5). Another possible reason is that there were considerable variations in scores between the participants in the bilateral listening condition compared to the unilateral condition as shown in Figure 6.6.

Nevertheless, the findings of the present study suggest that self-rated ability in everyday life of the bilateral CI participants could be represented by the spatial-listening tests (localisation and tracking tests), but not by the speech-in-noise tests used in this study. However, it should be stressed that this finding might be influenced by the relatively small sample size included in the current study. Therefore, if this study were repeated with a larger sample size, a significant correlation might be found between the SSQ and the speech tests.

6.6.7 Simultaneous vs. sequential bilateral CIs

Following establishing solid evidence for the cost-effectiveness of bilateral CIs for adults with bilateral severe hearing loss, another important aspect that should be considered is the time of getting the two implants, in other words, whether simultaneous bilateral CIs would provide better outcomes than sequential CIs. Previous studies have been limited to addressing this question for adult users. A recent randomised clinical trial (Kraaijenga *et al*., 2017) that included 38 participants found no difference on all objective and subjective outcome measures on hearing and quality of life between simultaneous CIs and sequential CIs with a 2-year interval between implants. However, this study did not consider the sequential CI users with a longer interval between the two implants. Although the auditory system is fully developed for adults with hearing loss, some studies showed the effect of the interval between implants and the length of deafness on the outcomes for adults with sequential bilateral CIs (Laske *et al*., 2009, Reeder *et al*., 2014). Laske *et al*. (2009) compared objective and subjective outcomes for adults with sequential CIs with an interval between implants ranging from 0 to 19 years. They found a significant correlation between the interval of the two implantations and speech test in quiet which showed better results with short intervals. Similarly, Reeder *et al.* (2014) found that participants with a longer duration of deafness for the second implant (more than 20 years) performed poorly and progressed more slowly over time than the participants with a shorter duration (less than 20 years). Additionally, a longer interval between the implants may affect normal binaural development (Basura *et al*., 2009). Therefore, the interval between the two implants for sequential users is a critical factor that should be considered when comparing the benefits of simultaneous CIs with sequential CIs for adults.

In the current study, the nature of bilateral CI participants was heterogenous in terms of getting the second implant. Five participants had simultaneous CIs and eight participants had sequential CIs. Three participants had a messy pattern in getting the bilateral CIs. For instance, participant BiCI3 had a unilateral CI but then due to the device failure, the CI company offered two simultaneous CIs. Participants BiCI7 and BiCI14 had simultaneous bilateral CIs, but then due to device failure on one side, they had a sequential CI. The time interval between the two implants for the sequential subgroup ranged from 2 to 11 years with a mean interval of 4.9 years (SD= 3.1 years). Statistical analysis was carried out to assess whether there is a difference between simultaneous CIs and sequential CI participants on the real-life test battery used in the current study. The results of this analysis are explained in Appendix P. The main finding indicated that there was no difference between simultaneous CIs and sequential CIs on speech in noise, localisation, tracking, and telephone in quiet tests. However, there was a significant difference between the two subgroups on the telephone-in-noise test. The sequential subgroup was better than the simultaneous subgroup by 36.8%. This is an interesting finding that could be explored further using a more standardised telephone test. For the SSQ questionnaire, a statistical analysis was not done due to the small sample size included in the analysis. The uncompleted questionnaire was excluded which resulted in a small number of participants having a complete SSQ (only three participants for the simultaneous subgroup).

Despite that, it should be stressed that this section would be considered a preliminary exploration and the generalisability of the findings is limited for two reasons. First, the relatively small sample size (five participants with simultaneous CIs and eight participants with sequential CIs were included in the analysis). Secondly, the control for confounding factors (age and device) was not considered. Therefore, further future studies are needed to substantiate the difference between simultaneous CIs and sequential CIs users on a real-life test battery.

6.7 General discussion and limitations

To the best of the researcher’s knowledge, the present study was the first study that used a real-life test battery which included both performance tests and subjective rating scales to assess the outcome of adult bilateral CI users. It has been argued that using standard measures, particularly for speech perception, in which a single loudspeaker placed in front of the listener to present both target speech and a noise masker, would underestimate the benefit of bilateral CI for adults in real-life listening situations. The findings from the present study confirmed the benefits of using two CIs over one CI for speech understanding in test settings that are more representative of real-life listening situations. Moreover, the study showed a significant improvement with using two CIs over one CI on localising the source of sounds, tracking moving sounds and the perceived benefits, altogether indicating the advantages of using two CIs on different aspects of auditory function in real-life environments. Therefore, it would be recommended to consider using a real-life test battery in measuring the benefits as well as the cost-effectiveness of bilateral CI.

Using linked AGCs seems a promising feature that would provide an additional benefit for bilateral CI users. There are few studies, as discussed earlier in Section 6.1.2 that examined the effectiveness of linked AGCs. Previous work showed a significant improvement in speech perception and localisation with linked AGCs over the independent AGCs (Potts *et al*., 2019, Gajecki and Nogueira, 2021). However, further research is needed to substantiate the findings of these studies. The current study assessed the advantage of linked AGCs for the participants who used AB devices when using Binaural VoiceStream Technology. There was a trend of improving speech perception in noise when using this technology (ZoomControl and StereoZoom). For using the DuoPhone, there was considerable inter-subject variability among the participants' scores; therefore the benefit of using DuoPhone over the phone for bilateral CI users was inconclusive. It should be stressed that statistical analysis could not be conducted due to the small sample size of only five participants. Future studies should consider using a large sample size and investigating the effectiveness of linked AGCs for other companies if available. Subsequently, the benefit of using linked AGCs should also be considered in the cost-effectiveness assessment for adult bilateral CI users.

The present study used a within-subject design to compare the outcomes with two CIs and with one CI. There are several advantages for using within-subject design particularly in terms of the statistical analysis of the results. For instance, more power may be obtained because of reductions in random error as a result of fewer individual differences. However, it should be noted that testing the bilateral CI with a within-subject design (one CI versus two CIs) is fundamentally different to between-subject design (comparing bilateral CI and unilateral CI users). One important difference is that using a within-subject design with bilateral CI users does not represent how participants listen normally in their real life in which testing in the one CI condition. Nyirjesy *et al.* (2020) justified that using this type of design would introduce an artificial and ''non-ecologically valid'' listening condition which is different from the participants' real life. The effect of the unfamiliarity of using one CI for bilateral CI participants was considered in the current study. The two listening conditions were counterbalanced for each test. In addition, the scores of listening tests and the SSQ questionnaire when using one CI for bilateral CI participants in the current study were compared with the scores of the Naida Link bimodal participants (for the study in Chapter 5) when they were tested with the CI only. There were no significant differences in the listening condition of using one CI between the two groups which suggests any effect of listening-condition familiarity is weak. However, it would be useful to administer the real-life test battery used in the present study to unilateral CI users and then compare their performance to bilateral CI participants to obtain an insight into the differences between the two groups in real-life listening situations. Moreover, there are few studies used in between-subject design to assess the performance of bilateral CI users compared to unilateral CI users, such as Dunn *et al*. (2010), Smulders *et al.* (2016a), and van Zon *et al.* (2017) (see Appendix A for a summary of studies which investigated the performance of adult bilateral CI users on speech in the presence of noise). Therefore, future studies would consider testing adults with unilateral CI using the real-life test battery.

In addition, it is important to consider investigating whether the amount of benefit found in the present study with two CIs especially in the speech-in-noise tests (approximately 2 dB) is clinically significant rather than statistically significant. McShefferty *et al*. (2016) argued that the minimum 2 to 3 dB SNR change does not necessarily mean this change is important for the listeners. They claimed that a change of 6 to 8 dB in dB SNR (depends on listening set-ups) would be required to consider it as meaningful (see Chapter 8 section 8.2.4 for detailed discussion).

The current study has some limitations that should be acknowledged. First, the sample size was relatively small particularly with increasing the inter-subject variability among CI users. One of the challenges of the current study was recruiting adult bilateral CI users given the recruitment was carried out at one CI service with a limited number of adults with bilateral CIs in the UK (only 8% of the adult CI population (BCIG, 2021)). Second, the participants of the current study were heterogeneous particularly in terms of the device, duration of deafness, having simultaneous versus sequential implants, and the time interval between the two implants for participants with sequential implants. No control has been considered for these confounding variables. For instance, duration of deafness of the participants ranged from 0 to 60 years. It was shown that there was an inverse correlation between the duration of deafness and the performance in speech tests (Laske *et al*., 2009). Although it was not significant, bilateral CI users with a shorter duration of deafness achieved a better performance in speech in quiet. Another confounding factor that might have an effect on the results was the time interval between the two implants (ranging from 2 to 11 years). As discussed in Section 6.6.7, the time interval between the implants has an influence on the performance (i.e. speech perception) and normal binaural development

(Basura *et al.*, 2009, Laske *et al.*, 2009, Reeder *et al.*, 2014). Therefore, the effect of heterogeneity on the results cannot be ruled out. It is worth considering how the results would be with more homogenous characteristics of participants, such as if all participants had simultaneous implants. Finally, one of the weaknesses of the current study is the telephone test used. The test is considered a rudimentary test that needs further work and development. Therefore, the results of the telephone test were inconclusive.

6.8 Conclusion

The outcomes and experiences of adult bilateral CI users were assessed using a real-life test battery. The conclusions of the current study are as follows:

- There was a statistically significant improvement with using the two CIs compared to one CI in speech-in-noise tests, spatial-listening tests (localisation and tracking) and subjective benefits reported on the SSQ, particularly on the spatial subscale
- Using Binaural VoiceStream Technology, specifically StereoZoom and ZoomControl, seem to offer advantages of improving speech understanding in noise for AB users
- There was a significant correlation between the spatial-listening tests and the spatial subscale of the SSQ
- There was no statistically significant difference between bilateral CIs and unilateral CI on the telephone-in-noise test. In addition, the benefit of using DuoPhone for AB bilateral users was inconclusive.

Chapter 7 Comparison of the outcomes of adults with normal hearing, bilateral cochlear implants, and integrated bimodal fittings on the real-life test battery

7.1 Introduction

The advantages of bilateral CI and bimodal hearing (standard technology) over one CI, as reported in the literature, are presented in Chapter 2. In addition, the findings from the experiments that were carried out for this PhD project (Chapters 5 and 6) showed the superiority of bilateral CI and integrated bimodal technology over unilateral CI.

Although the advantages of bilateral CI over one CI seem to outweigh the advantages of bimodal hearing, the cost-effectiveness of bilateral CI remains debatable (as discussed in Chapter 2 section 2.3.2.4).. Theriou *et al.* (2019) used an economic model to assess the cost-effectiveness of bilateral CI, bimodal hearing, and unilateral CI in adults with bilateral severe to profound hearing loss using a public healthcare system perspective based on data from the UK and the USA. The results showed that bilateral CI produces more health benefits as expressed in the Quality Adjusted Life Years (QALYs) than unilateral CI and bimodal hearing, yet it is highly unlikely to be considered as the most cost-effective due to the excessive costs needed when providing the two CIs. In contrast, the results of their evaluation showed that bimodal hearing is more cost-effective than unilateral and bilateral CI in the UK and US from a National Health Service perspective.

Evidence is needed to guide decision-making around bilateral and bimodal hearing in adults. Research is also needed to determine how well bilateral-CI and bimodal-hearing users perform in comparison to NH adults in real-life listening situations to better understand technology limitations and additional support required.

This chapter compares the outcomes of Naida Link bimodal participants (Chapter 5) and bilateral CI participants (Chapter 6) with the outcomes of NH participants on the real-life test battery which developed in the current study.

7.1.1 Bilateral CI versus bimodal hearing

The question of whether bilateral CI is better than bimodal hearing (with a standard HA), especially for those with residual hearing in the non-implanted ear, is still hard to answer. Several studies directly addressed this question by using between-subject comparisons (Cullington and Zeng, 2011, Gifford *et al.*, 2014, Kokkinakis and Pak, 2014, Blamey *et al.*, 2015, Dorman *et al.*, 2016b, Gifford *et al.*, 2018, Erdem and Ciprut, 2019, Gifford and Dorman, 2019) or by within-subjects comparisons (Luntz *et al*., 2014, Potts and Litovsky, 2014, Gifford *et al*., 2015, Yawn *et al.,* 2018, Sturm *et al*., 2021). A summary of the methodology and main findings for the between-subject design and within-subject design studies is shown in Tables 7.1 and 7.2 respectively. There is a considerable variation in the findings from these studies. Some studies showed the superiority of bilateral CI over bimodal hearing in terms of speech understanding (Blamey *et al*., 2015, Gifford *et al.*, 2015) while other studies showed that bimodal hearing might be superior in terms of the binaural hearing advantages particularly the summation effect (Kokkinakis and Pak, 2014). In a study conducted by Cullington and Zeng (2011), the performance of bimodal hearing and bilateral CI users was compared on four different pitch-related tasks: speech recognition in noise, music perception, identifying the tone of voice and discriminating different talkers. No significant differences were found between the two groups.

A review study by van Hoesel (2012) contrasted the benefits of a second CI versus a contralateral HA in CI users. They described the benefits of bilateral CI for spatial hearing, linked to a large head-shadow effect and improvement in localisation. The benefits of bimodal hearing are related to pitch discrimination and speech understanding (in conditions where spatial hearing is not applied) due to the provision of low-frequency information that is poorly accessed by the implant. However, van Hoesel concluded that the large individual variability found makes reaching a conclusion for the best option challenging.

Schafer *et al* (2011) used a repeated-measures meta-analytical approach to investigate the relative benefits of a second CI and a contralateral HA for the three binaural attributes (e.g. binaural squelch, binaural summation, and head-shadow effect). The analysis assessed 42 studies of speech perception in noise when using adaptive and fixed-test paradigms. Both groups showed a significant benefit in terms of binaural summation and the head-shadow effect, but only a second CI afforded the advantage of binaural squelch. Schafer *et al*. reached the conclusion that bilateral CIs have a slight advantage over bimodal hearing.

A systematic review (van Schoonhoven *et al*., 2013) drew attention to the limited number of studies that directly compared bilateral CI and bimodal hearing. Several studies have been published following the van Schoonhoven *et al*. review. For instance, Luntz *et al*. (2014) carried out a within-subjects comparison of ten experienced bimodal-hearing users with severe to profound hearing loss in the non-implanted ear who received a second CI in a period of between 2 and 11 years after their first implant. They used a comprehensive test protocol that included assessment of binaural cues, localisation and the SSQ. The performance with bilateral CI was better than bimodal hearing for localisation, speech perception when the noise and speech were spatially separated and for the SSQ. The bimodal hearing was better than bilateral CI only for differences between perception of natural prosody speech and speech with flattened fundamental frequency (F0) contour with speech and noise, both presented from the front. Based on their findings, the authors emphasised the importance of counselling unilateral CI users with severe profound hearing loss of the expected trade-off if they want to have a second CI. However, their findings cannot be generalised to other unilateral CI users who have more residual hearing. Recent studies showed mixed findings for speech perception in noise with bilateral CI and bimodal hearing (Gifford *et al*., 2018, Gifford and Dorman, 2019, Sturm *et al*., 2021); however better subjective benefits were found with bilateral CI over bimodal hearing (Yawn *et al*., 2018, Erdem and Ciprut, 2019).

Taken together, studies have directly compared bimodal hearing to bilateral CI which showed inconclusive findings regarding the overall benefits that might relate to methodological differences, small sample sizes and inter-subject variability including residual hearing. Additionally, they suggest a trade-off in listening abilities with greater spatial hearing and reduced ability to use low-frequency information with bilateral CI whereas bimodal hearing would improve sound quality and speech perception but produce limited spatial-hearing benefits. Therefore, there is still uncertainty of which option is better for adult unilateral CI users and more well-structured research (e.g. a randomised control trial) is needed in this area.

Table 7.1: Summary of studies that used between-subject design to compare bilateral CI and bimodal hearing (standard HA).

	Bilateral N	**Bimodal N**	**Outcome measures**	**Main findings**
Cullington and Zeng (2011)	13	13	1. Speech perception with a competing talker 2. Music perception 3. Affective prosody discrimination 4. Talker identification	The bimodal group performed better than the bilateral group in all of the four tests, but the difference was not statistically significant
Gifford *et al.* (2014)	30	35	Speech perception in a multi-talker babble at +5 dB SNR in three set-ups: • S0°N0° • S0°N90° • S0°N270°	No significant differences between bimodal and bilateral groups
Kokkinakis and Pak (2014)	7	7	Speech perception in a four-talker babble in three set-ups: • S0°N0° • S0°N+90° • S0°N-90°	• A significant difference in summation effect (S0°N0°) between the two groups (bimodal have a benefit of 7.6 dB compared to 2.4 dB for bilateral) • No significant difference between the two groups in S0°N+90° or S0°N-90° (the head shadow effect and squelch)
Blamey *et al.* (2015)	86	589	Speech perception in quiet and in noise	The bilateral group performed significantly better (although small) than the bimodal group by 5% in quiet and 7% in noise

Dorman et al. (2016b)	32	8	Sound localisation with 13 loudspeakers arrayed in 180° arc	A significant difference between the bimodal group (RMS error= 62°) and bilateral group (RMS error= 29°)
Gifford *et al*. (2018)	25	12	1. Speech perception in quiet 2. Speech perception in proprietary restaurant noise presented from 7 loudspeakers in two set-ups: • Set-up A: speech sentences fixed from either 0°, 90°, or 270° • Set-up B: speech sentences roved randomly from either 0°, 90° or 270°	No significant difference between bimodal and bilateral groups
Gifford and Dorman (2019)	36	49	1. Speech perception in quiet 2. Speech perception noise in two set-ups: • Set-up A: S0°N0° • Set-up B: S0°N0°, ±45°, ±90°, ±135°, and 180°	• No significant difference between the two groups in set-up A • A significant difference between the two groups in set-up B (the bilateral group had better performance than the bimodal group)
Erdem and Ciprut (2019)	14	30	SSQ	The bilateral group had a significantly better score than the bimodal group

Table 7.2: Summary of studies that used within-subject design to compare between bilateral CI and bimodal hearing (standard HA).

	N	**Outcome measures**	**Main findings**
Luntz *et al*. (2014)	10	1. Task-specific testing of bilateral binaural hearing that includes sound lateralisation, binaural summation/redundancy/unmasking, head-shadow effect) 2. Bimodal complimentary benefit (low-frequency information) 3. SSQ	• Bilateral CI was better than bimodal hearing: 1. speech lateralisation 2. speech perception of semantically unpredictable sentences in S0°N90° (noise at 1st implant) 3. SSQ • The bimodal hearing was better than bilateral CIs in: 1- perception of natural prosody speech 2- speech with flattened F0 contour when S0°N0°
Potts and Litovsky (2014)	4	1. CNC words perception in quiet 2. Localisation 3. SSQ	Bilateral CI was better than bimodal hearing for: 1. two participants in word perception 2. All the participants in localisation and SSQ
Gifford *et al*. (2015)	8	1. Speech perception in quiet 2. Speech perception noise in two set-ups: • Setup A: S0°N0° • Setup B: S0°N0°, ±45°, ±90°, ±135°, and 180°	• In set-up A: No difference between bimodal and bilateral CI conditions, only in test conditions of sentence at +5dB SNR (4 out 8 participants showed significant differences between bimodal and bilateral CI scores) • In set-up B: 6 out of 8 participants showed significant differences between bimodal and bilateral CI scores

Yawn *et al.* (2018)	22	1. Speech perception in quiet 2. Speech perception in multi-talker babble noise (+ 5 SNR) 3. SSQ 4. APHAB questionnaire	• Bilateral CI condition was significantly better than the bimodal condition in: 1. Speech perception in quiet 2. SSQ 3. APHAB questionnaire • No difference between bilateral CI and bimodal conditions in speech perception in noise
Sturm *et al.* (2021)	26	1. Speech perception in quiet at 35 dBHL and 50 dBHL 2. Speech perception in noise at 50 dBHL (+ 5 SNR)	• Bilateral CI was significantly better than bimodal only in quiet at 50 dBHL • No significant difference in quiet at 35 dBHL nor in noise

7.1.2 Bilateral CIs versus integrated bimodal technology

The above studies have focused on standard bimodal technology compared to bilateral implantation. To the best of the research's knowledge, there is currently no published study that has compared the outcomes of integrated bimodal technology (Naida Link bimodal) with bilateral CI. A single study has compared the effectiveness of StereoZoom (which is one of the features that are available in the integrated bimodal technology) for bimodal and bilateral CI users (Ernst *et al.*, 2019). The bilateral CI users had AB Naida CI sound processors and the bimodal users were fitted with a Phonak Naida Link HA and an AB Naida CI sound processor. There was no significant difference between the bimodal and bilateral CI users when they used the StereoZoom. Interestingly, both groups (with StereoZoom activated) performed as well as NH listeners for the easier test set-up where the speech was presented from the front loudspeaker and noise from loudspeakers placed at ±60°, ±120° and 180°. In the more challenging set-up, where speech was presented from the front and noise from ±30° and ±60°, only the bilateral CI users performed as well as the NH listeners. The standard settings of the integrated bimodal technology and the other features of Binaural Voice Stream Technology were not compared to the standard settings of bilateral CIs in the study by Ernst *et al*. (2019). Additionally, the number of participants in both groups was relatively small, with only 10 participants in each group. Therefore, there is still a need to understand the differences between these two technologies with a larger sample size and a more comprehensive test protocol. Thus, in the current chapter, the results of the Naida Link bimodal group (Chapter 5) are compared with the results of the bilateral CI group (Chapter 6).

7.1.3 Real-life listening environments

Another aspect that should be considered when comparing bimodal hearing and bilateral CI is that the tests are used to measure the differences between them. Gifford and Dorman (2019) argued that using standard clinical tests of speech perception with a single loudspeaker is not sufficiently sensitive to differentiate between the performance of bimodal and bilateral CI users. In preliminary work, Kolberg *et al*. (2015) used an array of eight loudspeakers to assess the effect of source azimuth for unilateral, bimodal and bilateral CI users in which the speech sentences were randomly roved from loudspeakers that were placed at 0°, 90° and 270° in a semi-diffuse restaurant noise. The preliminary results showed that the performance of the bimodal users, compared to the bilateral CI users, was quite variable according to source azimuth. However, only two bimodal users and seven bilateral CI users participated in that study. Therefore, the discrepancy between the two groups could have been attributed to the small sample size. Gifford *et al.* (2018) used the same test set-ups as Kolberg *et al*. (2015), but with a larger sample size to investigate the effect of source azimuth for 25 bilateral CI users and 12 bimodal users. Their results showed that bilateral CI users performed similarly across the three-source azimuth whereas the bimodal users performed significantly better when the speech sentence was presented to the better hearing ear compared to when the speech was presented from the front or to the poorer ear. The findings of the study by Gifford *et al.* (2018) indicated that bilateral CI users could overcome the effects of ear-source location as a result of a larger degree of symmetry between ears and the presence of bilateral head shadow, whereas bimodal users were significantly affected by the better-ear effect that they had. Therefore, using fixed speech presented from a single loudspeaker would not be enough to show the differences between bimodal hearing and bilateral CI when the speech was coming from different locations as it is in real-life environments.

In a further study, Gifford and Dorman (2019) compared the performance of 49 bimodal and 36 bilateral CI users with two different test set-ups. The first testing set-up was similar to the standard test settings used in most audiology clinics, with a single loudspeaker placed at 1 metre in front of the participant. In the second set-up, an array of eight loudspeakers placed in a 360° arc with 45° separation was used. The speech sentences were presented from the front loudspeaker in both testing set-ups. The noise in the first set-up was a multi-talker babble noise that was presented from the single speaker in the front. In the second set-up, semi-diffuse (propriety restaurant) noise was presented from all eight loudspeakers. There were no significant differences between the bimodal and bilateral CI groups in the standard testing set-up. However, a significant difference (approximately 2.1 dB) between the SRTs of the two groups was found in the second testing set-up. The findings suggested that the difference between bimodal hearing and bilateral CIs is more evident in more complex listening environments rather than standard testing set-ups.

7.2 Motivation and gap in knowledge

There is a need to investigate the differences between the benefits provided by the integrated bimodal (Naida Link bimodal) technology and those provided by bilateral CI. Moreover, using testing set-ups that mimic the listening environments in real life has been shown to be more sensitive in capturing the differences in the performance between bimodal and bilateral CI users than standard clinical tests. Therefore, the outcomes of Naida Link bimodal participants (Chapter 5) were compared to the outcomes of bilateral CI participants (Chapter 6) on the real-life test battery developed for this PhD project. The real-life test battery comprises performance tests and subjective rating scales. Performance tests include speech-in-noise tests that simulate common listening environments in real life, spatial-listening tests and telephone tests. To the best of the researcher's knowledge, there is no published study that has used a real-life test battery to examine outcomes of bimodal hearing users (specifically Naida Link bimodal users) and bilateral CI users, compared to NH adults.

This will help to provide a better understanding of how much help and benefit can be obtained by different technologies (bimodal hearing vs. bilateral CI) for adults with bilateral severe to profound hearing loss. Having a better understanding will help to inform clinical practice and potentially contribute to shaping national policy and funding for those with CI.

7.3 Aims

The aims were as follows:

1. To compare the outcomes of adult Naida Link bimodal participants versus bilateral CI participants versus NH participants of the real-life test battery that included speech-in-noise tests, spatial-listening tests (localisation and tracking moving sounds tests) and a telephone-in-noise test
2. To compare experiences of adult Naida Link bimodal participants versus bilateral CI participants on a self-reported measure, namely the SSQ
3. To compare the amount of benefit obtained from the integrated bimodal technology (calculated as the difference between the listening condition of CI+ Naida Link HA and the listening condition of using CI only) versus the amount of benefit obtained from the bilateral CI (calculated as the difference between the listening condition of using two CIs and the listening condition of using one CI only) on the real-life test battery. This is to determine whether there is a significant difference in the binaural benefit that can obtained from using an HA and a second implant in the non-implanted ear for adult unilateral CI users.

7.4 Method

7.4.1 Procedure

This chapter compares the outcomes of Naida Link bimodal participants (Chapter 5) and bilateral CI participants (Chapter 6) with the outcomes of the NH participants. In addition, a comparison was carried out when the Naida Link bimodal and AB bilateral CI participants used Binaural VoiceStream Technology. A summary of the tests administered to each group is presented in Table 7.3. It should be noted that the comparison between the three groups was not done for all the tests included in the test battery given that the Binaural VoiceStream Technology only applies to specific conditions and AB users. A description of the test battery and the procedure of each test for each group has been explained in the previous chapters (4, 5, and 6) in the method section. In addition, the demographic information for participants in each group can be also found in these chapters.

Table 7.3: The tests administered to each group.

		NH group	**Naida Link bimodal group**		**Bilateral CIs group**	
		N=45	**N=26** Standard settings (everyday map)	**N=26** Using Binaural VoiceStream Technology	**N=16**	**N=5** AB users using Binaural Voice Stream Technology
Speech in noise	**SrN±60°**	✓	✓		✓	
	S0°N±60°	✓	✓	✓ (StereoZoom)	✓	✓ (StereoZoom)
	S+90°N-90°	✓	✓	✓ (ZoomControl)		✓ (ZoomControl)
Localisation		✓	✓		✓	
Tracking		✓	✓		✓	
Telephone in quiet		✓	✓	✓ (DuoPhone)		
Telephone in noise		✓	✓	✓ (DuoPhone)	✓	✓ (DuoPhone)
SSQ			✓		✓	

✓= indicates that the test has been administered

7.4.2 Analysis

Both descriptive and inferential statistical analyses were carried out between the three groups for each test in the test battery. The descriptive analysis was done using GraphPad Prism software (version 9.1) and statistics were computed using IBM SPSS Statistical Analysis software (version 26).

As there was no statistically significant difference between the unilateral CI condition in the Naida Link bimodal and bilateral CI groups, the data of the unilateral CI condition for both groups were combined and are visually presented as the unilateral CI condition in this chapter. It should be noted that the unilateral CI condition was not included when computing the statistics because it included mixed data from the two CI groups.

Before computing the statistics, the normality distribution of the data was assessed using the Shapiro-Wilk test. Parametric statistical analysis tests were used, even if the assumption of normality was violated, since they are considered to be robust to non-normality (Maxwell and Delaney, 2004, Rasch and Guiard, 2004). Where there were multiple comparisons, post-hoc corrections were used. However, Bonferroni correction was not applied as it is generally conservative and overcorrects for Type I errors which affect the statistical power (Field, 2013, p.459). Tukey and Games-Howell (based on the assumption of homogeneity of variances) were used instead in these statistics as they have greater power than Bonferroni. This increase the possibility of detecting differences between means that might, in reality, be meaningful.

Furthermore, benefits obtained by the second implant and those from a Naida Link HA have been calculated and then compared using statistical tests. The benefit provided by a second implant for the bilateral group was calculated by taking the difference score between the two-CIs condition and one-CI condition for each test as:

The benefit obtained from a second CI = (two CIs) – (one CI)

The benefit provided by the Naida Link HA for the bimodal group was calculated by taking the difference score between the listening condition of CI with Naida Link HA and the listening condition of CI only for each test as:

The benefit obtained from a Naida Link HA = (Naida Link HA+ CI) – (CI only)

It should be noted that when calculating the benefit on the speech-in-noise tests, the score of the best-aided condition when using the CI with the Naida Link HA was used (i.e. when using StereoZoom in S0°N±60° test and using ZoomControl in S+90°N-90° test).

7.5 Results

7.5.1 Speech perception in noise

Figure 7.1 presents the SRTs for all three groups in the study (Naida Link bimodal, bilateral CI and NH groups) for the three speech-in-noise tests: SrN±60°, S0°N±60°, and S+90°N-90°. It should be noted that S+90°N-90° means the same as SHANCI for the purposes of comparing the Naida Link bimodal group with bilateral CI and NH groups. The figure also shows the combined unilateral CI condition for both the Naida Link bimodal and bilateral CI groups. It should be noted that the S+90°N-90° test was only administered for five bilateral CI users who have AB devices when using the standard settings (everyday map). This is because this test was developed specifically to assess the benefit of using ZoomControl; therefore only AB users with access to this feature were tested. The mean SRTs and the 95% confidence intervals for the three groups and the combined unilateral listening condition for the speech-in-noise tests are shown in Table 7.4.

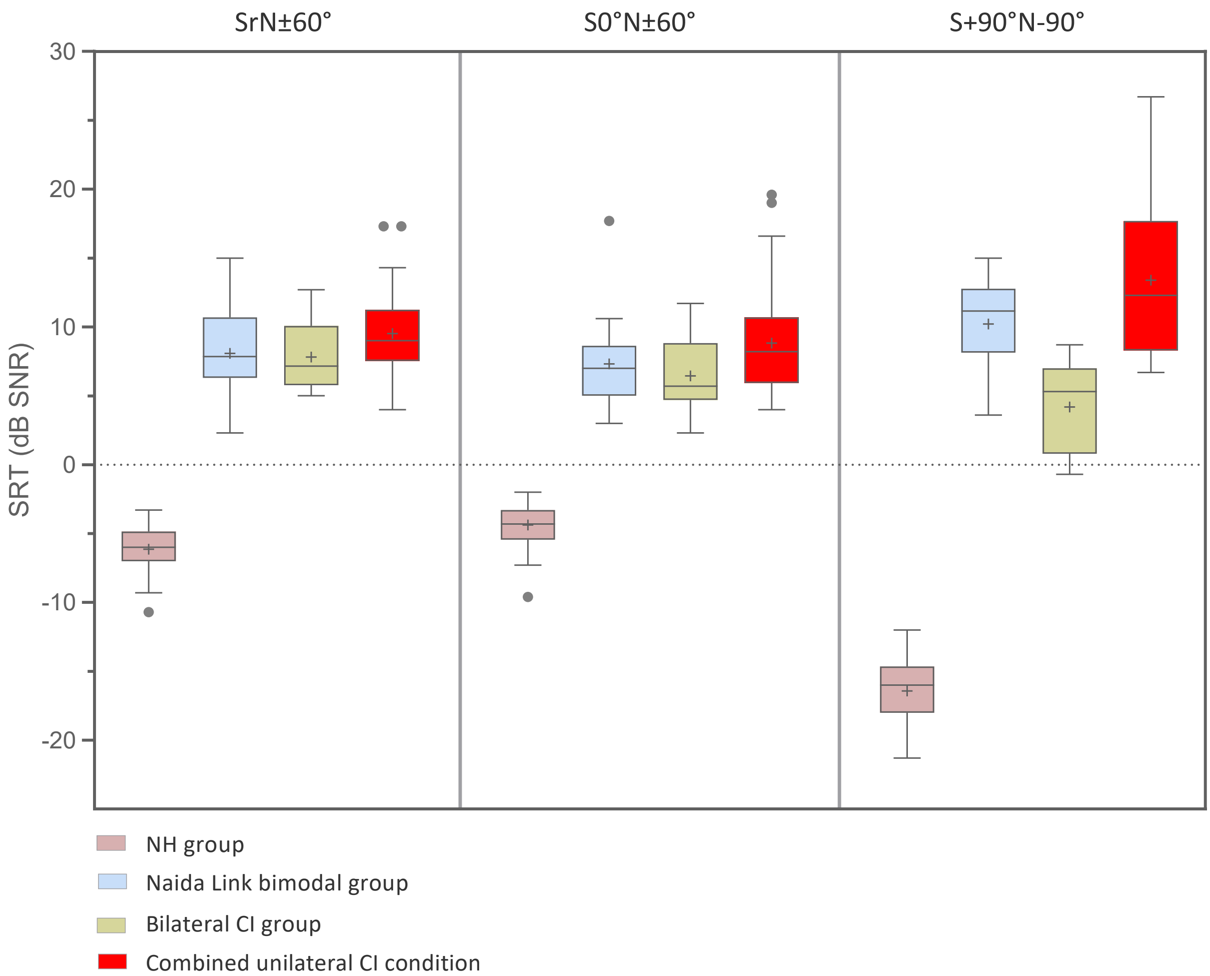

Figure 7.1: Box plots representing the SRTs in dB SNR for the three groups: (1) NH, (2) Naida Link bimodal, and(3) bilateral CI as well as the combined unilateral CI condition in SrN±60° (left), S0°N±60° (middle) and S+90° N-90° (right) tests. The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The outliers are plotted as solid circles. The combined unilateral CI condition includes data for the unilateral CI

condition for both the Naida Link bimodal and bilateral CI groups. For the +90° N-90° test, the speech was presented at the right ear for the NH participants, on the HA side for the Naida Link bimodal participants, and at the 2nd CI for bilateral CI participants. Binaural VoiceStream Technology was turned OFF for Naida Link bimodal and AB bilateral CI participants. Lower SRTs indicate better performance.

Table 7.4: Mean SRTs in dB SNR (95% confidence intervals) of the three groups and the combined unilateral CI condition in real-life speech-in-noise tests.

	NH group	**Naida Link bimodal group**	**Bilateral CI group**	**Combined unilateral CI condition**
SrN±60°	-6.1 (-6.7 to -5.6)	8.1 (6.9 to 9.2)	7.8 (6.4 to 9.2)	9.5 (8.6 to 10.5)
S0°N±60°	-4.4 (-4.8 to -3.9)	7.3 (6.1 to 8.5)	6.4 (5 to7.9)	8.8 (7.6 to 10)
S+90°N-90°	-16.4 (-17.1 to -15.7)	10.2 (8.9 to 11.5)	4.2 (-0.2 to 8.6)	13.4 (11.5 to 15.3)

The parametric statistical analysis test, one-way ANOVA, was carried out for each speech test separately. The assumption of homogeneity of variances was violated, as assessed by Levene's test for equality of variances in SrN±60° and S0°N±60° tests ($p < .05$). Therefore, the Welch ANOVA was used to interpret the results in these two tests. The results showed that there was a statistically significant difference in the SRTs between the three groups, except between the Naida Link bimodal and bilateral CI groups in the SrN±60° and S0°N±60° tests. Table 7.5 reports the results of one-way ANOVA post hoc tests, and the mean difference with the 95% confidence interval between the three groups for each speech-in-noise test.

Table 7.5: Results of one-way ANOVA post hoc tests and mean difference (95% confidence intervals) of the three groups for speech perception-in-noise tests. The significant difference is highlighted in bold font.

	F	Mean difference (dB)	P	95% confidence interval
SrN±60°	Welch's F (2, 32.3)= 385.3 **p < .001**	NH – Naida Link bimodal= -14.2	**< .001**	-15.7 to -12.7
		NH – Bilateral CI= -13.95	**< .001**	-15.8 to -12.2
		Bilateral CI - Naida Link bimodal= -0.3	0.99	-2.4 to 1.9
S0°N±60°	Welch's F (2, 30.6)= 252.9 **p < .001**	NH – Naida Link bimodal = -11.7	**< .001**	-13.2 to -10.2
		NH – Bilateral CI = -10.8	**< .001**	-12.7 to -8.99
		Bilateral CI –Naida Link bimodal = -0.9	0.6	-3.1 to 1.3
S+90°N-90°	F (2, 73)= 833.5 **p < .001**	NH - Naida Link bimodal= -26.6	**< .001**	-28.2 to -25
		NH – Bilateral CI= -20.6	**< .001**	-23.7 to -17.6
		Bilateral CI - Naida Link bimodal= -6.02	**< .001**	-9.2 to -2.9

Binaural VoiceStream Technology

The best-aided listening condition in the Naida Link bimodal and bilateral CI groups was compared as well as the NH group. The comparison was carried out in two ways. The first way compared outcomes when using StereoZoom in S0°N±60° test and ZoomControl in S+90°N-90° test for the Naida Link bimodal participants (n=26) and AB bilateral CI participants (n=5). Both listening conditions were also compared to the NH group. The second way compared the outcomes with and without using Binaural VoiceStream features for the Naida Link bimodal participants and bilateral CI participants (n=16) respectively, and again were also compared with the NH group (Figure 7.2).

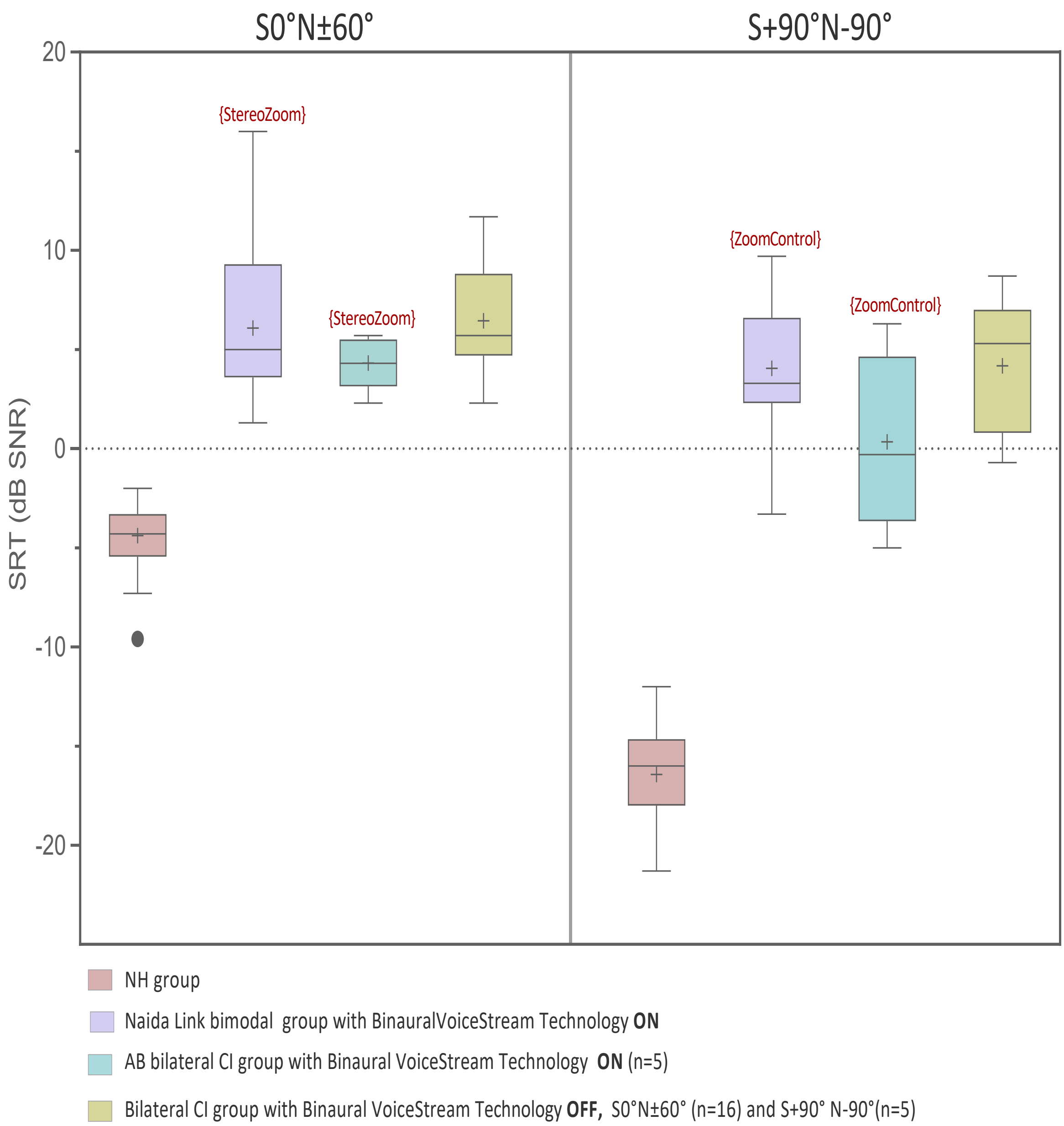

Figure 7.2: Box plots representing the SRTs in dB SNR for (1) NH group, (2) Naida Link bimodal group with Binaural VoiceStream Technology ON, (3) bilateral CI group with Binaural VoiceStream Technology ON (only AB users, n=5), and (4) bilateral CI group with Binaural VoiceStream Technology OFF in S0°N±60° (left), and S+90° N-90° (right) tests. The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The outliers are plotted as solid circles. Lower SRTs indicate better performance.

In both comparisons, a statistical analysis one-way ANOVA test was carried out for each speech-in-noise test separately. Levene's test for equality of variances indicated that the assumption of homogeneity of variances was violated for the S0°N±60° test, but it was met for the S+90°N-90°

test. Table 7.6 reports the results of analysis and post hoc tests. There was a statistically significant difference in the SRTs among the three groups across the two tests. The performance of the NH group was statistically significantly better (lower SRTs) than the Naida Link bimodal and bilateral CI groups with and without using Binaural VoiceStream features. The performance of the Naida Link bimodal group when using the StereoZoom was not statistically significantly different to the bilateral CI group with and without StereoZoom. When the Naida Link bimodal group used the ZoomControl feature, their performance was not statistically significantly different to the bilateral CI group (ZoomControl OFF); however, the performance of the bilateral CI group (ZoomControl ON) was statistically significantly better than the Naida Link bimodal group.

Table 7.6: Mean difference (95% confidence intervals) for the NH group, bilateral CI group, and Naida Link bimodal group (with and without Binaural VoiceStream Technology). Results from post hoc analysis are also listed. The significant difference is highlighted in bold font.

	Speech test	F	Mean difference (dB)	P	95% confidence interval
First comparison	**S0°N±60°**	Welch's F(2, 11.7)= 163.9 **p < .001**	NH - Naida Link bimodal (StereoZoom ON) =-10.3	**< .001**	-12.3 to -8.6
			NH - AB bilateral CI (StereoZoom ON)= -8.7	**< .001**	-10.7 to -6.7
			AB bilateral CI (StereoZoom ON) -Naida Link bimodal (StereoZoom ON)=-1.7	0.2	-4.1 to 0.6
	S+90°N-90°	F(2, 75)= 522.8 **p < .001**	NH - Naida Link bimodal (ZoomControl ON)= -20.5	**< .001**	-22 to -18.97
			NH - AB bilateral CI (ZoomControl ON)= -16.8	**< .001**	-19.7 to -13.8
			AB bilateral CI (ZoomControl ON) - Naida Link bimodal (ZoomControl ON)= -3.7	**<.01**	-6.8 to - 0.63
Second comparison	**S0°N±60°**	Welch's F(2, 29.99)= 189.4 **p < .001**	NH - bilateral CI (StereoZoom OFF)= -10.8	**< .001**	-12.7 to -8.99
			Bilateral CI (StereoZoom OFF) - Naida Link bimodal (StereoZoom ON)= 0.4	0.9	-2.03 to 2.8
	S+90°N-90°	F(2, 75)= 583.7 **p < .001**	NH - bilateral CI (ZoomControl OFF)= -20.6	**< .001**	-23.5 to -17.7
			Bilateral CI (ZoomControl OFF) - Naida Link bimodal (ZoomControl ON) = 0.12	0.99	-2.9 to 3.1

7.5.2 Spatial-listening tests

Sound localisation

The mean performance as a percentage-correct score for the sound-localisation test (30° separation) for the three groups (NH, Naida Link bimodal and bilateral CI) is shown in the left-hand panel of Figure 7.3 (A). The mean performance of the combined unilateral CI condition is also reported in Figure 7.3 (A) which shows that the mean score was close to the chance (mean=22.3%, SD=7.4). The performance was higher than a chance for all the other three groups. The performance of the bilateral CI group (mean=70%, SD=21.9) was better than the Naida Link bimodal group (mean=33.7%, SD=10.1). All the NH participants in the localisation test (n=17) scored 100% correct. As the NH group reached the ceiling effect and there was no variation in the data, the independent sample t-test was carried out to examine the difference in the mean performance between the Naida Link bimodal and bilateral CI groups. The assumption of homogeneity of variances was violated, as assessed by Levene's test for equality of variances ($p = .004$). The results indicated that the mean performance of the bilateral CI group was statistically significantly higher by 36.3% (95% CI, 24.1 to 48.5) compared to the Naida Link bimodal group, $t(18.98) = 6.2$, $p < 0.001$.

The RMS error for the three groups on the localisation test, as well as for the combined unilateral CI condition, is shown in the right-hand panel of Figure 7.3 (B). The difference in RMS error was examined only between the Naida Link bimodal and bilateral CI group for the same reasons mentioned in the previous paragraph. There was homogeneity of variances as assessed by Levene's test for equality of variances ($p > .05$). The independent sample t-test indicated that the mean RMS error of the bilateral CI group was statistically significantly lower by 21.3° (95% CI, 12.9 to 29.6) compared to the Naida Link bimodal group, $t(40) = 5.1$, $p < 0.001$.

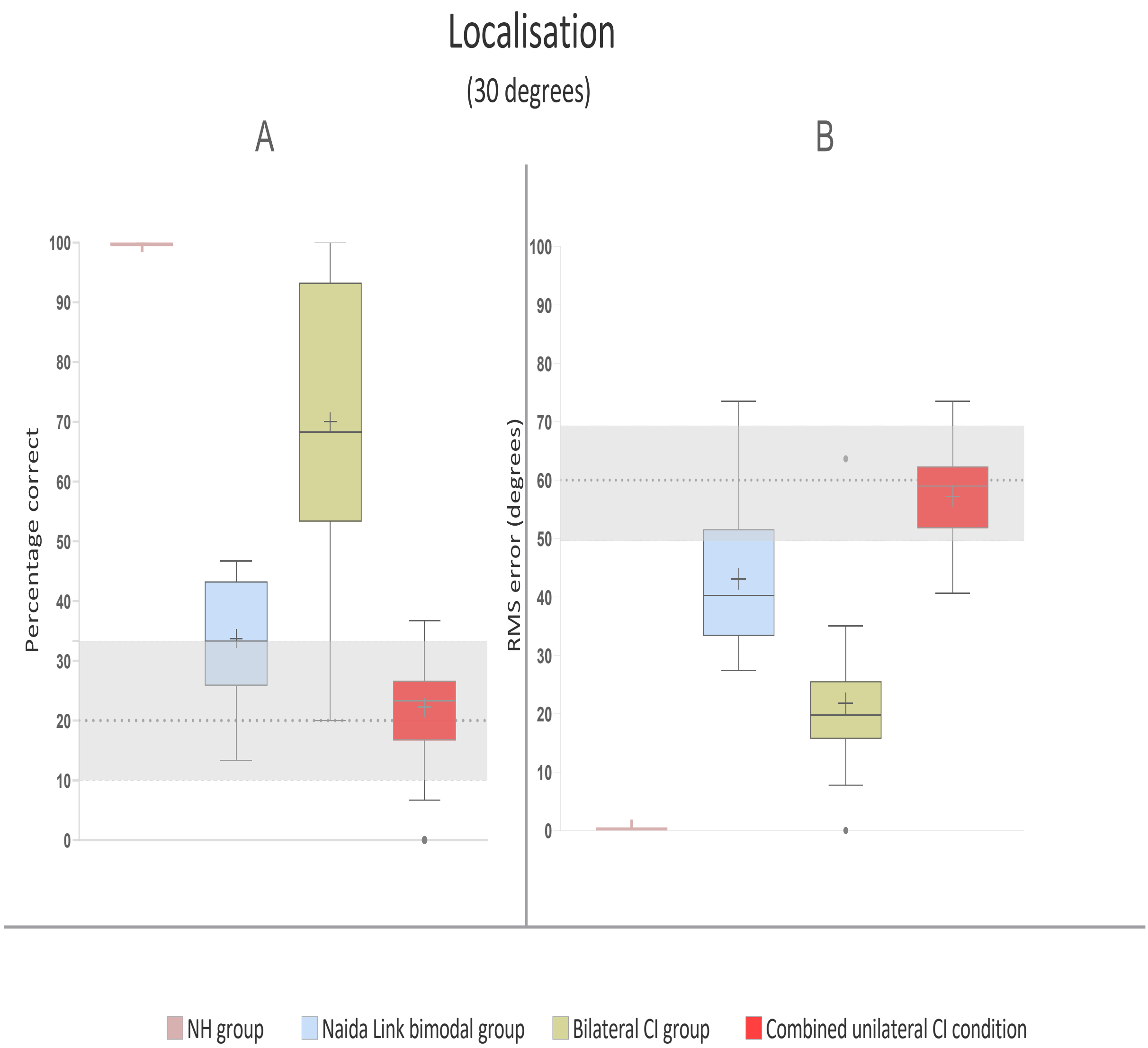

Figure 7.3: Results of the localisation test in percentage correct (left-hand panel) and RMS error (right-hand panel) for the three groups: (1) NH, (2) Naida Link bimodal, and (3) bilateral CI as well as the combined unilateral CI condition. The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The dashed horizontal line shows the level of performance expected by chance, with the grey shaded area showing the 5th and 95th percentiles of the change range. The outliers are plotted as solid circles.

Tracking

The mean performance on tracking test for the three groups (NH, Naida Link bimodal and bilateral CI) is shown in Figure 7.4. The mean performance of the combined unilateral CI condition is also reported in Figure 7.4 which shows that the mean score was close to the chance (mean=19.9%, SD=14.3). As for the localisation test, the mean performance was higher than the chance for all three groups. The performance of the bilateral CI group (mean=78.5%, SD=25.4) was better than the Naida Link bimodal group (mean=34.3%, SD=15.6). All the NH participants in the localisation test (n=17) scored 100% correct.

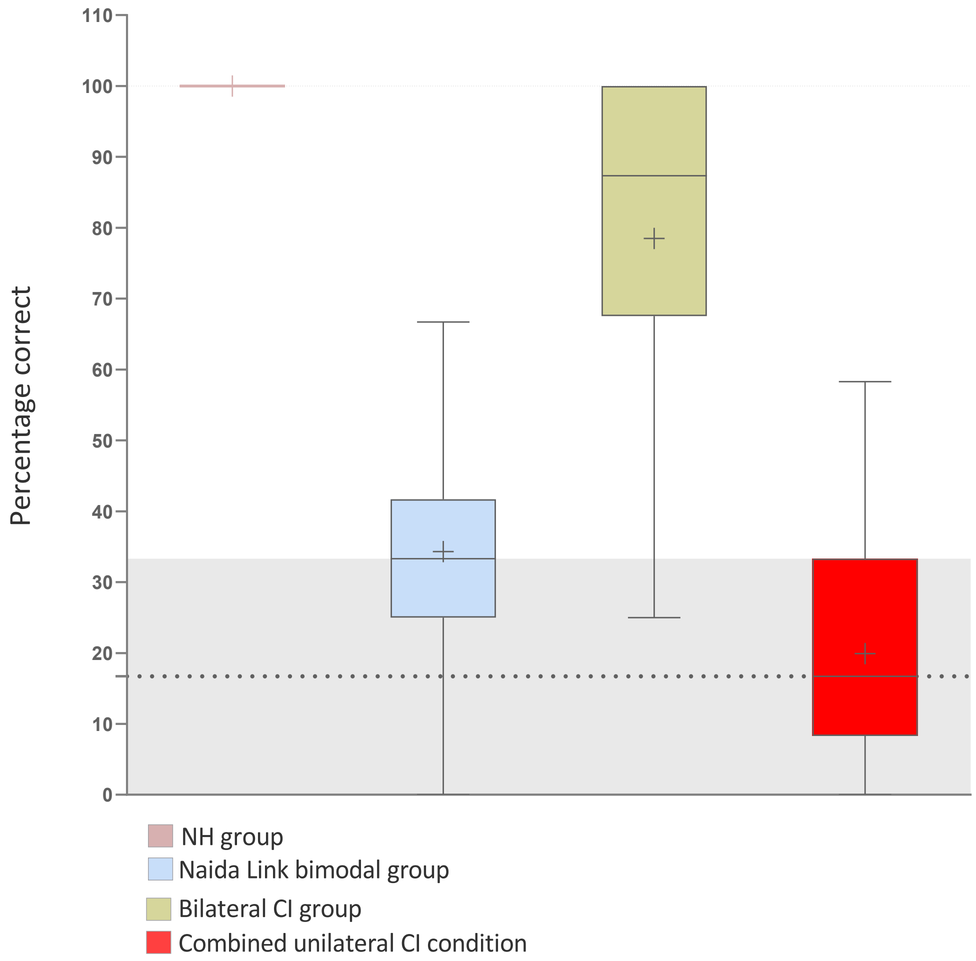

Figure 7.4: Results of the tracking test in percentage correct for the three groups: (1) NH, (2) Naida Link bimodal, and (3) bilateral CI as well as the combined unilateral CI condition. The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The dashed horizontal line shows the level of performance expected by chance, with the grey shaded area showing the 5th and 95th percentiles of the change range.

The mean performance of the NH group reached the ceiling effect and there was no variation in the data. Therefore, the independent sample t-test was carried out to examine the difference in the mean performance between the Naida Link bimodal and bilateral CI groups. The assumption of homogeneity of variances was violated, as assessed by Levene's test for equality of variances (p = .02). The results indicated that the mean performance of the bilateral CI group was statistically significantly higher by 44.2% (95% CI, 29.6 to 58.8) compared to the Naida Link bimodal group, t(22) = 6.3, p < 0.001.

7.5.3 Telephone test

Figure 7.5 shows the mean performance on the telephone test in quiet and in noise for the three groups. The mean performance for the unilateral CI condition for the bilateral CI group is also included. The Naida Link bimodal group was not tested with the unilateral CI condition on the telephone test in quiet and in noise as the main interest for this group was to assess the effectiveness of using DuoPhone. Also, it should be noted that the bilateral CI group in the listening condition of two CIs was only tested in telephone in noise due to time constraints of the test battery.

The mean performance for the NH group, Naida Link bimodal group and unilateral CI condition (of the bilateral CI group) on the telephone test in quiet is presented in the left-hand panel of Figure 7.5. The mean performance for the Naida Link bimodal group was the lowest (mean=91.8%, SD=7.8). However, both groups and the unilateral condition reached the ceiling effect, particularly the NH group where all the participants (n=17) achieved 100% correct.

In noise, the mean performance for the three groups and unilateral condition is presented in the right-hand panel of Figure 7.5. The NH group (n= 45) has the highest mean performance (mean=99.4%, SD=1.7) whereas the mean performance of the bilateral CI group was the lowest (mean=67.9%, SD=26.6). The unilateral CI condition was also not included in statistical analysis because it comprised data from the bilateral CI group. The statistical analysis test (independent sample t-test) was carried out to assess whether there is a statistically significant difference between the Naida Link bimodal and bilateral CI groups. The assumption of homogeneity of variances was violated, as assessed by Levene's test for equality of variances (p = .02). The results indicated that the mean performance of the bilateral CI group was lower than the Naida Link bimodal group by 12.2% (95% CI, -28.3 to 3.8). However, the difference was not statistically significant, t (16.9) = -1.6, p = 0.1. The data of the NH group were not included in the statistical analysis as the data reached the ceiling effect and there was no considerable variation.

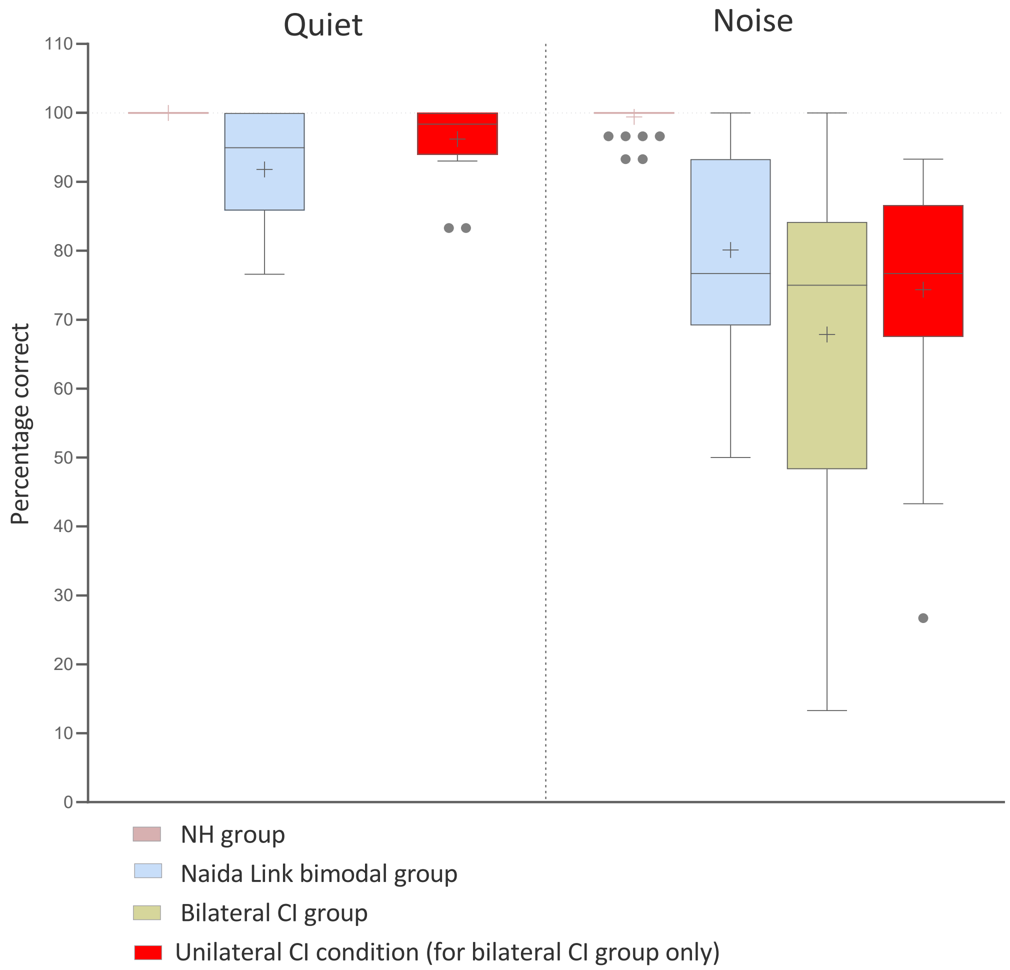

Figure 7.5: Results of the telephone test in quiet (left-hand panel) and in noise (right-hand panel) in percentage correct for the three groups: (1) NH, (2) Naida Link bimodal, and (3) bilateral CI as well as the unilateral CI condition of the bilateral CI group. The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. In quiet, the Naida Link bimodal in monoaural condition, and the bilateral CI in binaural condition groups were not tested. In noise, the Naida Link bimodal in monoaural conditions was not tested.

7.5.4 SSQ

Only complete questionnaires were included in the analysis. There were 24 complete Naida Link bimodal SSQs out of 26. For the bilateral CI group, all the participants completed the SSQ (16 participants).

Overall and the three subscales

Figure 7.6 shows the self-rated overall scores on the SSQ and each of the three subscales (speech, spatial and qualities) for the bilateral CI and Naida Link bimodal groups. Additionally, the figure shows scores of the combined unilateral CI condition which is the lowest compared to the two groups. The self-rated scores of the bilateral CI group were higher than the Naida Link bimodal particularly on the spatial subscale.

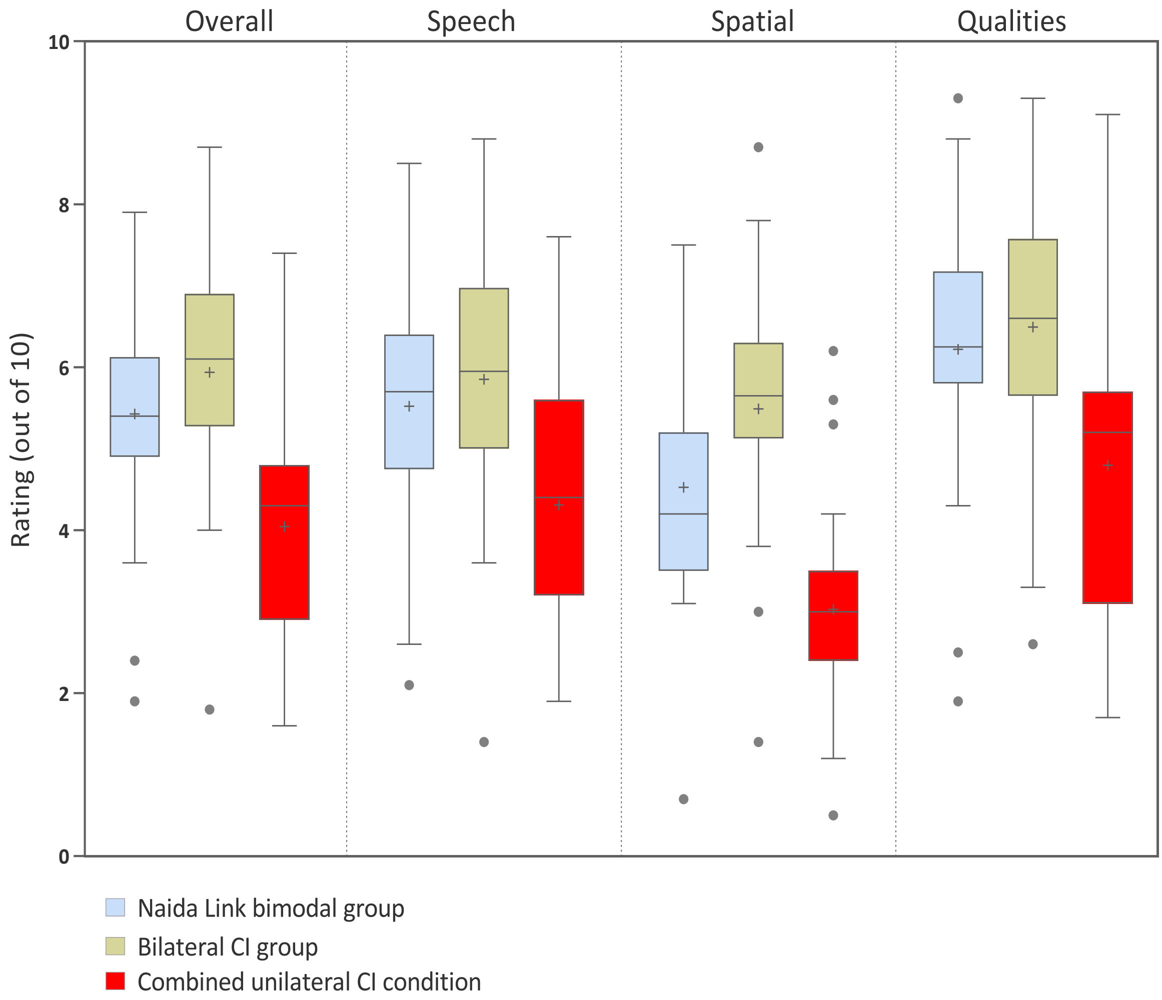

Figure 7.6: Scores of the overall SSQ and each of the three sub-scales: speech, spatial and qualities for (1) Naida Link bimodal group, (2) bilateral CI group, and (3) combined unilateral CI condition. The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The outliers are plotted as solid circles.

Statistical analysis was conducted to examine whether there is a statistically significant difference between the Naida Link bimodal group and the bilateral CI group on the scores of the three SSQ subscales. Additionally, statistical analysis was carried out to assess whether the difference between the Naida bimodal group and bilateral group on the spatial subscale was significantly greater than the difference on the other SSQ subscales. Therefore, a two-way mixed ANOVA was used with the participant group as the between-subject factor and the type of subscale as the within-subject factor. There was homogeneity of variances ($p > .05$) and covariances ($p = .09$), as assessed by Levene's test of homogeneity of variances and Box's test of equality of covariance matrices respectively. Additionally, Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, $\chi2(2) = 5.39$, $p = .07$. The results of the analysis are reported in Table 7.7.

Table 7.7: Two-way (participant group and SSQ subscales) mixed ANOVA results. Significant *p* value is highlighted in bold font.

Independent variables	Main effect	Interaction
Participant group **(2 levels)**	F (1, 38) = 1.12, p= 0.3	Group* subscales = F (2, 76) = 1.9, p = 0.2
SSQ subscales **(3 levels)**	F (1, 38) = 18.5, **p < .001** Post hoc pairwise: • Qualities - Speech = 0.7 points (**p<.001**) • Qualities - Spatial = 1.4 points (**p<.001**) • Speech - Spatial = 0.7 points **(p=.003)**	

Telephone use

The scores of two questions (13 and 14) in the speech subscale that related to telephone use were compared between the Naida Link bimodal group and the bilateral CI group. An independent-samples t-test was carried out on the rated scores of questions 13 and 14 to assess the difference between the Naida Link bimodal and bilateral CI groups for each question separately. The results showed that there was no statistically significant difference between the two groups on both questions, as shown in Table 7.8.

Table 7.8: Mean difference between the Naida Link bimodal and bilateral CI groups (95% confidence of the mean difference) and p values on questions 13 and 14 on the speech subscales of the SSQ.

	N	**Levene's test**	**T test**	***p***	**Mean difference (95% confidence interval)**
Question 13	Bimodal=23 Bilateral=15	0.01	t (20.5) = -1.7	0.1	-1.3 (-2.9 to 0.3)
Question 14	Bimodal=23 Bilateral=14	0.2	t (35) = -0.8	0.5	-0.6 (-2.1 to 0.96)

Music perception

To compare the difference in music perception between the Naida Link bimodal group and bilateral CI groups, the scores on questions 5, 7 and 8 on the qualities subscale were averaged. The number of data sets included in the analysis was 24 and 16 participants for the Naida Link bimodal and bilateral CI groups respectively. The assumption of homogeneity of variances was met, as assessed by Levene's test for equality of variance ($p > .05$). An independent-samples t-test revealed no statistically significant difference between the two groups, $t(38) = 0.3$, $p = 0.8$. The mean difference between the two groups was only 0.03 points (95% CI, -1.7 to 1.7).

7.5.5 Bilateral benefit versus Naida Link bimodal benefit

The benefit provided by a second implant was compared with the benefit provided by the Naida Link HA using the real-life test battery. The benefit provided by a second implant for the bilateral CI group was calculated by taking the difference score between the two-CIs condition and one-CI condition (two CIs – one CI). The benefit provided by the Naida Link HA for the bimodal group was calculated by taking the difference scores between CI with Naida Link HA condition and CI-only condition. It should be noted that when calculating the benefit on the speech-in-noise tests, the score of the best-aided condition when using the CI with Naida Link HA was used (i.e. when using StereoZoom in S0°N±60° and using ZoomControl in S+90°N-90°).

The aim was to determine whether there was a significant difference between the bilateral CI benefit and the Naida Link bimodal benefit on speech-in-noise tests, spatial-listening tests and the SSQ. However, comparing the benefits could not be done on the telephone test in quiet and noise as the test was not administered in all listening conditions for both groups as discussed above.

Table 7.9 shows the listening conditions of both the Naida Link bimodal and bilateral CI groups where the telephone test was administered.

Table 7.9: Telephone test administration for the Naida Link bimodal and bilateral CI groups.

		One CI	**Two devices**
Quiet	Naida Link bimodal group	*Not tested*	*Yes*
	Bilateral CI group	*Yes*	*Not tested*
Noise	Naida Link bimodal group	*Not tested*	*Yes*
	Bilateral CI group	*Yes*	*Yes*

Speech-in-noise tests

A two-way mixed ANOVA was used with the participant group as the between-subject factor and the speech test as the within-subject factor to assess whether there is a significant difference between the benefit provided by the second implant and the benefit provided by using a Naida Link HA on the speech-in-noise tests. Only the data from the two speech tests SrN±60 and S0°N±60 were included in the analysis. The S+90°N-90° test was administered for only the five AB bilateral CI participants. The data of the S+90°N-90° test were excluded from this statistical analysis. There was homogeneity of variances ($p > .05$) and covariances ($p = .58$), as assessed by Levene's test of homogeneity of variances and Box's test of equality of covariance matrices, respectively. Table 7.10 reports the results of the analysis.

Table 7.10: Two-way (participant group and speech tests) mixed ANOVA results. Significant *p* value is highlighted in bold font.

Independent variables	**Main effect**	**Interaction**
Participant group (2 levels)	$F(1, 40) = 0.1$, $p = 0.7$	Group* speech tests = $F(1, 40) = 2.5$, $p = 0.12$
Speech tests (2 levels)	$F(1, 40) = 4.4$, **p=.04** (difference=0.9 dB)	

An independent-samples t-test was conducted to examine whether there is a significant difference between the benefit provided by the second implant and the benefit provided by using a Naida Link HA in the S+90°N-90° test. There was homogeneity of variances as assessed by Levene's test ($p = .05$). Results revealed no statistically significant difference in the benefit provided by the second implant and the benefit provided by the Naida Link HA in S+90°N-90° test, $t(29) = -0.65$, $p = 0.5$. The mean difference in the benefit was -1.49 dB (95% confidence interval, -6.17 -3.19).

Spatial tests

The difference in the benefit provided by the second implant and by the Naida Link HA on the localisation and tracking tests was assessed. In the localisation test, the difference in the benefit was assessed in both per cent correct and RMS error. For the percentage-correct metric, the assumption of homogeneity was violated as assessed by Levene's test. An independent-samples t-test revealed that the benefit provided from the second implant was statistically significantly greater than the benefit provided from the Naida Link HA on the localisation test by 33.9% (95% confidence interval, 21.3- 46.6), $t(20) = 5.6$, $p < 0.001$. In terms of the RMS error, there was homogeneity of variances as assessed by Levene's test for equality of variances ($p > .05$). The results indicated that the benefit provided by the second implant was statistically significantly lower than the benefit provided by the Naida Link HA on the localisation test by 20.9° (95% confidence interval, 10.8 – 31.1), $t(40) = 4.2$, $p < 0.001$.

In the tracking test, the assumption of homogeneity was violated as assessed by Levene's test. An independent-samples t-test revealed that the benefit provided by the second implant was statistically significantly greater than the benefit provided by the Naida Link HA on the tracking test by 38.98% (95% confidence interval, 21.7 – 56.3), $t(22.1) = 4.7$, $p < 0.001$.

SSQ

To examine the difference between the benefit provided by using a second implant and the benefit provided by the Naida Link HA on the SSQ, a two-way mixed ANOVA was carried out with the participant group as the between-subject factor and the type of subscale as the within-subject factor. There was homogeneity of variances ($p > .05$) and covariances ($p = .21$), as assessed by Levene's test of homogeneity of variances and Box's test of equality of covariance matrices respectively. Mauchly's test of sphericity indicated that the assumption of sphericity was violated for the two-way interaction, $\chi2(2) = 8.91$, $p = .01$. Therefore, the Greenhouse-Geisser test was applied. There was a statistically significant interaction between the group and type of subscale on the SSQ score on the amount of the benefit, $F(1.6, 56.9) = 5.1$, $p = 0.01$, partial $\eta^2 = .13$. Consequently, the simple main effect of the group and the type of subscale was investigated.

The simple main effect of the group showed that there was a statistically significant difference between the benefit provided from bilateral implantation and the benefit provided by the Naida Link bimodal on the SSQ score of the speech, spatial and qualities subscales. The benefit provided by the bilateral CI was statistically significantly greater than the benefit provided by the Naida Link bimodal as shown in Table 7.11.

Table 7.11: The difference (95% confidence interval) between the benefit obtained from a 2nd CI and the benefit obtained from a Naida Link HA on three subscales of the SSQ: speech, spatial and qualities of hearing. Results from the analysis are also listed. The significant difference is highlighted in bold font.

	Difference between the benefit from 2nd CI and a Naida Link HA	**95% confidence interval**	**F**	***p***
Speech subscale	1.05	0.5 to 1.7	(1,36) =12.7	**0.001**
Spatial subscale	1.8	0.99 to 2.6	(1,35) =20.04	**<0.001**
Qualities subscale	0.9	0.1 to 1.7	(1,36) =5.5	**0.03**

The simple main effect of the type of subscale was also examined for each group separately. The results are shown in Table 7.12.

Table 7.12: Simple main effect of the type of SSQ subscale for the Naida Link bimodal and bilateral CI groups. The significant p value is highlighted in bold font.

Group	**Mauchly's test of sphericity**	**Simple main effect of SSQ subscale type**
Naida Link bimodal	$\chi2(2) = 2.7$, $p = 0.3$	F (2,44) =1.5, p= 0.2
Bilateral CI	$\chi2(2) = 5.97$, $p = 0.05$	F (2,26) = 9.3, **p=0.001** Post hoc pairwise: • Spatial -Speech = 1 point (**p=0.003**) • Spatial -Qualities = 0.99 points (**p=0.01**) • Speech-Qualities = 0.02 (p=0.9)

7.6 Discussion

This chapter aims to compare the outcomes of the three groups (NH, Naida Link bimodal and bilateral CI) in the real-life test battery. The main findings are summarised as follows:

- The SRTs of the NH group were statistically significantly lower (better) than the Naida Link bimodal and bilateral groups (when using both the standard settings or Binaural VoiceStream Technology) in the three speech-in- noise tests
- There was no statistically significant difference between the Naida Link bimodal and bilateral groups for the SrN±60° and S0°N±60°tests. The SRT of the bilateral group was, however, statistically significantly lower (better) than the Naida Link bimodal group for the S+90° N-90° test
- There was no statistically significant difference between the Naida Link bimodal group with StereoZoom activated and the bilateral CI group with and without StereoZoom activated
- There was no statistically significant difference between the Naida Link bimodal group with ZoomControl activated and the bilateral CI group with ZoomControl deactivated. However, when the AB bilateral CI participants used the ZoomControl, their performance was statistically significantly better than the Naida Link bimodal participants with ZoomControl activated
- The performance of the bilateral CI group was statistically significantly better than the Naida Link bimodal group for the localisation and tracking tests
- The performance of the bilateral group in telephone-in-noise test was lower (worse) than the Naida Link bimodal group; however it was not statistically significant
- There was no statistically significant difference between the Naida Link bimodal group and the bilateral CI group for the three subscales of the SSQ and specific questions related to telephone use and music perception
- There was no statistically significant difference in the benefit provided by a second implant and the benefit provided by the Naida Link HA for the CI participants in the three speech-in-noise tests. However, the benefit provided by a second implant was statistically significantly higher than the benefit provided by a Naida Link HA for the localisation and tracking tests as well as for the SSQ questionnaire.

7.6.1 Speech in noise

To the best of the researcher’s knowledge, this is the first study to examine the difference between the integrated bimodal technology and bilateral CI using a real-life test battery that included speech-in-noise tests more representative of real-life listening situations. The performance of the Naida Link bimodal group was not significantly different from the bilateral CI group for the two speech-in-noise tests: SrN±60° and S0°N±60° (the difference was less than 1 dB). This finding indicates that the integrated bimodal technology would provide a similar benefit as the bilateral CI in similar listening environments where the target speech is fixed from the front or roving within diffuse noise. However, this trend was not seen when the target speech was presented on one side and the noise on the opposite side. The SRT of the bilateral CI group was significantly better than the SRT of the Naida Link bimodal group. This would suggest that when the speech and noise are spatially separated, the bilateral CI users would perform better than the integrated bimodal users. However, this finding should be treated with caution for two reasons. Firstly, the number of bilateral CI participants in this test (S+90°N-90°) was only five. This test was only administered to the participants who had AB devices to assess the potential benefit of ZoomControl. Secondly, there was considerable variability in the SRTs of the five bilateral CI participants ranging from -0.2 to 8.6 dB SNR. Therefore, there is a need to examine the difference between the integrated bimodal and bilateral CIs in this test with a larger sample size for both groups to substantiate the finding. Recruiting adults within the UK with bilateral CI is however challenging, given that adults typically only receive one implant, in line with NICE guidance (NICE, 2009, NICE, 2019). This also makes it challenging to include only bilateral participants with a specific manufacturer's device. The results obtained highlight the need for further research in this area.

Although the statistical analysis was carried out without including the combined unilateral CI condition, the SRTs of the Naida Link bimodal and bilateral CIs groups were notably lower (better) than the unilateral CI. For instance, the SRT improved by 1.4, 1.5, and 3.5 dB with the Naida Link bimodal over the unilateral CI for the SrN±60°, S0°N±60°, and S+90°N-90° tests respectively. Similarly, an improvement of 1.7, 2.4 and 9.2 dB was found with the bilateral CIs over the unilateral CI in SrN±60°, S0°N±60°, and S+90°N-90° tests. Moreover, it has been shown previously in Chapters 5 and 6 (using a within-subject repeated measures design) that there was a statistically significant improvement in the SRT in the listening condition of using the Naida Link bimodal and using the two implants compared to the unilateral CI condition.

On the other hand, the SRTs of the NH participants were significantly lower than the SRTs of the CI participants in both Naida Link bimodal and bilateral CI groups with standard settings or with Binaural VoiceStream Technology. A large difference (ranging between 21 and 27 dB) was found in the S+90°N-90° test which suggests that the perceived benefit from the head-shadow effect found with CI participants was considerably smaller than the benefit perceived in NH participants. This finding lends support to previous findings in the literature that claimed a limited true binaural hearing for bimodal and bilateral CI users (Gifford *et al*., 2018). It has been shown that bilateral CI users have limited access to the ITD due to the lack of TFS for high channel-stimulation rates that are used in CI processing (Laback *et al*., 2004, Francart *et al*., 2009, Gifford *et al*., 2018). Similarly, although bimodal users have access to the ITD cues via low frequencies and TFS in the HA ear, bimodal users cannot transmit and process this information via the CI (Francart *et al*., 2009). This finding underscores the fact that even with an integrated HA or a second implant, CI users face more difficulty hearing than individuals with NH. This highlights the importance of providing additional support to the CI users such as communication strategies and assistive listening devices (detailed review of these devices in Kim and Kim (2014) and Miller *et al*. (2021)).

For Binaural VoiceStream Technology, there was no difference between the Naida Link bimodal participants with StereoZoom activated and bilateral CI participants (with devices from different manufacturers), and the AB bilateral participants with StereoZoom activated. This finding is in line with Ernst *et al*. (2019) who found no difference between the bimodal and bilateral groups with StereoZoom activated in two different test set-ups. The performance of bimodal and bilateral CI participants in the Ernst *et al*. (2019) study was similar to NH participants particularly for the easiest test set-up (S0°N ±60°, ±120° and 180°) they used. This is in contrast to the results of the current study where a significant difference was found between NH participants and CI participants (both groups). Although there was a similarity in the test set-up between the present study and the one by Ernst *et al*. (2019), there were differences that might be the reason behind this discrepancy. Ernst *et al*. (2019) used a steady-state masker (speech-shaped noise) presented from five loudspeakers simultaneously whereas the present study used multi-talker babble noise that was presented simultaneously from two loudspeakers. Given that CI users have limited ability of listening in the dips (glimpsing) in the presence of a fluctuating masker, such as babble noise (Nelson *et al*., 2003, Cullington and Zeng, 2008), the significant difference between NH participants and CI participants (with or without using the StereoZoom) in the present study might be related to the type of noise masker that was used. For the ZoomControl feature, the Naida Link bimodal participants with ZoomControl activated performed as well as the bilateral CI participants (with ZoomControl disabled). However, when the ZoomControl was activated for both bilateral CI and Naida Link bimodal participants, the performance of the bilateral CI participants was significantly lower (better) than Naida Link bimodal participants by approximately 3.7 dB. It should be noted that only five bilateral CI participants who had AB devices have been tested in the S+90°N-90° test. Therefore, this finding might not be representative of the CI users, and further study needs to be carried out with a larger sample size for the bilateral users.

Despite that, the testing set-ups that were used to assess speech perception in the present study differ from the standard clinical and many research testing set-ups, such as (Gifford *et al*., 2014, Kokkinakis and Pak, 2014, Blamey *et al.*, 2015, Yawn *et al.*, 2018) which use a single loudspeaker with fixed speech most commonly from the front. As discussed earlier in Section 7.1.3, it has been shown that speech tests with more complex settings that mimic real-life listening situations are more sensitive than the standard tests in showing the differences between bimodal hearing and bilateral CIs (Kolberg *et al.*, 2015, Gifford *et al.*, 2018, Gifford and Dorman, 2019). The present study did not find any significant difference between integrated bimodal technology and bilateral CI. However, it is not entirely clear whether the reason behind this finding was because the integrated bimodal fitting can provide similar benefits as bilateral CIs or whether the real-life tests used in the present study were not sensitive enough to detect possible differences between the two groups. To assess the sensitivity of the real-life tests, it would be useful to test bimodal listeners who use the standard technology on real-life speech-in-noise tests and compare their performance to the bilateral CI users in this study and those reported in the literature (Gifford *et al.*, 2018, Gifford and Dorman, 2019). This would provide a better understanding of the differences between technologies and the sensitivity of the real-life speech-in-noise tests to differentiate between them.

7.6.2 Spatial-listening tests

The findings of the present study showed that the performance of the bilateral CI group was significantly better than the Naida Link bimodal group in both localisation and tracking tests. It is important to note that all the NH participants achieved 100% correct results for both tests. It is thus evident that even though an integrated HA or a second implant offers significant benefits for the localisation and tracking of sounds, CI users perform poorly compared to those with NH.

For the localisation test, the RMS error difference found in the present study between the Naida link bimodal and bilateral CI groups was 21.3 degrees. A similar difference has been reported in the literature between the standard bimodal technology and bilateral CIs. For instance, *Luntz et al.* (2014) found a difference of 23.5 degrees in lateralisation of speech in the quiet task for 10 adult CI participants using a within-subject design. In another study that used a between-subject design, Dorman et al. (2016b) found a difference of 33 degrees between 8 bimodal participants and 32 bilateral CI participants. In terms of percentage correct, the difference found in the current study for localisation performance between the integrated bimodal and bilateral groups was 36.3%. The test set-up used in this study was similar to the set-up that has been used in the Goman (2014) study which reported a difference of 32% between bimodal (standard technology) and bilateral CI groups. Therefore, two conclusions can be drawn based on these results. Firstly, bilateral CIs provide better localisation accuracy than bimodal hearing (both the standard and integrated technology. Secondly, it seems there are no considerable differences between the standard and integrated bimodal technologies in localisation tasks. However, both bimodal technologies could provide more benefit than unilateral CI at least for some listeners.

Similar trends were also found in the tracking test. The bilateral group in the current study showed a significantly better performance tracking moving sounds than the Naida Link bimodal group. The difference was about 44.2% between the two groups. This is comparable to the difference reported in Goman (2014) between the bilateral CI group and bimodal group which was approximately 38.5%. However, there were two methodological differences between the current study and Goman's (2014) study. Firstly, the bimodal participants in Goman's (2014) study were fitted with standard HAs. Secondly, the tracking-moving-sounds test in Goman's study (2014) used only four trajectories with each trajectory presented once whereas the current study, as explained previously in Chapter 4 section 4.2.2.4, used six trajectories with each trajectory presented twice in a pseudo-random order. Furthermore, it should be noted that Goman (2014) did not carry out a between-subjects analysis between the two groups to determine whether the difference was statistically significant or not. The statistical tests have been done for each group (within-subjects) separately to compare the bilateral listening condition to the unilateral listening condition.

Limited research has been conducted to investigate the perception of moving sound, particularly for hearing-impaired listeners with different degrees of hearing loss. Carlile and Leung (2016) pointed to the performance of hearing-impaired listeners being poorer than NH listeners for two reasons. The first possible reason is the reduction in the location cues in hearing-impaired listeners particularly the mid- to high-frequency information which is important for ILDs cues. The second reason is related to the reduction in the fidelity of ITDs cues. To date, only one study compared the performance of NH listeners and bilateral CI users on tracking moving sounds (Moua *et al*., 2019). Their findings indicated that the bilateral CI users had poor sensitivity to determine the source of the moving sound as well as tracking the direction compared to NH listeners. In a further exploration of why bilateral CI users struggle to detect and track sound motion, Warnecke *et al*. (2020) investigated the contributions of low-frequency TFS and envelope cues in the perception of moving sound among NH listeners. They found that removing low-frequency TFS cues reduced the accuracy of moving-sound perception. Given that the CI processing removed TFS; therefore the reduced sensitivity of moving-sound perception for bilateral CI users would be most probably due to the limited low-frequency TFS cues available. However, it should be stressed that the perception of moving sound is difficult to quantify as it is highly dependent on dynamic parameters such as the duration and the velocity of the stimulus (Moua *et al*., 2019, Warnecke *et al.*, 2020). In addition, the mechanism of moving perception that helps NH listeners to detect and track moving sounds is not yet well understood as well as for hearing-impaired listeners (Carlile and Leung, 2016, Warnecke *et al.*, 2020). Therefore, there is still a need for further investigations of tracking moving sounds, especially for CI users.

7.6.3 Telephone test

In the quiet condition, the scores of NH and Naida Link bimodal groups, as well as the combined unilateral condition, reached a ceiling effect. Although there was an observed variability among the Naida Link bimodal group, it would be useful to use a standardised telephone test to determine the differences between the NH listeners and CI users.

For telephone in noise, the test was done with favourable SNR (+ 10 dB SNR), yet the performance of the Naida Link bimodal and bilateral CI groups was notably lower than the NH group. Another trend seen in the present study was that the performance of the bilateral CI group was lower than the Naida Link bimodal group as well as the combined unilateral CI condition. Although the difference in the performance was not statistically significant, this finding would suggest that the second implant would be more sensitive than the Naida Link HA in attending to speech and background noise. As discussed in Chapter 4 section 4.2.1.4, there is currently no standardised telephone test available. The test developed for this study proved to have a number of limitations, particularly the ceiling effect in both test conditions (quiet and noise) for all NH participants and many CI participants. Further research is needed to develop a telephone test that can be used in further research and ultimately also in clinical practice.

7.6.4 SSQ questionnaire

The self-rated scores for the bilateral CI group were compared to the Naida Link bimodal group. The findings in this present study revealed that the scores of the bilateral CI group tend to be higher than the scores of the Naida Link bimodal group particularly in the spatial subscale of the SSQ; however the difference between the two groups was not statistically significant. In addition, there was no statistically significant difference between the two groups on the SSQ questions in the speech and qualities subscales that related to telephone use and music perception. Previous studies have shown scores on the SSQ for bilateral CI users were significantly higher than the SSQ scores of bimodal listeners using the standard HA technology (Noble *et al*., 2008, Goman, 2014, Luntz *et al*., 2014, Potts and Litovsky, 2014, Yawn *et al*., 2018, Erdem and Ciprut, 2019). Therefore, the findings from this study would suggest that integrated bimodal technology may provide similar subjective benefits as with bilateral CIs.

Despite that, the mean overall SSQ scores were 5.9 and 5.4 points for the bilateral CI (n=16) and Naida Link bimodal (n=24) participants respectively, which were at the mid-range of the rating scale. Banh *et al*. (2012) and Demeester *et al.* (2012) found that the mean overall SSQ score for younger NH adults (age range= 18-25 years) ranged from 8.2 to 8.9 points and older adults with clinically normal hearing below 4kHz ranged from 7.7 to 8.1 points. Demeester *et al.* (2012) determined SSQ-disability cut-off points 2SDs from the mean SSQ-disability scores of the younger NH adult group for the overall SSQ, speech, spatial, and qualities subscales as 7.3, 6.8, 6.1, 8.2 points respectively. Based on this, the overall SSQ scores found in the present study for both the bilateral CI and Naida Link bimodal participants indicated a significant degree of disability. Although there was a significant improvement with bilateral CIs and Naida Link HA over the unilateral CI (as shown in Chapters 5 and 6), CI users still experience some degree of improvement in everyday life.

7.6.5 Which provides more benefit: bimodal hearing vs. bilateral CI?

The previous sections discussed the difference between the scores of Naida Link bimodal participants and the scores of bilateral CI participants in the listening conditions of using the two devices. However, it would be worth comparing the benefit provided by the Naida Link HA (bimodal benefit) to the benefit provided by the second implant (bilateral CI benefit). The benefit for each group was calculated as the difference between the listening condition of using the two devices (two CIs or CI + Naida Link HA) and the listening condition of using the CI only. From a clinical perspective, the performance and experience of the bimodal and bilateral CI users were usually measured and assessed in relation to using one CI. Moreover, the Naida Link bimodal and bilateral CI groups in the current study were independent groups. Therefore, from a research perspective, the participants in both groups were assessed and asked about their experiences of binaural hearing listening in relation to unilateral CI. Therefore, calculating the benefit obtained from the Naida Link HA and the second implant, and then comparing the difference in the benefit would provide a wider picture about the differences between these two technologies.

There was no significant difference between the benefit obtained from the Naida Link HA and that obtained from the second CI in the three speech-in-noise tests. It should be noted that the analysis of the speech test (S+90°N-90° test) was carried out separately as it was not administered for all bilateral CI participants due to time constraints of the testing. The S+90°N-90° test was only administered for the five participants that had AB devices whereas the other two tests were administered for all bilateral CI participants. This finding is in line with Goman (2014) who also did not find a significant difference in the amount of benefit provided by a second CI and that provided by a standard HA for CI participants when speech and noise were spatially separated. However, Goman (2014) found a significantly greater benefit obtained from a second CI than that obtained from a HA when the noise was presented at the 1st CI side which is opposite to the findings in the current study. However, the interpretation of the findings for this case in the present study should be treated with caution due to the number of bilateral CI participants included in the analysis for this test condition (S+90°N-90° test) being considerably small. Therefore, further investigation is needed with a large bilateral CI sample to substantiate this finding.

For spatial-listening tests, the benefit obtained from a second CI was significantly greater than that obtained from a Naida Link HA in both localisation and tracking tests. This fits well and also confirms the large difference found between scores of the two groups in the direct comparison in Section 7.5.2.

For the SSQ questionnaire, the rated scores of the bilateral CI group were higher than the rated scores of the Naida Link bimodal group on the three subscales of the SSQ; however these were not statistically significant as discussed in Section 7.6.4. Interestingly, the benefit from a second CI was significantly higher than the benefit from a Naida Link HA for the three subscales of the SSQ. The largest difference (about 1.8 points) was in the spatial subscale. This finding suggests that although the Naida Link bimodal and bilateral CI groups gave similar rating scores in the SSQ, the perceived benefits by the bilateral CI participants for everyday hearing functions seem to be greater than the perceived benefits by the Naida Link bimodal participants which may not be captured by the newly developed real-life speech-in-noise tests. Another interesting finding in the current study is that there was no difference in the perceived benefit from a Naida Link HA among the three subscales of the SSQ for the Naida Link bimodal group. In contrast, the perceived benefit from a second CI in the spatial subscales was significantly higher than the perceived benefit in speech and qualities subscales of the SSQ for the bilateral CI group. These findings substantiate the evidence of the superiority of bilateral CI in spatial listening tasks over using different modalities.

In short, comparing the benefit obtained from a second CI to the benefit obtained from a HA would provide additional useful information with the direct comparison of the scores for independent samples. The present study showed that the benefit obtained from a second CI was found to be significantly larger than those obtained from a Naida HA on spatial-listening tests and the SSQ.

7.7 General discussion and limitations

This chapter examined the differences in the performance and experiences between Naida Link bimodal participants and bilateral CI participants, as well as NH listeners. Based on a literature search, only one study assessed the difference in the functionality of StereoZoom, which is one of the features available with integrated bimodal technology, for bilateral CI and Naida Link bimodal users (Ernst *et al*., 2019). To the best of the researcher's knowledge, this study would be considered as the first study that provided a comprehensive examination for the difference between these two technologies using a real-life test battery that included speech-in-noise, localisation, tracking, telephone-use, and self-reported tests, with a comparison to baseline data (NH scores).

The findings from the current study indicate that there are clear binaural advantages when using integrated bimodal technology compared to using one CI. Similarly, the findings indicated the significant binaural benefits obtained from bilateral CIs over one CI. The benefits were found in improving speech understanding in noise, spatial listening, and self-reported benefits of everyday hearing functions. Therefore, binaural hearing (either with a Naida Link bimodal or bilateral CI) would be strongly recommended for unilateral adult CI users.

On the other hand, the answer for the question of which binaural option is the better (or in other words, would integrated bimodal technology provide similar benefits as those provided by bilateral CI?), is still not entirely clear particularly for improving speech understanding in noise. This is because there was no significant difference in the performance of the two groups or in the benefit provided from the two devices on speech-in-noise tests. However, the performance of bilateral CI participants was better than Naida Link bimodal participants when the noise and speech were spatially separated with noise on the CI side for Naida Link users (on 1st CI side for bilateral CI users). Interestingly, one of the most important findings of this study is that when the Naida Link bimodal participants used the Binaural VoiceStream feature (ZoomControl) which was designed for this kind of situation, the performance of these participants was improved and the difference between them and bilateral CI participants was reduced. However, further research is still needed as the number of bilateral CI participants was relatively small. Another important finding is that the present study confirms the superiority of bilateral CI over bimodal hearing (both standard and integrated technology) in localisation and tracking moving sounds. Additionally, the present study showed that the perceived subjective benefits with bilateral CI for everyday hearing functions seems greater than that with integrated bimodal technology. Moreover, linked AGCs for bilateral CIs seems a promising technology that would provide an additional improvement particularly for improving speech in noise as discussed in Chapter 6 section 6.6.2. However, further investigations need to be carried out with a larger sample size.

Based on this, it would be hard to say that integrated bimodal technology can provide the same binaural benefits to those provided by bilateral CIs in real-life listening situations. This is because there was a clear superiority of bilateral CI in spatial listening and subjective benefits which are considered important skills of everyday auditory functions. Further investigation is needed to examine the difference between integrated bimodal technology and bilateral CI on other important hearing skills which need access to low-frequency sounds, such as sound segregation, sound quality, and music perception using objective measures. It would be expected that as with standard bimodal technology, the integrated bimodal technology would be better than the bilateral CI in providing better sound quality and segregation as well as music perception (Zhang *et al*., 2010, Dincer D'Alessandro *et al*., 2018).

When bilateral implantation is considered (i.e. self-funded in the UK), it is important to provide CI users with counselling about the expected outcomes for each option (integrated bimodal technology versus bilateral CI) and the trade-off in listening abilities. For example, better spatial listening (localisation and tracking) with limited access to low-frequency information would be obtained from bilateral CI or possible better sound quality and music perception due to access to low-frequency sounds, yet limited ability in localisation and tracking sounds. On the other hand, a review of the cost-effectiveness of bilateral CI and the integrated bimodal technology using a real-life test battery should be considered particularly in countries where bilateral CI is not available for adults. This will help in providing more accurate guidance and recommendations for adult bilateral CI candidacy.

This study also shows that the performance of NH listeners was superior to the performance of both the Naida Link bimodal and bilateral CI groups for all the tests (speech-in-noise, spatial-listening, and telephone tests). This finding demonstrates just how CI users have considerable struggles for everyday hearing functions such as understanding speech in background noise, identifying sounds source, and using a telephone. In addition, the self-rated scores of the CI participants (both groups) in the current study were below the disability cut-off points (7.3 points) on the SSQ (Demeester *et al.*, 2012), which indicates that CI users experience some degree of disability for everyday hearing functions. This thereby underlines how important it is to provide CI users with additional support. For instance, providing CI users with assistive listening devices and digital wireless technology should be taken into consideration. The assistive listening devices can improve the effectiveness of hearing instruments such as HAs and CIs, and improve ease of listening which can enhance the quality of life (Kim and Kim, 2014). In addition, digital wireless technology has been shown to improve SNR and convenience (a comprehensive review for assistive listening devices and digital wireless technology can be found in Kim and Kim (2014)).

It should be noted that the between-subject comparison in this chapter was carried out among the three groups: NH listeners, Naida Link bimodal, bilateral CI. The combined unilateral CI condition which comprised mixed data of Naida Link bimodal and bilateral CI participants in the listening condition of using one CI were not included in the statistical analysis. Although there was no significant difference in the unilateral CI condition of the two groups which suggests that the effect of listening condition familiarity is weak, it would be beneficial to have an independent unilateral CI group as a control group to allow statistical analysis. This is because testing bimodal or bilateral CI users in the unilateral CI listening condition may not represent how they listen normally in real-life situations which might introduce an artificial listening condition (Nyirjesy *et al.*, 2020). Another reason is that results might be affected by the subject's bias toward the technology (a second implant or a HA in the non-implanted ear) when testing the bimodal or bilateral CI users in their unilateral CI listening condition. This is particularly relevant when using subjective rating scales to assess the experiences in real-life situations. For instance, Devocht *et al.* (2020) assessed the subjective experiences of 22 unilateral CI and 26 bimodal hearing users using a set of self-rating scales for hearing disability, hearing handicap, general quality of life particularly, SSQ, HHQ, HU13 and AVETA (Amsterdam Questionnaire for Unilateral or Bilateral Fittings) questionnaires. There were no significant differences between the two groups across scales. However, within-group comparison, bimodal participants did rate their hearing ability in the bimodal hearing significantly higher (better) than using the CI only in the SSQ and AVETA. Therefore, testing unilateral CI users on the real-life test battery which developed in the current study would provide a wider picture for all categories of CI users in the same outcome measures.

7.8 Conclusion

The outcomes and experiences of adult Naida Link bimodal, bilateral CI, and NH participants were compared using the real-life test battery. Based on the results, the following can be concluded:

- The performance of bilateral CI participants was significantly better than Naida Link bimodal participants in speech perception in noise when the noise was on the CI side (at 1st implant for bilateral CI users), localisation, and tracking of moving sounds
- The benefit provided from a second CI was significantly higher than that provided from a Naida Link HA in the localisation test, tracking test, and the self-reported questionnaire (SSQ)
- There was no significant difference between the Naida Link bimodal and bilateral CI participants in speech perception in noise when the speech was roving and when it was presented from the front in diffuse noise
- Using the Binaural VoiceStream Technology, specifically the ZoomControl, seems to improve the performance of Naida Link bimodal participants to be comparable with bilateral CI participants (using the standard settings) when the noise was on the CI side

- The performance of NH participants was significantly better than the performance of CI participants (both Naida Link bimodal and bilateral CI users) in speech perception in noise, localisation, tracking moving sounds, and using the telephone in noise. Therefore, additional help and support for CI users should be offered.

Chapter 8 Summary, general discussion and conclusions

This chapter summarises the findings of the studies included in this thesis and discusses the implications of those findings. Recommendations for future research and clinical practice are suggested.

8.1 Summary of findings

8.1.1 Main findings of the study reported in Chapter 3 (International survey of bimodal hearing and bilateral cochlear implant service provision for adults)

- The average percentage of adult unilateral CI users is higher than bilateral CI users with approximately 46% of unilateral CI users using an HA in the non-implanted ear
- The main funding source of unilateral CI varies across the world regions. It is mainly state-funded in Europe and Asia, while a mixed model of funding sources is available in the Americas, Oceania and Africa
- Simultaneous and sequential bilateral CI for adults is primarily funded through state or self-funding in Europe and Asia, whereas private insurance and self-funding are the primary sources in Oceania and Africa. Adults in the Americas have different funding sources to obtain simultaneous and sequential bilateral CI
- State- and self-funding are the primary funding sources for providing contralateral HAs for adult unilateral users in all the world regions, except Africa, where private insurance is one of the primary sources
- There is no specific practice pattern for fitting and maintaining contralateral HA in most world regions. However, CI professionals recognise the value of fitting contralateral HAs at CI services, with audiology departments and private HA dispensers playing an ongoing role in general maintenance and support
- The benefits of integrated technology are not clear yet, particularly whether it could provide more benefits than standard technology. Therefore, more research is needed.

8.1.2 Main findings of the study reported in Chapter 4 (Development of a real-life test battery, analysis of measurement precision and collection of reference data on NH listeners)

- A real-life test battery was developed with a rationale based on a review of the literature. The test battery incorporates a combination of performance tests and subjective rating scales that would allow assessing the essential listening skills in real life, including:
  - Speech perception in noise involving three test set-ups simulating common real-life situations
  - Localisation
  - Tracking moving sounds
  - Telephone use in quiet and in noise
  - SSQ questionnaire
  - Telephone-Use questionnaire
- The new speech-in-noise tests, specifically when the speech was roving and when it was presented from the front in diffuse noise, could provide additional information about the performance of NH listeners compared to standard speech-in-noise tests (fixed speech and noise presented from the front)
- The new speech-in-noise tests showed a good reliability and validity level
- A reference interval (defined as the range between which 95% of values for a particular population fall into where 2.5% of the time will be higher than the upper limit of this range and 2.5% of the time it will be less than the lower limit of this range) for the new speech-in-noise tests has been obtained
- The new speech-in-noise, localisation, and the modified tracking tests are feasible and easily administered using the AB-Crescent of Sound.

8.1.3 Main findings of the study reported in Chapter 5 (The performance of adult CI users with integrated bimodal technology on a real-life test battery)

- Bimodal users who used integrated bimodal technology (CI + Naida Link HA) showed better performance than when they used the CI only in the three speech-in-noise tests and spatial-listening tests (localisation and tracking tests).
- Bimodal users who used integrated bimodal technology (CI + Naida Link HA) gave a higher rating on the overall and the three subscales of the SSQ questionnaire compared to when using the CI only or when using their old HAs (standard HA) with CI.
- Using the Binaural VoiceStream Technology, specifically the StereoZoom and ZoomControl, added a statistically significant additional improvement for speech

understanding in noise, whereas the benefit of using DuoPhone for CI users with integrated bimodal technology is inconclusive due to the telephone test's limitations.

8.1.4 Main findings of the study reported in Chapter 6 (The performance of adult bilateral CI users on a real-life test battery)

- Bilateral CI users showed significantly better performance using the two implants compared to one CI in the following:
  - Speech-in-noise tests
  - Spatial-listening tests (localisation and tracking)
  - Overall and three subscales of the SSQ questionnaire
- There was no significant difference between using the two CI and one CI in the telephone test
- Using Binaural VoiceStream Technology, specifically the StereoZoom and ZoomControl, seems to offer advantages in improving speech understanding in noise for AB users.

8.1.5 Main findings of the study reported in Chapter 7 (Comparison of integrated bimodal hearing and bilateral CI users versus NH listeners on the real-life test battery)

- The performance of NH participants was significantly better than the performance of CI participants (both Naida Link bimodal and bilateral CI users) in speech perception in noise, localisation, tracking moving sounds, and using the telephone in noise
- The benefit provided from a second CI was significantly higher than that provided from the integrated bimodal technology (CI+ Naida Link HA) in the localisation test, tracking test, and the self-reported questionnaire (SSQ)
- There was no significant difference between Naida Link bimodal and bilateral CI participants in speech perception in noise when the speech was roving and when it was presented from the front in diffuse noise. However, when the speech and noise were spatially separated with noise presented on the CI side (at 1st implant for bilateral CI users), bilateral CI participants showed better performance than the participants with integrated bimodal technology
- Using the Binaural VoiceStream Technology, specifically the ZoomControl, seems to improve the performance of Naida Link bimodal participants to be comparable with bilateral CI participants (using the standard settings) when the noise was on the CI side.

8.2 General discussion

8.2.1 Should adult unilateral CI users be encouraged to use a second CI or an HA in the non-implanted ear?

Binaural hearing for adult CI users can be optimised by fitting the non-implanted ear with a second implant or an HA. The findings from Chapters 5 and 6 showed that the integrated bimodal technology and bilateral CI provided a significant improvement in speech perception in noise, localisation, tracking of moving sounds, and self-reported benefits over using the unilateral CI. This finding confirms previously reported advantages in the literature of bilateral CI and bimodal hearing over the unilateral CI for adult users, such as Verschuur *et al*. (2005), Summerfield *et al*. (2006), Litovsky *et al.* (2009), Morera *et al*. (2012), Devocht *et al*. (2017), van Zon *et al*. (2017), Lee (2018), Devocht *et al*. (2020). In addition, this thesis considered assessing the effectiveness of using the Binaural VoiceStream Technology which enhances binaural hearing by linking the two devices wirelessly and streaming full bandwidth audio signals for both ears in real time. The results showed that this technology added additional improvement, specifically StereoZoom and ZoomControl, on speech perception in noise for both integrated bimodal and bilateral CI users. Therefore, it would be advisable to encourage adults with unilateral CI to use a second implant or an HA in the non-implanted ear.

However, the performance of both integrated bimodal and bilateral CI participants (when using two devices) was significantly worse compared to the NH participants on all performance tests. The rated scores on the SSQ questionnaire (for bimodal and bilateral CI groups) were at the mid-range of the rating scale which indicated a significant degree of disability (Demeester *et al.*, 2012). This underscores the importance of providing CI users with additional help and support to optimise binaural hearing, such as assistive listening devices and digital wireless technology.

8.2.2 Which option is better to provide more binaural benefits (integrated bimodal technology versus bilateral CI)?

The next question that needs to be answered is whether the bilateral CI provides more binaural benefits than bimodal hearing or vice versa. Findings from studies that directly compared bimodal hearing (standard technology) to bilateral CI were inconclusive. However, there is a tendency to have better spatial listening with bilateral CI and better access to low-frequency information (i.e. of music perception and sound quality) with bimodal hearing (Cullington and Zeng, 2011, Kokkinakis and Pak, 2014, Luntz *et al.*, 2014, Yawn *et al*., 2018). Some studies, such as Luntz *et al*.

(2014), emphasised an importance of counselling adult unilateral CI users about the expected trade-off if they want to have a second CI or an HA in the non-implanted ear.

One important difference between bimodal hearing and bilateral CI is the different device modalities with bimodal hearing (HA and CI) in terms of loudness mismatch, different signal-processing schemes, and fitting them separately. To overcome this limitation, integrated bimodal technology has been introduced recently where the CI and HA work on the same platform using matched compression algorithms and time constants. To the best of the researcher's knowledge, this thesis was the first study to compare the binaural benefits provided by bilateral CI to those provided from the integrated bimodal technology. It was anticipated that the integrated bimodal technology would provide comparable benefits to bilateral CI particularly in spatial listening as a result of matching signal processing between the HA and CI. The findings from this thesis showed that the benefits provided by the bilateral CI were statistically significantly better than those provided by the integrated bimodal technology in spatial-listening tests (localisation and tracking) and self-reported benefits on the SSQ questionnaire. For speech understanding in noise, there was no significant difference in the benefits between these two technologies, yet the performance of bilateral CI participants was significantly better than that of the participants using the integrated bimodal technology when the speech and noise were spatially separated with speech presented on the worst side (on the HA side for bimodal participants and the 2nd CI for bilateral CI participants). The number of bilateral CI participants included in this test condition was only five, thus a further investigation is needed to substantiate this finding. Nevertheless, the findings from this thesis are in line with previous literature that compared standard bimodal technology to bilateral CI regarding the superiority of bilateral CI in spatial-listening tasks.

This thesis was also considered to assess the difference between the two technologies on the accessibility to low-frequency information by examining the questions related to music perception on the qualities-of-hearing subscale of the SSQ questionnaire. There were no significant differences in the average score of these questions between the two groups (bilateral CI and integrated bimodal group). However, this needs to be further investigated with an independent performance measurement (i.e. music perception, pitch perception, or sound-quality tests) before making any conclusion.

Based on the above, it would be hard to answer the question of whether bilateral CI is better than integrated bimodal hearing. It seems that there is also a trade-off option of better spatial listening with bilateral CI or better sound quality and music perception with integrated bimodal technology. But further investigation is needed particularly for the benefits of integrated bimodal technology on using low-frequency information.

8.2.3 Benefits of using a real-life test battery for CI users

Another novelty of this thesis was developing and using a real-life test battery to assess the outcomes of adult CI users when using one CI, integrated bimodal technology and bilateral CI. The motivation of developing and using such a test battery rather than standard speech tests was based on two reasons. First, standard speech tests, where the speech and noise are presented from a single speaker placed at the front, do not represent the listening situations encountered in real life where speech and noise are constantly changing in the level and location. Second, standard speech tests do not provide enough information about other important auditory functions needed in real life, such as identifying the source of sounds, music perception and using the telephone. Therefore, using standard speech tests only might underestimate the value of the bimodal hearing and bilateral CI for listening in real-life situations.

The real-life test battery included performance tests to assess the essential auditory functions needed for listening in real life, particularly (1) understanding speech in background noise, (2) localising the source of sounds, (3) tracking of moving sounds, and (4) telephone use. All of these skills are important for effective communication, safety and threat detection. The ability to understand speech in noise has been assessed with three new speech- in-noise tests that simulate common listening situations in real life: (1) a group conversation in a noisy background where the target speech is randomly roved in location (2) one-to-one conversation in a noisy background with target speech fixed in front of the listeners and (3) having a conversation while driving a car where the speech is at one side of the listener. To the best of the researcher's knowledge, few studies used speech tests with set-ups simulating a real-life listening situation, particularly using roving speech, to test the performance of CI users (Gifford et al., 2018, Gifford and Dorman, 2019, Dorman et al., 2020). The assessment of the measurement precision of these new speech-in-noise tests on NH listeners showed that these tests are reliable and valid. In addition, these new tests particularly roving speech test can provide additional information about the listener's performance in similar situations in real life that could not be obtained from the standard test where the speech and the noise are presented from one loudspeaker placed at the front. The administration of roving speech test is easy and feasible when using the AB-York Crescent of Sound apparatus. Furthermore, using a dynamically roving speech test can offer the potential to assess the spatial hearing. Bizley et al. (2015) and Salorio-Corbetto et al. (2022) used a dynamically roving speech to assess different spatial hearing abilities for NH listeners. Therefore, it would be recommended to consider including this test in clinical and research settings. Accordingly, further work is needed to measure the test-retest reliability and the validity of using this test for adult CI users.

The findings from localisation and modified tracking tests in the present study shows that these two tests offer a potential information about the spatial hearing for the CI users and the differences between bilateral CI and integrated bimodal technology. Thus, it important to consider including these tests in clinical and research settings. Given there was a significant positive correlation between localisation and tracking as shown in the studies reported in Chapters 5 and 6, using localisation test only would be enough to assess the spatial hearing particularly if there are time constraints.

The telephone test was included in the test battery primarily to assess the effectiveness of DuoPhone for adult CI users. However, the test is in a rudimentary stage and has several limitations, as discussed in Chapter 4 Section 4.2.2.5.5, in terms of the procedure and the applicability. Further work is needed to develop reliable, valid, and feasible telephone tests that can be used for to assess the effectiveness of the different technologies that developed to facilitate the telephone use for CI users.

The subjective rating scales were also included in this test battery to gauge the perceived benefits from CI users' perspective. The SSQ was used as it provides an assessment for a wide range of hearing functions that are important in real life specifically speech understanding, spatial hearing, and qualities of hearing. The SSQ also has been shown to be sensitive to assess the differences in monaural and binaural hearing for CI users (Noble *et al.*, 2008, Noble, 2010). The findings from this study indicate using a such subjective rating scale offered valuable information about auditory functions of CI users in different real-life listening situations, advantages of using integrated bimodal technology and bilateral CIs over using the CI only, and the difference between the integrated bimodal technology and bilateral CIs. However, informal feedback from the participants was that the SSQ was lengthy and took a long time to complete. It would be recommended to consider using a short version or similar short questionnaires. Nevertheless, using subjective rating scales in clinical and research settings would be recommended to have a better understanding of a wide range of hearing functions in real life.

In short, the real-life test battery would provide a better understanding of the differences for using one CI, integrated bimodal technology, and bilateral CI compared to NH listeners in real-life listening situations. Professionals and researchers in the field of CI would be encouraged to use such a test battery that provides more information about the performance of CI users in different real-life listening situations. Additionally, it would be recommended to incorporate assessment tests for using low-frequency information (i.e. music perception, sound quality) in the test battery.

8.2.4 Clinical significance

All the significant benefits mentioned in this thesis were referred to as statistical significance. It is widely known that a small difference in the measurement of health-related quality of life might be statistically significant but not important clinically (Hays and Woolley, 2000). Therefore, the concept of the important clinical difference has been introduced.

The minimum clinically important difference (MCID) was first defined by Jaeschke *et al.* (1989) as the smallest difference in score in the domain of interest which patients perceive as beneficial and subsequently would lead to a change in the patient's management plan. The meaningful change can be expressed from the patient's perspective as any reduction in symptoms or improvement in function, or from the clinician's perspective as any change in treatment or in the prognosis of the disease (Cook, 2008, Mouelhi *et al.*, 2020). Therefore, MCID should be taken into consideration particularly if a new intervention has been introduced. This is relevant in terms of the management of hearing loss. It is crucial to decide which management option would provide appreciable benefits for individuals with severe to profound hearing loss (for example integrated bimodal hearing vs. bilateral CI).

The SNR level is the most important parameter that affects understanding of speech in noise. It is not clear yet how much improvement in SNR would be important and meaningful to the listeners particularly those with hearing loss. An early work (Killion, 2004) suggested that more than 2 dB change in the SRT might be needed to perceive the benefit, particularly in real-life listening situations. McShefferty *et al.* (2015) measured a just-noticeable difference (JND) in SNR of speech in noise for 69 participants of varying hearing ability including NH and hearing-impaired listeners. Two intervals were presented to the participants, and they were asked which of the two intervals was clearer. The level of the two intervals was roved independently by using a 4 dB level-roving range (±2 dB) with one at a reference SNR (either -6 dB, 0, or + 6 dB) and the other at a variably higher SNR. The results showed that the average SNR JND was 3 dB across both NH and HI participants for both procedures. However, the authors acknowledged a few limitations that indicated the results of their study might have over-or under-estimated the value of SNR JND for several reasons relating to the technical procedure used to present the stimuli.

In their second study, McShefferty *et al*. (2016) emphasised the importance of carefully differentiating between the noticeable difference and meaningful difference. They argued that a 3-dB SNR change is necessary to have a noticeable difference, yet it does not indicate whether this difference is meaningful or not. They defined the just-meaningful difference (JMD) as the minimum increase in SNR necessary to motivate the individual with hearing loss to seek intervention. In contrast to JND, the JMD is measured using subjective techniques which fundamentally rely on the listener's opinion. Two intervals of IEEE sentences in same-spectrum noise were presented where each trial mimicked examples of pre-and post- benefit. To measure the JMD, the participants were asked: (1) to rate better/worse the change in SNR in the paired examples (2) if they were willing to swap the worse for the better SNR (i.e. swap device), and (3) if they would be willing to attend the clinic for a given increase in the SNR. The results showed that the mean JMD in SNR was 6 to 8 dB depending on the difficulty of the listening situation. In addition, the results of the two studies (McShefferty *et al.*, 2015, McShefferty *et al.*, 2016) have indicated that the hearing loss and the age factors were not correlated to the JND and the JMD.

The findings from the aforementioned studies suggest that a minimum 2 to 3 dB increase in the SNR would be required to perceive a noticeable difference. However, it should be noted that the minimum important difference would vary according to the listening condition as well as to the type of speech and the noise masker. MacPherson and Akeroyd (2014) showed in their systematic survey by re-examining the psychometric functions for 885 individuals that the slope and the amount of the perceptual benefit which could be obtained from an improvement in SNR depend greatly on the listening environment including both the target and the masker. Therefore, it would be recommended for future studies to investigate the minimum clinically important difference for the newly developed speech-in-noise tests included in the real-life test battery in the current study.

8.3 Conclusion

The main conclusions of this PhD thesis are as follows:

- Binaural hearing for adult unilateral CI users is not well supported in terms of funding for a second implant or HA, and that there is no clear practice guidance for fitting and maintaining the contralateral HA in most world regions
- Both integrated bimodal technology and bilateral CI are more beneficial than unilateral CI for adult CI users on speech perception in noise, spatial listening, and self-reported benefits compared to using one CI for adult CI users
- Bilateral CI provides greater benefits in spatial-listening ability and self-reported benefits than integrated bimodal technology
- Technology designed to enhance binaural streaming seems to be advantageous to improve speech understanding in noise for adult CI users who have integrated bimodal technology or bilateral implants
- There was a substantial difference between the performance of the NH listeners and CI users on the real-life test battery which emphasised the importance of providing additional support for CI users

- Using a test battery that involved both real-life representative performance tests and subjective rating scales provides a better understanding of the performance of CI users

8.3.1 Recommendations for clinical practice

The findings from this thesis showed the benefits of using a second device (an HA or second implant) in the non-implanted ear for adult unilateral CI users on a wide range of auditory functions needed for listening in real-life. However, the opportunity to have a second device does not seem to be well supported for adult unilateral CI users in current clinical practice worldwide. The findings from the international survey (Chapter 3) indicated that bilateral CI is not available for adults in many countries due to cost constraints. For example, many countries in Europe, Asia, Oceania and Africa regions do not provide funding support (state-funding) for the second implant for adults (i.e. the UK, Netherlands, and Belgium). The second CI is obtained mainly via self-funding where limited follow-up support is given. Similarly, using an HA in the non-implant ear is not well supported in terms of funding and fitting procedure. Most respondents of the survey indicated that they do not use a specific protocol for introducing and fitting the HA following implantation. Therefore, clinical practice should be encouraged to provide support for optimising binaural hearing for adult CI users. This can be achieved by reviewing the policy and recent evidence and providing funding support for bilateral CI. It would also be recommended to consider using recommended procedure to fit and balance the HA with CI.

Another important recommendation for clinical practice is providing appropriate counselling about the expected benefits and trade-off of using an HA or a second implant in the other ear particularly if the two options are available for patients. For example, both bilateral CI and bimodal hearing can be obtained via private insurance in the USA. Based on the results from this thesis and the previous literature, bilateral CI provided better spatial listening and perceived benefits compared to bimodal hearing (both standard and integrated technologies), whereas bimodal hearing (standard technology) provided better access to low-frequency information. The clinicians, therefore, need to give sufficient explanations for these differences to patients and consider patients' needs and expectations.

Lastly, it would be advisable to consider using a test battery that includes more representative tests of real-life listening situations when assessing the performance of CI users in clinical practice. This would help to provide a better understanding of patients' needs and appropriate rehabilitation plans.

8.3.2 Recommendations for future research

Recommended future research is as follows:

- It is still unclear whether the integrated bimodal technology can provide additional benefits compared to standard bimodal technology. It was anticipated that matching compression algorithms and time constants between the HA and CI would enhance binaural hearing. If this is the case, then such a finding would have a considerable impact on service provision where integrated bimodal technology should be facilitated rather than standard technology. Therefore, future studies should consider examining the difference between standard and integrated bimodal technologies
- Consider testing adults using one CI only (unilateral CI users) for between-subject comparison with bimodal and bilateral groups. In this thesis, the unilateral listening condition of using one CI for bimodal and bilateral CI groups has been assessed; therefore, it was not possible to include these data in the statistical analysis in the between-subject comparison
- Assessing the effect of heterogeneity of bilateral CI group on the results particularly in terms of the device, having simultaneous versus sequential implants, and the time interval between the two implants for those with sequential implants
- Measuring test-retest reliability and validity of the new speech-in-noise tests for adult CI users
- Further development for the telephone test. The test developed in this thesis was affected by the ceiling effect and limited practicability when administering the test
- The advantages of having access to low-frequency information on music perception and sound quality have not been assessed in this thesis due to time constraints of the test battery. It was anticipated that integrated bimodal technology would improve music perception and the quality of sounds compared to unilateral and bilateral CI; however this could not be tested. Thus, it is recommended that the real-life test battery incorporates measurements for music perception and sound quality.

Appendix A Summary of studies that investigated the performance of adult bilateral CI users on speech in the presence of noise

	Sample size	Design	Device	stimuli	Set-up	Procedure	Type of noise	Results
Gantz et al. (2002)	10	WS	Cochlear	CUNY sentence	• S0°N0° • S0°N+45° • S0°N-45°	Fixed (+10 dB SNR)	multi-talker babble	The improvement is only seen when the noise on the same side of CI (head shadow effect)
Mueller et al. (2002)	9	WS	MED-EL	HSM sentence	• S0°N90° • S0N270°	Fixed (+10 dB SNR)	Speech-shaped noise	• Score with bilateral CI was 31.1 % significantly higher than unilateral CI (noise at CI side) • Score with bilateral CI was 10.7 % significantly higher than unilateral CI (noise opposite CI side)
Schon et al. (2002)	9	WS	MED-EL	HSM sentence	• If better CI (right CI)= S (45°,225°) N (135°,315°) • If better CI (left CI)= S (135°,315°) N (45°,225°)	Adaptive	Not mentioned	Statistically significant bilateral benefit (SNR improved by 4dB on average)
Tyler et al. (2002a)	7	WS	Cochlear	CUNY and HINT sentences	• S0°N0° • S0°N+90° • S0°N-90°	Fixed (different SNRs, set individually)	Not mentioned	• S0°N0° = significant advantage of bilateral condition only for 4 participants • When the ear opposite to the noise added: significant advantage in all participants (head showed effect) • When the ear ipsilateral to noise was added: a significant advantage was seen only for only one participant (squelch effect)

van Hoesel and Tyler (2003)	5	WS	Cochlear	BKB	• S0°N0° • S0°N+90° • S0°N-90°	Adaptive	broadband noise	• S0°N0°= no significant difference between the bilateral and unilateral conditions • In spatially separated conditions: there is a bilateral advantage from head shadow but weakly significantly (less than 2 dB)
Laszig et al. (2004)	37	WS	Cochlear	Oldenburger sentences	• S0°N0° • S+45°N-45° • S-45°N+45°	Adaptive	speech-simulating continuous noise	• Significant effect of binaural summation with bilateral condition (S0°N0°) • Significant effect with the bilateral condition when the noise is close to the testing ear (head shadow effect) • No significant binaural squelch effect
Schleich et al. (2004)	18	WS	MED-EL	Oldenburger sentence	• S0°N0° • S0°N+90° • S0°N-90°	Adaptive	Speech-shaped noise	• Significant head shadow effect (6.8 dB) and summation effect (2.1 dB) for all test conditions • Squelch effect was significant for noise from the left side only (0.9 dB)
Ramsden et al. (2005)	28	WS	Cochlear	• CNC words • CUNY sentences	• S0°N0° • S0°N+90° • S0°N-90°	Fixed (different SNRs, set individually and ranged from +5 to +15 dB)	eight-talker babble	Binaural advantage, head shadow benefit, squelch effect, and redundancy have all been shown only for some participants
Senn et al. (2005)	5	WS	MED-EL	HSM test	• S0°N0° • S0°N±90°	Fixed (different SNRs, set individually)	CCITT noise	An improvement with bilateral CI from the head shadow effect 32.6%
Litovsky et al. (2006a)	34 (by 6-month post-activation)	WS	Cochlear	BKB-SIN Test	• S0°N0° • S0°N+90° • S0°N-90°	Adaptive	four-talker babble	• Significant bilateral benefit when ear opposite to the side of the noise was added (head shadow effect) • Bilateral benefits for binaural summation and squelch are only seen in a few participants.
Ricketts et al. (2006)	16	WS	MED-EL	• HINT (adaptive) • CST (fixed)	• S0° • N (30°, 105°, 180°, 255°, & 330°)	fixed (+10 dB SNR) and an adaptive	uncorrelated noise (combination of HINT and CST	• A significant bilateral benefit of 3.3 dB using the adaptive-SNR method. • A significant bilateral benefit of 9% was also measured using a fixed +10 dB SNR.

							noise with some variation on the spectrum)	
Tyler et al. (2007)	7	WS	Cochlear, MED-EL	CUNY sentences	• S0°N0° • S0°N+90° • S0°N-90°	Fixed (different SNRs, set individually and ranged from +2 to +10 dB)	multi-talker speech babble	• S0°N0°= all participants showed significant bilateral benefit (n=6) • Significant head shadow effect for all participants (n=4) • Significant binaural squelch effect for all participants (n=4)
Wackym et al. (2007)	7	WS	All three manufacturers (Advanced Bionics, Cochlear, MED-EL)	• HINT sentences • SPIN test	S0°N0°	Fixed (+8 dB SNR)	-Speech-weighted noise (HINT test) - 12-talker speech babble (SPIN test)	• Significant improvement with bilateral CI in HINT test for 6 of the 7 participants (the difference 12.43%) • The difference between the bilateral and unilateral condition in the SPIN test is 10.67%
Buss et al. (2008)	26	WS	MED-EL	CUNY sentences (presented via Direct Audio Input (DAI))	• S0°N0° • S0°N+90° • S0°N-90°	Fixed individually SNR	Not mentioned	• Significant bilateral benefit from head shadow (37.5%) • Bilateral benefit from binaural summation (up to 5.7%) • Bilateral squelch did not appear until one-year post-implantation (10.6%)
Zeitler et al. (2008)	11	WS	All three manufacturers (AB, Cochlear, MED-EL)	BKB-SIN	• S0°N0° • S0°N+90° • S0°N-90°	Adaptive	4-talker babble	Significant improvement with bilateral CIs
Laske et al. (2009)	29	WS	Cochlear	Oldenburger sentences	• S0°N0° • S+45°N-45°	Adaptive	Not mentioned	Slightly better performance with bilateral but not statistically significant (for summation and squelch effects)
Litovsky et al. (2009)	17	WS	Cochlear	BKB-SIN	• S0°N0° • S0°N+90° • S0°N-90°	Adaptive	Babble noise	Better performance with bilateral CI when the speech and noise were spatially separated
Mosnier et al. (2009)	27	WS	MED-EL	disyllabic words	S0° N (5 loudspeakers placed from -90° to +90° with 45° separation	Fixed (+5,+10, +15 dB SNR)	cocktail party noise	An improvement (+5-10 %) with bilateral CI for all three periods

						Testes for 3 periods after implantation (3,6 and12)		
Dunn et al. (2010)	BiCI=30 UniCI=30	BS	Cochlear	'Cueing-the-Listener' test (spondee words)	8 loudspeakers placed from -54° to +54° (Speech roved randomly with Noise from opposite speaker)	Adaptive	Competing speech	BiCI group showed better significant better compared with the unilateral CI group
Koch et al. (2010)	11	WS	Advanced Bionics	HINT sentences (presented with head-related transfer functions (HRTFs))	• S0°N0° • S0°N+90° • S0°N-90°	Fixed (+8 dB SNR) and adaptive	speech-spectrum noise	• Only 9 of 11 participants demonstrated a bilateral redundancy effect • All the participants demonstrated a head shadow advantage • Large variability across the participants for binaural squelch effect
Dunn et al. (2012)	13	WS	All three manufacturers (Advanced Bionics, Cochlear, MED-EL)	'Cueing-the-Listener' test (spondee words)	8 loudspeakers placed from -54° to +54° (Speech roved randomly with Noise from opposite speaker)	Adaptive	Competing speech	• Significant benefit with bilateral CI in 8 participants • One participant showed a significant worse score with bilateral CI • Other participants showed no difference • The average bilateral benefit =4.6 dB
Smulders et al. (2016a)	38 BiCi=19 UniCI= 19	BS (RCT)	AB	U–STARR	• S0°N0° • S best CI N opposite side • S worst CI N opposite side	Adaptive	Not mentioned	A significant difference between the two groups only in the test condition of presenting the speech at worst CI side
Rana et al. (2017)	7	WS	Cochlear	Helen test sentences	• S0°N0° • S0°NCI • S0°N±90°	Adaptive	two speech talkers (one talker from one speaker)	• Signiant bilateral benefit (7.5 dB) when compared to the unilateral condition with noise at the CI side • Bilateral benefit (3 dB) but not significant in the condition where the noise presented from each side

van Zon et al. (2017)	38 BiCi=19 UniCI= 19	BS (RCT)	Advanced Bionics	U–STARR	• S0°N0° • S best CI N opposite side • S worst CI N opposite side	Adaptive	Not mentioned	A significant difference between the two groups only in the test condition of presenting the speech at worst CI side

BiCI= bilateral CIs, **Uni**=unilateral

Design: BS= Between-subject, **WS**= Within-subject, **RCT**= randomised control trial

Stimuli: BKB = Bamford-Kowal-Bench, **CST**= Connected Speech Test, **CUNY** = City University of New York, **CNC**= consonant-nucleus-consonant, **HINT**= Hearing in Noise Test, **HSM**= Hochmair/Schulz/Moser sentence test, **SPIN**= Speech Perception in Noise, **U–STARR**= Utrecht -Sentence Test with Adaptive Randomized Roving,

Appendix B Summary of studies that investigated localisation performance of adult bilateral CIs users

Studies	Sample size	Design	Device	Test setting	Type of stimulus	Presentation levels	Results
Gantz et al. (2002)	10	WS	Cochlear	Two speakers placed at ± 45 degree	pulses of speech weighted noise	Roving intensity level (the range not mentioned)	Significant improvement with bilateral CI for all the participants
Tyler et al. (2002a)	7	WS	Cochlear	Two loudspeakers at 45° azimuth.	bursts of speech-weighted noise	70 dB SPL (varied over a 10-dB range)	Scores with the bilateral CI were significantly higher for 6 participants than with one CI
van Hoesel and Tyler (2003)	5	WS	Cochlear	Eight loudspeakers spanning a horizontal arc of 108°(15.5° separation)	a sequence of four 170-ms pink-noise bursts	65 dB SPL (with 64 dB random variation)	Clear improvement in localisation ability with bilateral CI (the average binaural RMS errors were around 10°)
Laszig et al. (2004)	16	WS	Cochlear	12 loudspeakers at intervals of 30°	a shortened sentence from the HSM sentence test	55–60 dB SPL or 65-70 dB SPL (According to the participants' aided threshold)	Significant improvement with the bilateral condition compared to the unilateral condition (RMS 50° for bilateral condition)
Nopp et al. (2004)	20	WS	MED-EL	Nine equally spaced loudspeakers with 22.5 ° separation	speech-shaped noise bursts	randomly chosen to be 60 dB, 70 dB, or 80 dB SPL	Significant improvement with bilateral CI for 18 of the 20 participants (the RMS errors for bilateral condition= 15.9°, the amount of improvement is 30.1 ° over unilateral CI
Seeber et al. (2004)	4	WS	MED-EL	Eleven loudspeakers array span an angle of -50° left to + 150° right with a spacing of 10°	Gaussian white noise divided into five pulses	64- and 76-dB SPL (3-dB steps variation)	The participants showed better performance with bilateral CI compared to unilateral CI.

Verschuur et al. (2005)	20	WS	Cochlear	11-loudspeaker array (18° separation)	five stimuli (speech, tones, noise, transients, and reverberant speech	Varied between the stimuli (60-70 dB SPL)	RMS errors with Bilateral CI was 24° compared with 67° for unilateral CI (bilateral condition significantly better than monaural conditions for all participants)
Grantham et al. (2007)	22	WS	MED-EL	an array of 43 numbered loudspeakers extending from –90° to +90° azimuth	Noise burst and speech sample	70 dB SPL	• For noise stimulus: the mean Cˆ is 24.1° with bilateral CI where is 50.5° with unilateral CI • For speech stimulus: the Cˆ is significantly lower (21.5) than for the noise stimulus in the bilateral condition *
Neuman et al. (2007)	8	WS	Cochlear	nine-loudspeaker array in a large classroom with 22.5° separation	speech stimulus and pink noise bursts	70 dB SPL (±3 dB rove)	• Significant better localisation ability with bilateral CI (RMS errors 29 degrees) than with unilateral CI (range from 46.5 to 54 degrees) • No difference between speech and pink noise stimuli
Tyler et al. (2007)	7	WS	Cochlear, MED-EL	Eight loudspeakers spanning a horizontal arc of 108°(15.5° separation)	16 everyday sounds	70 dB(C)	• Different RMS errors with bilateral CI ranging from 13° to more than 40° • Only two participants did the test with bilateral CI and unilateral CI. Both showed an improvement in localisation ability
Dunn et al. (2008)	74 BiCI= 32 UniCI=32	BS	Advanced Bionics, Cochlear	eight-speaker array spanning, an arc of approximately 108	16 everyday sounds	70 dB (C)	A significant difference between both groups where the bilateral CI group have better RMS error by 25.4°
Laske et al. (2009)	29	WS	Cochlear	12 speakers arranged in a circle	a broadband noise	65 dB SPL	Mean deviation from the actual sound source of 57 degrees with bilateral CI
Mosnier et al. (2009)	27	WS	MED-EL	Five loudspeakers positioned at 45° intervals, ranging from –90° to +90°	disyllabic words in the presence of noise	Roving from 60 to 80 dB SPL	Variable results (localisation not improved in 12 of 27)

Litovsky et al. (2009)	17	WS	Cochlear	8 loudspeakers arranged in a semi-circular shape and spanning-70° to +70° azimuth (20° separation)	Five bursts of pink noise	randomly roved within a 12 dB window spanning 54 to 66 dB SPL	Significant improvement with bilateral CIs compared to unilateral CI for 14 of 17 participants
Koch et al. (2010)	15	WS	Advanced Bionics	12 equally spaced loudspeakers in the horizontal plane	a wideband impulse stimulus (a 'gunshot')	around a comfortable level (±3 dB rove)	• Performance with unilateral CI at chance level • Performance with bilateral CI was better than unilateral CI
Dunn et al. (2012)	13	WS	All three manufacturers (Advanced Bionics, Cochlear, MED-EL)	Eight loudspeakers spanning a horizontal arc of 108°	16 everyday sounds played in noise	60 dB(C)	• Significant improvement in 9 participants (improvement ranging from 17° to 41°) • The other participants showed no difference
Goman (2014)	12	WS	All three manufacturers (Advanced Bionics, Cochlear, MED-EL)	Three testing settings: • 3 loudspeakers with 60° separation (-60°, 0°, and +60°) • 5 loudspeakers with 30° separation (±60°, ± 30°, and 0°) • 5 loudspeakers with 15° separation (± 30, ±15°and 0°)	Speech sentence "Hello what's this?"	65dB SPL to 75 dB SPL	Significant improvement with bilateral CI compared to unilateral CI in the three test settings
Smulders et al. (2016a)	38 BiCi=19 UniCI= 19	BS (RCT)	Advanced Bionics	9 speakers arranged in a circle	Not mentioned	Not mentioned	Significant difference between the two groups With 15° separation = 30% With 30° separation = 36.6% With 60° separation = 50 %
Rana et al. (2017)	7	WS	Cochlear	13 loudspeakers (9 loudspeakers frontal horizontal plane spacing of 22.5, where the three	Two talkers (male and female) speech	60 dB SPL	Localisation varied between the participants, but there is a clear bilateral benefit

				behind loudspeakers at 135°, 135, and 180°)			
van Zon et al. (2017)	38 BiCi=19 UniCI= 19	BS (RCT)	Advanced Bionics	9 speakers arranged in a circle	Not mentioned	Not mentioned	Significant difference between the two groups With 15° separation = 30% With 30° separation = 36.6% With 60° separation = 50 %

BiCI= bilateral CI, **Uni**=unilateral, **BS**= Between-subject, **WS**= Within-subject, **RCT**= randomised control trial

*The score presented as an adjusted constant error (Cˆ): The relationship between source azimuth and response azimuth

Appendix C Summary of studies that investigated self-reported benefits of adult bilateral CIs users

Study	Sample size	Design	Device	Measure	Results
Litovsky et al. (2006a)	34	WS	Cochlear	APHAB	Better results with bilateral than unilateral
Summerfield et al. (2006)	24	WS	Cochlear	SSQ, GHSI, HUI3, EQ-5D, VAS, Tinnitus questionnaire	• SSQ: significant increase in spatial hearing rating with 2nd CI • The only significant positive change in quality of life measures with bilateral CI was in GHSI • Mean annoyance due to tinnitus increased with receiving the 2nd CI
Wackym et al. (2007)	7	WS	All three device manufacturers	APHAB	The mean difference between listening with bilateral CI and preoperative hearing: • Ease of communication: 44.6 • Reverberation: 39.0 • Background noise: 38.9
Noble et al. (2008)	BiCI=36 UniCI=105	BS	Not mentioned	SSQ	Bilateral CI showed significantly higher ability ratings than unilateral CI in the spatial hearing domain and on most aspects of other qualities of hearing (segregation, naturalness, and listening effort)
Laske et al. (2009)	29	WS	Cochlear	SSQ	• Better mean and median for bilateral CI compared to one CI in all categories but were just below statistical significance. • Difference in speech section= 1.7, Spatial hearing =1.4, Hearing quality= 1
Smulders et al. (2016a)	BiCI=19 UniCI= 19	BS	Advanced Bionics	SSQ	Significant better results on all three sections for bilateral CI group compared to the unilateral CI group
				NCIQ	Bilateral group reported better hearing capabilities than unilateral CI group but not significant
				TTO	Significant better results for bilateral CI group compared to unilateral CI group
				VAS	Significant better results for bilateral CI group compared to unilateral CI group

van Zon et al. (2017)	BiCI=19 UniCI= 19	BS	Advanced Bionics	SSQ	• Significantly better results on speech subscale SSQ (understating in silence, background noise, resonating environments, and on the telephone) bilateral CI group= 5.9 and unilateral CI group=3.1 • Significant benefit on the spatial subscale. (Bilateral CI group =6.6 versus unilateral CI group= 2.4) • Qualities subscale SSQ = better scores for bilateral CI group but not significant
				NCIQ	Better results with bilateral CI group but no significant difference between the two groups
				QoL questionnaires (VAS, TTO, EQ-5D, HU13)	No significant results between the two groups
Lee (2018)	BiCI=15 UniCI=15 (young adults)	BS	Not mentioned	SSQ	Bilateral CI showed significantly better performance in all three sections than those with unilateral CIs

BiCI= bilateral CIs, **Uni**=unilateral

APHAB =Abbreviated Profile of Hearing Aid Benefit, **EQ-5D**= EuroQol EQ-5D, **GHSI**= Glasgow Health Status Inventory, **HUI3**=the Health Utilities Index Mark III, **NCIQ**= Nijmegen Cochlear Implantation Questionnaire, **SSQ**= Speech, Spatial and Qualities Hearing Scale, **TTO**= Time Trade-off, **VAS**= visual analogue scale

Appendix D Summary of studies that investigated the performance of adult CI users with bimodal hearing on speech in noise

Study	Sample size	CI device	HA device	stimuli	Set-up	Procedure	Type of masker	Results (CI alone vs. Bimodal)
Armstrong et al. (1997)	12	Cochlear	Not mentioned	• CUNY sentences • CNC words	S0°N0°	Fixed • +5 dB SNR (only for five subjects • +10 dB SNR (for all participants)	4- talker babble	Significant improvement for the bimodal condition in comparison to the CI alone
Tyler et al. (2002b)	3	Cochlear Advanced Bionics	Bosch, Oticon, Phonak	CUNY sentences	• S0°N0° • S0°NCI • S0°NHA	Fixed SNRs (set individually)	Multi-talker babble	• S0°N0° =2 out of 3 have shown improvement • S0° NHA= no benefit • S0°NCI= 1 out three have shown improvement
Ching et al. (2004)	12 (experienced HA users) + 9I (new users HA)	Cochlear	Bernafon AF120	BKB sentences	• S0°N0° • S+60°N-60° (speech at HA side)	Fixed • +10 dB SNR for both test configurations • +15 dB SNR for S+60°N-60°	8 –talker babble	Significantly better scores for bimodal compared to CI alone both setups

Flynn and Schmidtke (2004)	8	Cochlear	Oticon SUMO XP	CUNY sentences	• S0°N0° • S0°NCI • S0°NHA	Fixed (+5 and + 10 dB SNRs)	4-talker babble	Significant improvement of speech in all bimodal conditions compared to the CI alone
Iwaki et al. (2004)	6	Cochlear	Not mentioned	HINT sentences	• S0°N0° • S0°NCI • S0°NHA	Adaptive	Multi-talker babble	A significant improvement with bimodal condition than CI alone only in S0°N0°
Dunn et al. (2005)	12	Cochlear Advanced Bionics	Senso, Starkey, Siemens, Lifestyle, Danavox, Telex, Phonak, Phonic	CUNY sentences	• S0°N0° • S0°NCI • S0°NHA	Fixed (individually SNRs ± 10 dB; if the participant's score was ≥90%, then SNR was decreased, if the score was≤ 10%, then the SNR was increased)	Multi-talker babble	• Varied results; some participants showed significant improvement in some conditions, and others showed a small benefit. Few participants showed a decrement in the bimodal condition compared to CI alone. • S0°NHA: showed less bimodal benefit
Kong et al. (2005)	4	Cochlear Advanced Bionics	Not mentioned	IEEE sentences	S0°N0°	Fixed (+20, +15, +10,+5 and 0 dB SNRs)	A competing sentence was spoken by a different male talker or a female talker. (The same competing sentence was used during testing)	Significant improvement in the bimodal condition than the CI alone, particularly at higher SNRs

Morera et al. (2005)	12	Cochlear	Not mentioned	Words (Spanish)	• S0°N0° • S0°NCI • S0°NHA	Fixed (+10 dB SNR)	4- talker babble	• S0°N0°: better performance for the majority in the bimodal condition (but not significant) • S0°NCI and S0°NHA: Significant binaural squelch, but no significant effect for the head shadow effect.
Ching et al. (2006)	21	Cochlear	Not mentioned	BKB sentences	• S0°N0° • SHANCI at± 60°	Fixed (+10 dB SNR)	8 –talker babble	A significant benefit with the bimodal condition compared to CI alone in all test configurations
Mok et al. (2006)	14	Cochlear	Bernafon, Phonak	CUNY sentences	S0°N0°	Fixed (+10 and +5 dB SNRs)	4- talker babble	Large variability in benefits
				Spondees words (closed set only five words)	• S0°N0° • S0°NCI • S0°NHA	Adaptive	broadband noise	The benefit was most common when the noise was presented to the side of the CI
Dorman et al. (2008)	15	Not mentioned	Not mentioned	AzBio sentence	• Speech at 0° • Noise (not mention)	Fixed (+ 10 and +5 dB SNRs)	4-talker babble	• At +10 dB SNR: significant difference between CI alone (42.6%) and CI+HA (65.2%) • At +5d dB SNR: significant difference between CI alone (21.8%) and CI+HA (43.8%)
Berrettini et al. (2010)*	10	Cochlear	Starkey PXP 675	Disyllabic words	• S0°N0° • S0°NCI • S0°NHA • S0°N180°	Fixed (+10 dB SNR)	Babble masker	• ***At the moment of 1st bimodal fitting; (N=10)*** Significant improvement in words recognition with bimodal hearing

								compared to CI alone in all test configurations (except $S0°N_{HA}$ condition, there is an improvement but not significant). • ***After six months of bimodal hearing experience: (N=9)*** Significant improvement in words recognition with bimodal hearing in comparison to CI alone in all test configurations.
Pyschny et al. (2011)	12	All three manufactures	Siemens, Phonak	OISa (speech material consists of 5-word nonsense sentences)	S0°N0°	Fixed (0 dB SNR)	Single competing talker (sentence similar to the target sentence but contained randomly other words used in the target)	• Small benefit for the bimodal condition in comparison to CI alone • No benefit for target-masker separation with bimodal was found
Morera et al. (2012)	15	Cochlear	Not mentioned	HINT sentences	• S0°N0° • $S0°N_{CI}$ • $S0°N_{HA}$	Adaptive	Not mentioned	• S0°N0°: significant improvement (3dB) • $S0°N_{CI}$: significant improvement (5.3 dB) • $S0°N_{HA}$: significant improvement (3.6 dB)
Jang et al. (2014)	17	All three manufactures	Not mentioned	Disyllabic words	Speech at 0^o Noise: diffuse	Fixed (+ 10 dB SNR)	Multi-talker babble	Significant improvement for bimodal condition compared to CI alone

Kokkinakis and Pak (2014)	7	Cochlear	Phonak Naida, ReSound Pixel, Oticon 380P	BKB -SIN	• S0°N0° • S0°NCI • S0°NHA	Adaptive	4- talker babble	Improved except in condition S0°NCI
Bouccara et al. (2016)	10	All three manufactures	Phonak , Senso P38, Siemens 8DF, Widex, C18+, Acuris, Nitro CIC, Centra SP, Oticon, Sumo DM, Savia 311	HINT sentences	Speech at 0° Noise (lateral sides)	Fixed (0 and +5 dB SNRs)	Cocktail party	Varied results (some cases had limited or -ve benefit)
Devocht et al. (2017)	15	Advanced Bionics	Oticon, Siemens, Phonak	Dutch Matrix sentences	• S0°N0° • S0°NCI • S0°NHA	• Noise fixed at 65 dB SPL • Speech level was adjusted using an adaptive procedure	Stationary noise	Significant improvement S0°NCI= 5.9 dB S0°N0°=4.2 dB S0°NHA=2.6
Hua et al. (2017)	17	Cochlear, MED-EL	Widex, Phonak, Oticon, Unitron, Resound	Swedish HINT test	S0°N0°	Adaptive	Steady-state noise	SRT= 10.7 dB

BKB = Bamford-Kowal-Bench**, CUNY** =City University of New York, **CNC**= consonant-nucleus-consonant, **HINT**= Hearing in Noise Test, **IEEE**= Institute of Electrical and Electronics Engineers

S= speech**, N=**noise**, HA=**hearing aid**, CI=** cochlear implant

All studies within-subject design

*****The reported benefit for only 8 out of 10

Appendix E Summary of studies that investigated localisation performance of adult CI users with bimodal hearing

Studies	Sample size	CI device	HA device	Test setting	Type of stimulus	Presentation levels	Results
Tyler et al. (2002b)	3	Cochlear Advanced Bionics	Bosch, Oticon, Phonak	2 loudspeakers at ± 45 °	4 bursts of speech noise	73--83 dB SPL (varied randomly)	Improved for 2 participants out of 3 (85-95%)
Flynn and Schmidtke (2004)	8	Cochlear	Oticon SUMO XP	3 loudspeakers (front, left and right)	Speech shaped noise, total presentations 30 (10 random presentations from each of the three directions)	65 dB A	The localisation ability was significantly above chance only in the bimodal condition
Seeber et al. (2004)	11	Cochlear, MED-EL	Phonak	Eleven loudspeakers array span an angle of - 50° left to + 150° right with a spacing of 10°	Gaussian white noise divided into five pulses	64 and 76 dB SPL (3-dB steps variation)	Half of the participants showed improvement with bimodal hearing over CI alone. One participant showed significant improvement similar to NH
Dunn et al. (2005)	12	Cochlear Advanced Bionics	Senso, Starkey, Siemens, Lifestyle, Danavox, Telex, Phonak, Phonic	Eight loudspeakers array spanning an arc of 108° (loudspeakers 1 and 8 were placed 45°) other six loudspeakers were placed 15.5° apart)	16 different everyday sounds, each sound was repeated six times (ex.; Westminster chime, telephone ring, many birds, a child laughing)	(60 dB A	• Variables results (RMS error ranged from 27.6° up to 48.7°), the average total RMS error = 42.7° • Only 2 out of 12 were able to localise in bimodal conditions
Ching et al. (2004),	18	Cochlear	Bernafon AF120	11 loudspeakers in 180 degrees horizontal arc (placed 18° apart)	Pulsed pink noise (.83 sec)	70 dB SPL (with	• 12 of the 18 participants made significantly less RMS errors with bimodal condition compared to CI alone.

Ching et al. (2006)						variation +/- 3 dB)	• RMS for bimodal 32º vs. CI alone (39º)
Potts et al. (2009)	19	Cochlear	Widex Senso Vita 38	Fifteen loudspeakers array span an angle of -70° to + 70° with a spacing of 10°	CNC words presented randomly from a set of 10 loudspeakers in the array	60 dB SPL with roving level (± 3 dB SPL)	• Significant performance with bimodal condition (except 3 participants, there was no difference in their localisation ability between test conditions) • Mean RMS error for bimodal = 39.32, which is 14.45 degrees lower than the CI alone
Morera et al. (2012)	6	Cochlear	Not mentioned	13 loudspeakers array with an inter-speaker angle of 15°	Pink noise pulse	65 dB SPL	Significant improvement in localisation ability From RMS 69.48º with CI alone to 32.87º with bimodal hearing
Jang et al. (2014)	17	All three manufactures	Not mentioned	12 loudspeakers in 360 degrees horizontal arc (placed 30 º apart)	Disyllabic words (in quiet and noisy conditions)	70 dB SPL	• For quiet condition: Bimodal condition (72º) vs. CI alone (84.1º) =small significance For noisy conditions: Bimodal condition (79.3º) vs. CI alone (77.3º)= No significant difference
Goman (2014)	12	All three manufactures	Not mentioned	Three testing settings: • 3 loudspeakers with 60° separation (-60°, 0°, and +60°) • 5 loudspeakers with 30° separation (±60°, ± 30°, and 0°) • 5 loudspeakers with 15° separation (± 30, ±15°and 0°)	Speech sentence “Hello what’s this?”	65dB SPL to 75 dB SPL	• For 60° and 30° separation: There was no significant improvement with bimodal hearing • For 15° separation: There was a significant improvement with the bimodal condition compared to CI alone

Appendix F List of countries from which professionals were invited to participate in the survey

1. Algeria	17. Costa Rica	33. Italy * **(n=1)**	49. Nigeria	65. Sri Lanka * **(n=1)**
2. Argentina	18. Czech Republic	34. Japan	50. Norway	66. Syrian Arab Republic
3. Australia* **(n=3)**	19. Denmark	35. Jordan * **(n=1)**	51. Pakistan	67. Sweden* **(n=1)**
4. Austria*(n=1)	20. Ecuador	36. Latvia	52. Panama	68. Switzerland* **(n=1)**
5. Bahamas	21. Egypt	37. Lebanon	53. Poland	69. Thailand
6. Bahrain	22. Finland * **(n=2)**	38. Lithuania	54. Portugal ***(n=1)**	70. Tunisia
7. Bangladesh * **(n=1)**	23. France * **(n=4)**	39. Kuwait * **(n=1)**	55. Republic of Moldova	71. The United States of America * **(n=6)**
8. Belarus	24. Georgia	40. Malaysia	56. Romania	72. United Kingdom * **(n=7)**
9. Belgium ***(n=2)**	25. Germany	41. Maldives	57. Russian federation	73. United Arab of Emirates
10. Bosnia Herzegovina	26. Greece	42. Magnolia	58. Saudi Arabia ***(n=13)**	74. Uruguay
11. Brazil* **(n=3)**	27. Guatemala * **(n=1)**	43. Mexico	59. Serbia	75. Yemen Republic* **(n=1)**
12. Bulgaria	28. Hong Kong	44. Morocco	60. Singapore	
13. Canada * **(n=1)**	29. Hungary * **(n=2)**	45. Netherlands * **(n=4)**	61. Slovak Republic	
14. Chile	30. Indonesia	46. Nepal	62. Slovenia	
15. China* **(n=1)**	31. Iraq	47. New Caledonia	63. South Africa * **(n=2)**	
16. Croatia	32. India * **(n=1)**	48. New Zealand	64. Spain	

Asterisk (*) indicates the responses were received from the country with number of respondents.

Appendix G Online questionnaire used for (International survey of bimodal hearing and bilateral cochlear implant service provision for adults)

Q No.	Question statement	Answer options
Section A: Participant demographic information		
1	What is your job description within your cochlear implant programme? [It is possible to give more than one answer]	• Audiologist • Head of Service • Psychologist • Speech and Language Therapist • Surgeon • Rehabilitationist • Other, please specify:____________
2	In which country do you work?	
3	Please indicate how many years of experience you have with: ○ Working with cochlear implant patients ○ Working with hearing aid patients	• Less than 1 year • 1-4 years • 5-9 years • 10-19 years • More than 20 years
Section B: Bimodal and bilateral cochlear implant service provision		
4	How is **unilateral** adult cochlear implantation funded at your programme?	• State funded • Private insurance • Self-funded (i.e., patient pays from their own money) • Other, please specify:____________

5	How is **simultaneous bilateral** adult cochlear implantation funded at your programme?	• State funded • Private insurance • Self-funded (i.e., patient pays from their own money) • Other, please specify:____________
6	How is **sequential bilateral** adult cochlear implantation funded at your programme?	• State funded • Private insurance • Self-funded (i.e., patient pays from their own money) • Other, please specify:____________
7	How many adult cochlear implant users do you have at your programme?	• 1-50 • 50-100 • 100-500 • More than 500
8	Approximately what percentage of adult cochlear implant users at your programme have: ○ A unilateral cochlear implant? (%) ○ Bilateral cochlear implants? (%)	
9	Approximately what percentage (%) of your adult unilateral cochlear implant users wear a contralateral hearing aid?	
10	Why you think adult unilateral cochlear implant users choose to wear a hearing aid in the contralateral ear after implantation? [It is possible to give more than one answer]	• Better sound quality • Improved localisation • Improved speech recognition in quiet • Improved speech recognition in noise • Greater enjoyment of music • Balanced hearing • Reduces the head shadow effect • Reduces listening effort • Other, please specify:____________
11	Why you think adult unilateral cochlear implants users choose not to wear a hearing aid in the contralateral ear after implantation? [It is possible to give more than one answer]	• The sound of the cochlear implant and hearing aid are too different to be integrated meaningfully • No longer wish to wear an earmould • Receive no benefit from a hearing aid • A hearing aid cannot be fitted for audiological or medical reasons • Additional expense

		• Other, please specify:____________
12	How is the contralateral hearing aid for adult unilateral cochlear implant users funded at your programme?	• State funded • Private insurance • Self-funded (i.e., patient pays from their own money) • Other, please specify:____________
13	Who is responsible for **fitting** the contralateral hearing aid of your adult cochlear implant users?	• The cochlear implant service • The local audiology department (government funded hospital or audiology clinic) • Private hearing aid dispenser • More than one of the above options • Other, please specify:____________
14	Is there an opportunity for fitting and balancing the hearing aid and the cochlear implant at the same time? Please explain:______________________	• Yes • No
15	Do you follow a specific protocol for introducing the hearing aid following the implantation, i.e., a specific time scale and acclimatisation process? If Yes, please provide more information:_____________________	• Yes • No
16	Who is responsible for **maintaining** the contralateral hearing aid after the initial fitting? (i.e., ear moulds, batteries, repairs)?	• The cochlear implant service • The local audiology department (government funded hospital or audiology clinic) • Private hearing aid dispenser • More than one of the above options • Other, please specify:____________
17	Who do you think should be responsible for **fitting** the contralateral hearing aid of your adult cochlear implant users?	• The cochlear implant service • The local audiology department (government funded hospital or audiology clinic) • Private hearing aid dispenser

	Please explain the reason for your answer and how the hearing aid fitting could be optimised.:_______________	• Other, please specify:____________
18	Who do you think should be responsible for **<u>maintaining</u>** the contralateral hearing aid of your adult cochlear implant users (i.e., ear moulds, batteries, repairs)? Please explain the reason for your answer:____________________	• The cochlear implant service • The local audiology department (government funded hospital or audiology clinic) • Private hearing aid dispenser • Other, please specify:____________
19	How experienced is your cochlear implant service in the field of hearing aids?	• Significant experience • Experienced • Some experience • No experience • Other, please specify:____________
20	How well informed is your cochlear implant service about updates in the field of hearing aids?	• Well informed • Informed • Not informed • Other, please specify:____________
Section C: Integrated bimodal technology service provision		
21	Which company's cochlear implants do you use at your service?	• Advanced Bionics • Cochlear • MED-EL • Oticon Medical • Nurotron • Other, please specify:____________
22	Do any of your adult Advanced Bionics unilateral cochlear implant users have the new Naida Link hearing aid or Naida Link CROS technology? If Yes, approximately what percentage are using the following technology: ○ Naida Link Bimodal hearing aid (%) ○ Naida Link CROS (%)	• Yes • No

23	Does the new Naida Link hearing aid offer more benefit than standard hearing aids?	• Yes • No • Don't know
	<u>If Yes</u>, what are the benefits? [It is possible to give more than one answer]	• Improved speech recognition in quiet • Improved speech recognition in noise • Improved localisation • Improved ability to tracking of moving sounds • Greater enjoyment of music • Improved telephone use • Reduced level of stress about getting a good seat at dinner, meetings or in a car • Comfort sitting between people in a conversation • Other
	<u>If No</u>, please explain why?___________	
24	Does the new Naida Link CROS technology offer more benefit than standard CROS technology?	• Yes • No • Don't know

	<u>If Yes</u>, what are the benefits? [It is possible to give more than one answer]	• Improved speech recognition in quiet • Improved speech recognition in noise • Improved localisation • Improved ability to tracking of moving sounds • Greater enjoyment of music • Improved telephone use • Reduced level of stress about getting a good seat at dinner, meetings or in a car • Comfort sitting between people in a conversation • Other
	<u>If No</u>, please explain why?___________	
25	Any other comments you wish to make?	

Appendix H Summary of the changes made based on validation stages of the questionnaire

	Summary of the changes made
Stage 1	• use a pull-down menu with a list of common job titles as well as an "other" • use a pull-down menu with a list of countries as well as an "other" • use a pull-down menu for questions 3 and 6 • add a comment box for some questions • ask about sequential and simultaneous bilateral CI in separate questions • add question about hearing aid funding • add a question to ask about any mechanism for adjusting the hearing aid and implant together • add question asking about training on hearing aid fitting and how well informed are the implant audiologists about updates • add further option for the question asked about the benefit of HA for unilateral CI: (balanced hearing) • split the question ask about the fitting and maintain HA into separate questions • add question about using any a special protocol for introducing the HA following implantation and with comment box to explain on they believe hearing aid fitting could be optimised • add a question about either a total number of AB adult users to quantify or to ask for a percentage figure • add further option for the question asked about the benefit of Naida Link HA and CROS 'improvement in quiet' to the options list
Stage 2	• add other options e.g., Rehabilitationist for question asked about Job description • change the wording from 'fitting' cochlear implants to 'working with cochlear implant' in question 3 • specify national and local funding to state funding • explain the terms of 'unilateral', 'bilateral', 'simultaneous bilateral' • allow multi-select answers • used word (overall) to ask about CI service experiences and well-informed with recent technology to avoid the individual difference within the teams • split the question for the Naida Link HA and CROS into two separate questions • adding word 'approximately' in questions 8,9, and 22

Appendix I Invitation email

Dear Head of Service/ Cochlear implant colleague,

This is an invitation to take part in an international survey looking at bimodal technology outcomes in adult cochlear implant users around the world using an online survey that takes just 5-10 minutes to complete.

This project forms part of my PhD in Faculty of Engineering and the Environment at the University of Southampton under the supervision of *Dr. Nicci Campbell* (Associate Professor/Principal Audiological Scientist) and *Dr. Daniel Rowan* (Associate Professor Audiology).

The purpose of this international survey is to gauge contralateral hearing aid use in adult cochlear implants users around the world. The information will offer an insight into the current practice. Further details are available in the attached ***Participant Information Sheet***.

The research has been approved by the University of Southampton Ethics Board (ID: 40048) and complies with the Data Protection Act 1988. All responses to the survey are anonymous and treated as confidential. In line with the new GDPR regulations that came into force in May 2018 we also attach the from the University of Southampton's ***Privacy Notice for Research Participants*.**

We would most grateful if you or an appropriate member of staff would be willing to complete this survey. You can access the survey via the following link:

https://isurvey.soton.ac.uk/28119

We would be happy to make the findings available to you upon completion of the project.

Thank you.

Yours sincerely,

Manal Alfakhri

Postgraduate research (PhD) student , *University of Southampton*

mna1g13@soton.ac.uk

***Nicci Campbell*, PhD (Research supervisor)**

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Appendix J Hearing Health Screening Questionnaire

UNIVERSITY OF Southampton

Participant Hearing Health Screening Questionnaire Sheet

Study Title: The performance of normal hearing adults on real-life listening tests using the AB-York Crescent of Sound

Researcher: Manal Alfakhri **ERGO number:** 46618

Participant code number: ....

Participant date of birth: ....

Participant sex: ....

Please fill in the following questionnaire to determine your eligibility for this experiment. (Please select as appropriate).

1. Do you have a known hearing impairment YES/ NO
2. Have you had any recent ear pain, infections, discharge or bleeding? YES/NO
3. Do you experience tinnitus (ringing, buzzing, whistling sounds in your ears)? YES/NO
4. Do you suffer from sensitivity to loud sounds (hyperacusis)? YES/NO
5. Have you been exposed to any loud sounds over the past 24 hours? YES/NO
6. Is English your native language? YES/NO

Signature of participant..

Date..

[31/01/2019] [Version 1] [Ethics reference *(46618)*]

Appendix K Modifications made to the SSQ questionnaire for the current study (Naida Link bimodal group)

Question No.	Subscale	Modification	Justification
14	speech subscale	The question was modified to 'You are listening to someone on the telephone and someone next to you starts talking. Can you follow what's being said on the phone?' instead of 'being said by both speakers'	To assess the telephone use
15	qualities subscale	The question was removed	It does not apply to bimodal CI users
16	qualities subscale	3. Re-labelled as question 15 4. The question was re-formulated from 'When you are the driver in a car can you easily hear what someone is saying who is sitting alongside you?' to 'When you are driving in a car can you easily hear what someone is saying on the side opposite to your cochlear implant?'	To make clearer
17	qualities subscale	3. Re-labelled as question 16 4. The question was re-formulated from 'When you are a passenger can you easily hear what the driver is saying sitting alongside you?' to 'When you are driving in a car can you easily hear what someone is saying on the same side as your cochlear implant?'	To make clearer

Appendix L Telephone-Use questionnaire

No. of question	Question statement	Answer options
1	How often do you use your mobile phone/telephone?	• Every day • 3-4 times in the week • Time to time (a couple of times in a year) • Never • Other: ………
2	How confident are you in using a telephone the 'standard' way, i.e., relying on hearing only?	• Not confident at all • Somewhat confident • Confident • Very confident
3	To whom do you speak when using the telephone using the 'standard' way, i.e., relying on hearing only?	• Familiar people • Unfamiliar people
4	How do you use the telephone?	• Rely on your hearing only (the standard way) • Rely on both hearing and seeing the face of speaker e.g. Skype or WhatsApp call etc • Text messages (Preferred method:____)
5	What telephone do you prefer to use? (if applicable):	
6	Do you use any special features, programs, or any accessories ex. Bluetooth, ComPilot, DuoPhone, etc.	• Yes • No • If yes, please specify:
7	Would you be interested in attending a telephone-training workshop at USAIS?	• Yes • No

Appendix M The SRTs for Naida Link bimodal participants in for SrN±60°, S0°N±60° and SHANCI tests

Participant	SrN±60°		S0°N±60°			SHANCI		
	CI only	CI + Naida Link HA	CI only	CI + Naida Link HA	CI + Naida Link HA + StereoZoom	CI only	CI + Naida Link HA	CI + Naida Link HA + ZoomControl
Naida1	14	9.3	19.6	10.6	16	21.3	13	3.6
Naida2	8	12	9	7	8.3	18.6	11.3	6.6
Naida3	17.3	11	19	10	11.6	13.3	12	1.6
Naida4	6.3	6.3	6	7	3	11.6	11.6	1
Naida5	11	6.3	9	7	5.3	8.3	7.6	2
Naida6	7.6	7	6	5.6	1.3	9.3	5	-3.3
Naida7	7.6	11	8	8.6	5	15	8.3	6.6
Naida8	9	8.3	16.6	10.3	10	12.3	3.6	2.3
Naida9	10.3	4.3	10.7	7.7	5	20.3	12	2.7
Naida10	11	9	11.3	9	9.3	8.3	9.7	7.7
Naida 11	5.7	2.3	5	3	3.6	7.3	5.3	3

Naida12	14	10.7	11.7	8.7	5	23	13	8
Naida13	12.6	12.3	16.3	17.7	9.7	21	15	9.7
Naida14	7.7	7.7	10.7	8.3	7.3	8.3	12.7	1.7
Naida15	12.6	9	10.7	8	10.7	26.7	10.7	3
Naida16	6.3	6.3	5	5	5.3	12.7	3.7	3.7
Naida 17	8.2	7.6	6	6	3.6	10.7	11	2.7
Naida 18	6.3	5	5	4.3	3.6	11.6	9	3.6
Naida 19	10.3	8	7	6.3	5	14	15	2.7
Naida 20	12.6	10.7	8	8	9.3	18.6	13	7.7
Naida 21	5.7	6.3	5	5	1.3	8.3	10.7	3
Naida 22	12.6	15	9	7	5	17.7	11.6	7.7
Naida 23	6.3	5	5	3.6	3	9.3	8.3	3.6
Naida 24	5.7	5	4	3.6	1.3	8.3	11.6	6.6
Naida 25	7.7	6.3	5	5	3.6	8.3	7.6	2.3
Naida 26	9	8.3	6	7.7	6	13.3	13	5.7

Appendix N Results of correlation analyses, r values (95% confidence interval), between the unaided thresholds of non-implanted and the performances scores when using the Naida Link HA

Performance test	PTA (500-1000-2000 Hz)	PTA (250-500 Hz)	1000Hz	500Hz	250 Hz
Average speech tests with best aided condition	-0.1 (-0.4 to 0.3)	-0.1 (-0.5 to 0.3)	-0.1 (-0.5 to 0.3)	-0.1 (-0.5 to 0.3)	-0.1 (-0.5 to 0.3)
Average spatial tests	-0.1 (-0.5 to 0.3)	0.2 (-0.2 to 0.5)	-0.2 (-0.5 to 0.2)	0.1 (-0.3 to 0.4)	0.3 (-0.1 to 0.6)
Average telephone tests with best aided condition	0.1 (-0.3 to 0.5)	0.1 (-0.3 to 0.4)	0.2 (-0.2 to 0.5)	0.2 (-0.2 to 0.5)	-0.1 (-0.4 to 0.3)
SSQ overall*	0.1 (-0.3 to 0.5)	0.4 (-0.1 to 0.7)	0.1 (-0.3 to 0.5)	0.4 (-0.01 to 0.7)	0.3 (-0.1 to 0.6)

*n=24

Appendix O The modifications that have been done on the SSQ questionnaire for the current study (Bilateral CI group)

Question No.	Subscale	Modification	Justification
14	speech subscale	The question is modified to 'You are listening to someone on the telephone and someone next to you starts talking. Can you follow what's being said <u>on the phone</u>?' instead of 'being said <u>by both speakers'</u>	To assess the telephone use
16	qualities subscale	The question was re-formulated from 'When you are the driver in a car can you easily hear what someone is saying who is sitting alongside you?' to 'When you are driving in a car can you easily hear what someone is saying on the side opposite to your cochlear implant?'	To make clearer
17	qualities subscale	The question was re-formulated from 'When you are a passenger can you easily hear what the driver is saying sitting alongside you?' to 'When you are driving in a car can you easily hear what someone is saying on the same side as your cochlear implant?'	To make clearer

Appendix P Simultaneous vs. sequential bilateral CI

The bilateral CI participants have been divided into two subgroups depending on the time they received the second implant into: (1) simultaneous and (2) sequential. The statistical analysis has been carried out to examine whether there is any statistically significant difference between the two subgroups on the 'real life' test battery. Five participants have received simultaneous bilateral implantation while 8 participants had sequential implantation. The remaining three participants were excluded from the analysis due to the messy pattern in getting the bilateral implants (BiCI3, BiCI7 and BiCI14).

Speech in noise

Shapiro-Wilk test has been applied to assess the distribution of the data sets included in the analysis. Half of the datasets were not normally distributed ($p < 0.05$). However, A parametric statistical test was used because it is robust to non-normality (Maxwell and Delaney, 2004, Rasch and Guiard, 2004). Two-way mixed ANOVA has been used with the subgroup as the between-subject factor and the listening condition as the within-subject factor.

In the SrN±60° test, there were no outliers, as assessed by examination of studentized residuals for values greater than ±3. The assumption of homogeneity of variances was violated ($p < .05$) as assessed by Levene's test. There was homogeneity of covariances, as assessed by Box's test of equality of covariance matrices ($p = .34$). Mauchly's test of sphericity was not applied as the listening conditions have only two levels. There was no statistically significant interaction between the subgroup and the listening conditions, $F (1, 11) = .79$, $p = .39$, partial $\eta 2 = .07$. The main effect of the subgroup did not show any statistically significant difference between the simultaneous and sequential subgroups on the SrN±60° test, $F (1, 11) = 1.04$, $p=.33$, partial $\eta 2 = .07$. The main effect of the listening conditions showed that the bilateral condition was statistically significantly better than one CI condition by 1.67 dB, $F (1, 11) = 11.1$, $p=0.007$, partial $\eta 2 = .5$.

In S0°N±60° tests, there were no outliers, as assessed by examination of studentized residuals for values greater than ±3. There was homogeneity of variances ($p > .05$) and covariances ($p =.56$), as assessed by Levene's test of homogeneity of variances and Box's test of equality of covariance matrices, respectively. Mauchly's test of sphericity was not applied as the listening conditions have only two levels. There was no statistically significant interaction between the subgroup and the listening conditions, $F (1, 11) = .002$, $p = .97$ partial $\eta 2 = .00$. The main effect of the subgroup did not show any statistically significant difference between the simultaneous and sequential subgroups on the SrN±60° test, $F (1, 11) = .46$, $p=.511$, partial $\eta 2 = .04$. The main effect of the listening conditions showed that the bilateral condition was statistically significantly better than one CI condition by 2.5 dB, $F(1, 11) = 15.56$, $p=0.002$, partial $\eta 2 = .59$.

Spatial- listening tests

Localisation and tracking scores were normally distributed, as assessed by the Shapiro-Wilk test and by Normal Q-Q Plot. Two-way mixed ANOVA has been conducted with the subgroup as the between-subject factor and the listening condition as the within-subject factor.

For the localisation test, there were no outliers, as assessed by examination of studentized residuals for values greater than ±3. There was homogeneity of variances ($p > .05$) and covariances ($p =.113$), as assessed by Levene's test of homogeneity of variances and Box's test of equality of covariance matrices, respectively. Mauchly's test of sphericity was not applied as the listening conditions have only two levels. There was no statistically significant interaction between the subgroup and the listening conditions, $F(1, 11) = .125$, $p = .73$, partial $\eta 2 = .011$. The main effect of the subgroup did not show any statistically significant difference between the simultaneous and sequential subgroups on the localisation test, $F(1, 11) = .15$, $p=.71$, partial $\eta 2 = .013$. The main effect of the listening conditions showed that the bilateral condition was statistically significantly better than one CI condition by 45.6%, $F(1, 11) = 49.15$, $p<0.001$, partial $\eta 2 = .82$.

Similarly, there were no outliers, as assessed by examination of studentized residuals for values greater than ±3 in the tracking test. There was homogeneity of variances ($p > .05$) only for the listening condition of using one CI as assessed by Levene's test of homogeneity of variances. Box's test of equality of covariance matrices showed that there was homogeneity of covariances ($p =.22$). Mauchly's test of sphericity was not applied as the listening conditions have only two levels. There was no statistically significant interaction between the subgroup and the listening conditions on the tracking test, $F(1, 11) = 1.82$, $p = .20$, partial $\eta 2 = .14$. The main effect of the subgroup did not show any statistically significant difference between the simultaneous and sequential subgroups, $F(1, 11) = .71$, $p=.42$, partial $\eta 2 = .061$. The main effect of the listening conditions showed that the bilateral condition was statistically significantly better than one CI condition by 54.16%, $F(1, 11) = 47.66$, $p<0.001$, partial $\eta 2 = .81$.

Telephone test

Telephone test in quiet has been administered only with the condition of using one CI. Both data sets (simultaneous and sequential subgroup) were not normally distributed as assessed by Shapiro-Wilk's test ($p < .05$). Therefore, a Mann-Whitney U test was run to assess whether there is a statistically significant difference between the two subgroups. Distributions of the scores for both subgroups were similar as assessed by visual inspection. Median score for simultaneous (96.7%) and sequential (98.35%) was not statistically significantly different, U = 18.5, z = -.24, p = .81. Additionally, an independent-samples t-test has been used since the test is robust for normality violations. In the line with a Mann-Whitney U test's finding, independent-samples t-test revealed no statistically significant difference between the two subgroups in telephone test in quiet, t(11)=-0.25,p=0.8. The mean difference between the two subgroups was only .87% (95% confidence interval, -8.7 to 6.9).

For the telephone test in noise, only 4 participants with simultaneous CIs and 7 participants with sequential CIs were included in the analysis. The two participants were excluded due to missing data (the test was not administered for them). All the data sets were normally distributed, as assessed by Normal Q-Q Plot and Shapiro-Wilk test (p>0.05). Two-way mixed ANOVA has been conducted with the subgroup as the between-subject factor and the listening condition as the within-subject factor to assess the difference between the two subgroups. There were no outliers, as assessed by examination of studentized residuals for values greater than ±3. There was homogeneity of variances (p > .05) only for the listening condition of using one CI as assessed by Levene's test of homogeneity of variances. Box's test of equality of covariance matrices showed that there was homogeneity of covariances (p =.14). Mauchly's test of sphericity was not applied as the listening conditions have only two levels. There was a statistically significant interaction between the subgroup and the listening condition, F (1, 9) = 8.04, p = .020, partial η2 = .47. Therefore, the simple main effect of the listening conditions and the subgroup groups have been assessed. The simple main effect of the listening condition showed there was no statistically significant difference between the two subgroups, F (1, 9) = .10, p=.75, partial η2 = .009 on the unilateral condition. However, it showed that there was a statistically significant difference between the two subgroups on the bilateral condition, F (1, 11) = 10.47, p=.01, partial η2 = .84. The sequential subgroup was better than the simultaneous subgroup by 36.8%. Simple main effect of subgroup showed there was no statistically significant difference between the two listening conditions for the simultaneous subgroup (F (1, 3) = 7.4, p=.07, partial η2 = .71) and for sequential subgroup (F (1, 6) = .03, p=.88, partial η2 = .004). It should be noted that the telephone has been run using the standard map without using any special feature.

List of References

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