Speech-recognition-in-noise Performance of Prelingually-Deafened Mandarin-speaking Children with Bilaterally Fitted Hearing Aids, and Those with Bimodally Fitted Cochlear Implants and Hearing Aids in Contralateral Ears

by

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Statement of Originality

I, QIU, Xin Yue, hereby declare that I am the sole author of this thesis and that the material presented herein is my original work, except as indicated in the Acknowledgement. I Furthermore declare that I have followed the university's policies and regulations on academic honesty, copyright, and plagiarism in writing this thesis, and no material presented herein has been submitted to attain a degree at this or any other university.

Abstract

This study investigated the binaural benefits and spatial release from masking of group and intra-participant comparisons in Mandarin Chinese-speaking preschool children with binaural hearing aids and bimodal fitting cochlear implants, and explored the relationship between hearing audibility and speech-recognition-in-noise performance. Participants (2.9-7.5 years) were tested using the Mandarin Spoken Word-Picture IDentification Test (Adaptive version) to yield the adaptive signal-to-noise ratio for a 50% correct score as the outcome measure. The speech stimuli were presented from the 0° azimuth, and the noise was presented from the 0, +90, and −90° azimuths. Furthermore, the participants were tested under monaural- and binaural-aided hearing conditions. The participants with a binaural-fitted hearing aid significantly benefited from binaural redundancy, head-shadow and achieved a significant spatial release from masking with a monaural left hearing aid when the noise moved from the front to the right. In contrast, the participants with a bimodal-fitted hearing aid significantly benefited from binaural redundancy, binaural squelch, and head-shadow and achieved a significant spatial release from masking with a monaural cochlear implant and a bimodal-fitted hearing aid when the noise moved from the front to the hearing-aid side. Although the speech intelligibility index obtained from the monaural hearing aids could predict the speech-recognition-in-noise performance of the participants with the monaural-fitted hearing aid, the same obtained from the monaural cochlear implants could not predict the speech-recognition-in-noise performance of the participants with the monaural-fitted cochlear implant. The Mandarin Spoken Word-Picture IDentification Test (Adaptive version) is a powerful and efficient tool for assessing the speech-recognition-in-noise performance of children in clinical settings and binaural-aided hearing is important for obtaining binaural and spatial benefits that could maximise the potential speech-recognition-in-noise performance of children with bilateral hearing loss.

Keywords: speech recognition in noise, binaural benefit, spatial release from masking, hearing aid, cochlear implant

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List of Abbreviations

AGC	automatic gain control
AI	Articulation Index
BR	binaural redundancy
BR-HAcon	binaural redundancy after adding a hearing aid on contralateral ear with an existing monaural cochlear implant fitting
BR-HAL	binaural redundancy after adding a hearing aid on the left ear
BR-HAR	binaural redundancy after adding a hearing aid on the right ear
CI	cochlear implant
CICI	binaural cochlear implants fitting
CIHA	bimodal fitting
CPP	cocktail-party problem
DA	device advantage
DA-CI	device advantage of the ear with the cochlear implant
DA-HAcon	device advantage of the ear with the addition of a hearing aid contralateral to the cochlear implant
DA-HAL	device advantage of the hearing aid on the left ear
DA-HAR	device advantage of the hearing aid on the right ear
dB	decibels
dB HL	decibels in hearing level
dB SNR	decibels in signal-to-noise ratio level
dB SPL	decibels in sound-pressure level

DHL	disabling hearing loss
F0	fundamental frequency
FCI	noise source is moved from the front to the cochlear implant side
FCI-CI	spatial release from masking of the participant with monaural cochlear implant fitting when the noise source is moved from the front to cochlear implant side
FCI-CIHA	spatial release from masking of the participant with bimodal fitting when the noise source is moved from the front to the cochlear implant side
FHA	noise source is moved from the front to the hearing aid side
FHA-CI	spatial release from masking of the participant with monaural cochlear implant fitting when the noise source is moved from the front to the hearing aid side
FHA-CIHA	spatial release from masking of the participant with bimodal fitting when the noise source is moved from the front to the hearing aid side
FL	noise source is moved from the front to the left side
FL-HAHA	spatial release from masking of the participant fitted with binaural hearing aids when the noise source is moved from the front to the left side
FL-HAL	spatial release from masking of the participant with a hearing aid on the left ear when the noise source is moved from the front to the left side
FL-HAR	spatial release from masking of the participant with a hearing aid on the right ear when the noise source is moved from the front to the left side

FM	frequency modulation
FR	noise source is moved from the front to the right side
FR-HAHA	spatial release from masking of the participant with binaural hearing aid fitting when the noise source is moved from the front to the right side
FR-HAL	spatial release from masking of the participant with a hearing aid on the left ear when the noise source is moved from the front to the right side
FR-HAR	spatial release from masking of the participant with a hearing aid on the right ear when the noise source is moved from the front to the right side
HA	hearing aid
HAHA	binaural-fitted hearing aids
HAL	monaural-fitted HA on the left ear
HAR	monaural-fitted HA on the right ear
HAT	hearing assistance technology
HS	head-shadow effect
HS-HAcon	head-shadow effect of adding hearing aid on contralateral ear in a monaural cochlear implant fitting
HS-HAL	head-shadow effect of adding a hearing aid on the left ear
HS-HAR	head-shadow effect of adding a hearing aid on the right ear
ILD	interaural level differences
ITD	interaural time differences
NCI	speech is presented from the front and noise is presented at 90° azimuth from the cochlear implant side

NCO	speech presented from the front and noise contralateral to the ear with the monaural hearing aid
NF	both speech and noise are presented from the front
NH	normal hearing
NHA	speech is presented from the front and noise is presented at 90° azimuth from the hearing aid side
NIP	speech presented from the front and noise ipsilateral to the monaural HA ear
NL	speech is presented from the front and noise is presented at -90° azimuth on the left
NR	speech is presented from the front and noise is presented at +90° azimuth on the right
NS	speech is presented from front and noise is presented at 90° azimuth from one side
NS60	speech is presented from the front and noise is presented at 60° azimuth from the cochlear implant side, and speech is presented at 60° azimuth from the hearing aid side
QuickSIN	quick speech-in-noise test
RAU	rationalised arcsine unites
RMS	root mean square
SDT	speech detection threshold
SII	speech intelligibility index
SL	sensation level
SNHL	sensorineural hearing loss
SNR	signal-to-noise ratio

SNR50	accurate identification of 50% of speech in noise
SQ	binaural squelch
SQ-HAcon	binaural squelch after adding hearing aid on contralateral ear in addition to monaural cochlear implant fitting
SQ-HAL	binaural squelch after adding a hearing aid on the left ear
SQ-HAR	binaural squelch after adding a hearing aid on the right ear
SRiN	speech recognition in noise
SRM	spatial release from masking
SRS	speech recognition score
SRT	speech recognition threshold
TF	transfer function
WDRC	wide dynamic range compression
WHO	World Health Organisation

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Chapter 1: Introduction

1.1 Scopes of This Research

1.1.1 Hearing Loss and Compensation

Hearing loss is a worldwide health issue. According to a report by the World Health Organisation (WHO) in 2020, approximately 466 million people worldwide—6.1% of the world population—have disabling hearing loss (DHL) (i.e. hearing loss > 40 dB in the better-hearing ear in adults or > 30 dB in the better-hearing ear in children), including 34 million children (WHO, 2020). In China, the Second National Sample Survey on Disability in 2006 reported that over 27.8 million people were suffering from DHL, including over half-a-million children, and approximately 20 to 30 thousand neonates in China are born with hearing loss each year (China Disabled Persons' Federation, 2006). Another recent survey in 2016 reported that the number of people with hearing loss, and those who suffer from moderate or severe hearing loss in China were over 200 and 60 million, respectively, and the prevalence of all hearing loss, and moderate or severe hearing loss were 15.84 and 5.17%, respectively (Hu, Xiang Yang et al., 2016). In 2018, the WHO (WHO, 2018) estimated that the number of people with DHL in East Asia, including China, the Hong Kong Special Administrative Region (SAR) (China), Macau SAR (China), and the Democratic People's Republic of Korea was 100 million, which was higher than any of the other regions in the world except for the South Asia Region (131 million). However, the prevalence of DHL in East Asia was lower than those in Central/Eastern Europe and Central Asia, South Asia, and the Asia Pacific.

Hearing loss broadly and profoundly impacts people's quality of life, delays the development of spoken language, reduces communication ability and academic performance, and leads to social isolation (WHO, 2020). However, hearing loss can be partially compensated for by utilising hearing prostheses such as hearing aids (HA), cochlear implants (CIs), and other assistive devices.

HAs can amplify acoustic signals and enhance auditory input for people with hearing loss and HA fitting is one of the most well-established methods for treating patients with mild to severe hearing loss (Browning et al., 2017; Dillon, 2001). However, for individuals with severe to profound sensorineural hearing loss, cochlear implants (CIs) have proven effective for rehabilitating the hearing and speech abilities of patients who cannot benefit sufficiently from HAs (Ching et al., 2004; Eisenberg et al., 2006; Gantz et al., 2005; Schafer & Thibodeau, 2006). CIs translate acoustic sounds into electric pulses, which directly stimulate the auditory nerves (Loizou, 1999; Moore, J. A. & Teagle, 2002). In 2014, approximately 400,000 people worldwide had received CIs including 200,000 children, and 60,000 people had received bilateral CIs in 2014 (i.e. bilateral recipients) (Zeng et al., 2015). Since 1995, there has been more than 10,000 CI recipients in China, in which 85% of them were children younger than 7 years old (CDPF, 2006). Up to 2006, there were more than 100,000 children younger than 6 years old have received CI, showing an average annual growth rate of 25%. The price of CI devices from the CI manufactures, such as Cochlear Limited, Medical Electronics, and Advanced Bionics in China ranges from $25, 000 to $46, 000 US; thus, the high cost has always discouraged cochlear implantation. Therefore, the Chinese government launched several funding programs in 2009. In addition, private donations, charities, and local government assistance projects have improved the affordability of CIs, which has resulted in more patients receiving them. Thus, CIs are a fairly common intervention for people experiencing hearing loss in China (Li, J. N. et al., 2017; Liang, Q. & Mason, 2013).

1.1.2 Speech Recognition Ability

Receiving and recognising speech signal are the most important auditory functions for human beings. If clinicians have to choose only one measurement to assess auditory function, it should be a speech audiometry test (Mueller & Hall, 1998), which is defined as a testing procedure using speech signal as stimuli to assess the functional hearing abilities for incoming speech information (Bamford & Bench, 1979; Konkle & Rintelmann, 1983). Although a regular pure-tone audiometry test can assess the sound detection threshold at different frequencies, it cannot evaluate the speech recognition ability of an individual. Speech audiometry tests measured in a quiet environment cannot predict abilities or evaluate speech-recognition handicaps in people showing hearing loss in everyday communication (Houtgast & Festen, 2008; Vermiglio et al., 2012; Xi, 2012; Xi, 2013).

In daily life, individuals typically struggle to recognize speech information in noisy environments such as crowded restaurants. Difficulty understanding speech in noisy environments is also a frequent complaint from individuals with hearing loss, and they encounter greater difficulties than their peers with normal hearing (NH) (Caldwell & Nittrouer, 2013; Smits et al., 2013; Zeng & Galvin III, 1999). However, children inevitably learn in adverse listening environments in educational settings, such as frolicking sound from students, reverberation in the classroom, and long communicative distances between the speaker and listener (e.g. teacher and child). Compared to children with NH, children with hearing loss face more educational and academic difficulties in noisy listening environments

(Bess et al., 1998; Goldsworthy Raymond & Markle Kali, 2019; Klatte et al., 2010). Therefore, some researchers have emphasised that the difficulties the hearing-loss population faces in understanding speech in noisy environments should be directly quantified (Carhart & Tillman, 1970; Killion & Niquette, 2000). Subsequently, many audiologists and clinical protocols have incorporated speech audiometry testing in noise into routine evaluations for children and adults with hearing loss (Luxford, 2001; Nilsson et al., 1996; Uhler et al., 2017). Speech-audiometry testing in noise is necessary to determine the speech-hearing functions of people with hearing loss, and the results of such tests can provide important clinical information for determining the hearing-device settings, goals of auditory-verbal rehabilitation plans, and communication methods or modes for education (McArdle & Wilson, 2009).

1.1.3 Binaural-Aided Hearing

Binaural-aided hearing has been suggested for people with bilateral hearing loss to improve speech understanding in noisy environments (Ching et al., 2005; Dillon, 2001; Sammeth et al., 2011). Considering binaural stimulation, a bilateral hearing aid (HAHA) is a standard clinical device used to help people with mild to severe bilateral hearing loss (Ahlstrom et al., 2009; Potts et al., 2009). CI recipients with severe to profound bilateral hearing loss have two potentially beneficial options: using a CI in one ear and an HA on the contralateral non-implanted ear (bimodal fitting, CIHA) or using a CI on each ear (binaural cochlear implant fitting, CICI) (Basura et al., 2009; Ching et al., 2007; Offeciers et al., 2005). However, although patients with severe to profound hearing loss qualify for binaural CI fitting, CI is traditionally implemented as a unilateral fitting, especially in regions with limited insurance coverage by government programs (Nilakantan et al., 2018). For example, the financial aid policy in China only provides a single CI for each child with binaural severe to profound sensorineural hearing loss (SNHL) once in their lifetime (Program office of China Rehabilitation Research Center for Hearing and Speech impairment, 2012); thus, CI recipients in China typically use only monaural CI or bimodal fittings. In addition to economic pressures, medical and surgical risks in the second implantation surgery could hinder patients from receiving CICI fittings (Basura et al., 2009; Potts et al., 2009). For example, CI on both ears simultaneously can increase the anaesthetic time and potential blood loss, and double-sided surgery results in two surgical wounds, thereby posing higher risk of injury or damage to the temporal bone and related structures. Moreover, the current CI method is invasive and usually damages the residual acoustic hearing. Thus, the second CI may not be recommended for individuals with considerable residual hearing remaining in the non-implanted ear. Another disadvantage of implanting the second CI is the failure to maintain some degree of functional hearing in the non-implanted ear for future potential therapies including advanced applications, residual hearing-preserving CIs, and biological hair-cell regeneration. In such cases, bimodal CIHA fitting is a more viable, affordable, and less invasive approach for unilateral CI recipients compared to a second CI implantation (Basura et al., 2009; Potts et al., 2009).

1.2 Aims of This Research

The above backgrounds introduced the importance of the speech-in-noise test and explained the bilateral fitting for individuals with hearing loss in clinical practice. However, the effects of binaural hearing condition on the hearing and speech recognition ability for the patients with hearing loss are not clear. For example, the speech recognition in noise (SRiN) performance of young Mandarin Chinese-speaking children with hearing loss using binaural hearing prostheses is not clear. Therefore, the present study aimed to provide more empirical evidence of SRiN performance in young Mandarin Chinese-speaking children with hearing loss, which can help clinicians and families to have a glimpse of their listening to noise abilities in everyday life. Furthermore, it is also important to validate if there are any binaural benefits on the SRiN performance listening in binaural hearing condition when compared to the monaural hearing condition. The outcomes can justify the fitting method for children with hearing loss. The comparative SRiN performance of binaural hearing condition versus monaural hearing condition can provide evidence for parents to consider the necessity of binaural hearing condition in the rehabilitation and educational development of their children. The outcomes can guide future clinical practice on the optimal mode of hearing prosthesis fitting for maximising the potential benefits on the SRiN performance of children with hearing loss. The specific aims of the present study were as follows:

1. To investigate SRiN performance in different noise directions of Mandarin Chinese-speaking young children with hearing loss using HAHA or CIHA fittings.
2. To quantify differences in SRiN performance of children listening in binaural hearing condition versus monaural hearing condition.
3. To explore the relationship between aided hearing audibility (aided SII) and SRiN performance.

1.3 Significance of This Research

Patients with hearing loss usually encounter difficulties in understanding speech signal in noise. This problem can be a significant challenge for children with hearing loss because they are often in situations at school or in everyday life wherein there is noise and the signal-to-noise ratio (SNR) is poor (Mok et al., 2007). The present study investigated the SRiN performance of young children with hearing loss at the age of 3–6, because these children were receiving the intervention of fitting hearing prostheses and were at a critical stage of hearing, speech, and language rehabilitation. To develop hearing, speech, and language abilities, children with hearing loss need to receive clear instructions from their teachers and recognize them accurately, even in noisy educational environments. Speech recognition ability is related to the speech, language, and educational development (van Wieringen, Boudewyns, Sangen, Wouters, & Desloovere, 2019; Yoshinaga-Itano, 2003; Yoshinaga-Itano, Baca, & Sedey, 2010). Therefore, it is important to improve the SRiN performance of young children with hearing loss for positive rehabilitation outcomes and long-term academic performance. The present study aimed to examine the binaural benefits of binaural-aided hearing on the SRiN performance of young children. Comparative performance studies between binaural and monaural hearing condition can help parents understand the effect of binaural hearing condition on children's rehabilitation and educational development. A comparison study of the SRiN performance was conducted under two different noise conditions—speech and noise co-located condition and speech and noise spatially separated condition. By evaluating if there are any spatial benefits on the SRiN performance, the present study can investigate the development of spatial release from masking (SRM) in young children with hearing loss, and the components that yield SRM. The findings from the exhaustive measurements on young children with the different device fitting conditions in different noise directions can support future clinical counseling on the optimal fitting mode of hearing prostheses for maximizing the SRiN performance of children with hearing loss.

1.4 Structure of This Thesis

This thesis consists of five chapters, including this introduction. This chapter ends with a brief description of the rest of the chapters. Chapter 2 reviews the literature on speech audiometry tests, binaural hearing, and the speech-recognition-in-noise (SRiN) performance of individuals with hearing loss. Furthermore, the factors affecting SRiN performance are reviewed. Chapter 3 is the method section of the present study, which evaluates the hearing ability and SRiN performance of children with HAHA- or CIHA-fitted devices. Chapter 4 presents the results of the hearing ability and SRiN performance of the participants in the present study, and Chapter 5 discusses the study findings, limitations, and potential directions for further research as well as the conclusions.

Chapter 2: Literature Review

2.1 Speech Audiometry Test

2.1.1 Tests under Quiet and Noisy Conditions

The use of speech stimuli, such as lists of words or sentences, for auditory assessment (called 'speech audiometry tests'), has a long history in the evaluation of speech-hearing ability (Bamford & Bench, 1979; Katz, 2002). There are no definite answers when it comes to the best type of material for speech audiometry because there are pros and cons of using either words or sentences as materials (Ricketts et al., 2017; Wilson & McArdle, 2008). For example, sentences are more valid and are like listening to everyday conversation, and words lack lexical, semantic, and syntactic redundancies. In contrast, context cues within sentences, the syntactic and semantic structure of sentences, and sentence length could influence the performance, which leads to difficulty in determining the basic auditory function. Although it is difficult to completely separate hearing, linguistic, and cognitive skills in speech audiometry tests, they primarily aim to assess hearing (Bamford & Bench, 1979). Thus, it is important to select materials within the linguistic ability of the participants whose hearing ability is being tested. To minimise the effect of linguistic competence, the target words should be within the vocabulary of the individual. Similarly, if the speech material is a sentence, the grammar should be within the grammatical ability of the listener, while the length should be within the working memory span of the individual (Bamford & Bench, 1979; Howes, 1957). If these requirements are not met, the speech audiometry test results could be confounded by factors other than those associated primarily with hearing loss.

The speech detection threshold (SDT) and speech recognition threshold (SRT) are typically used in speech audiometry testing under quiet conditions (American Speech-Language-

Hearing Association, 1988). SDT is the minimum hearing level at which people can detect speech 50% of the time and is reported in decibels in hearing level (dB HL) or decibels in sound-pressure level (dB SPL), while SRT is the minimum hearing level at which people can correctly recognize speech 50% of the time and is reported in dB HL or dB SPL. In clinical practice, a typical suprathreshold measurement under quiet conditions is the speech recognition score (SRS) or word recognition score (WRS), which is the percentage of correctly recognised tokens measured at a presentation level above the SRT (McArdle & Hnath-Chisolm, 2015). Speech audiometry testing is conducted under quiet conditions to predict the real-life speech understanding ability in quiet situations when the presentation level is loud enough to obtain the maximum SRS.

In 1970, researchers recommended that speech audiometry testing under noisy conditions should be added to audiologic assessments to evaluate the speech ability of people in noisy environments in daily life (Carhart & Tillman, 1970). Speech audiometry testing was conducted under noisy conditions wherein speech signal were mixed with background noise. In speech audiometry testing in noise, at least two types of masking effects of noise (energetic and informational masking) can prevent speech signal from being heard and recognized (Freyman et al., 1999; Hornsby et al., 2006; Kidd et al., 1998). Energetic masking is closely related to the energy of speech and noise signal and occurs when the neural excitation evoked by the noise exceeds the excitation produced by the speech signal; thus, portions of the speech signal are inaudible at the periphery (Brungart, 2001). Informational masking is an additional interference independent of the energetic masking and occurs when the speech and noise signal (that is, multiple-talker babble noise) are both audible but the auditory detection of target signals embedded in similar-sounding noise signal is degraded (Jerger, 2006; Kidd et al., 1994; Leek et al., 1991; Watson et al., 1976).

However, to understand the masking effect of noise on the SRiN performance, the relative intensity difference between the speech signal and noise must be determined. The signal-to-noise ratio (SNR) is one of the most important physical characteristic factors for speech audiometry testing in noise and is defined as the ratio of the intensity of speech signal to that of noise signal, as measured in decibels (dB) (Katz, 2002). Specifically, a positive SNR indicates that, on average, the speech signal is more intense than the noise signal, while a negative SNR indicates the opposite. In clinical settings, speech audiometry testing in noise can be conducted using a fixed or adaptive SNR testing paradigm. With fixed SNR measurements, the SNR is not adjusted in the testing procedure, and the percent-correct recognition is scored at a selected SNR (McArdle & Wilson, 2009). However, fixed SNR measurement is inherently limited by floor or ceiling effects (Gifford et al., 2008; Nilsson et al., 1994). For example, two participants with different speech recognition abilities may obtain zero scores under very poor SNR conditions or 100% scores under very high ones. With adaptive SNR measurements, either the intensity of the speech signal or noise is fixed and the intensity of the other signal is varied. Adaptive SNR typically measures an SNR at which people can correctly identify 50% of the target signals in noise (SNR50), as measured in dB SNR (dB SNR) (Nilsson et al., 1994). A lower SNR50 result represents better SRiN performance of the individual, whereas a higher SNR50 (including negative and positive values) represents worse SRiN performance.

2.1.2 SRiN Performance of Individuals With NH

The psychometric function for speech audiometry testing in quiet measures speech understanding ability as a function of speech presentation level, while the function for speech audiometry testing in noise measures the speech understanding ability as a function of SNR (Wilson & Carter, 2001). In addition, the psychometric function of an individual with NH is a monotonically increasing function. The percent-correct recognition performance is low when the speech presentation level or SNR is low, and the performance increases with increasing level (Nissen et al., 2005; Wilson, 2003). In speech audiometry testing under quiet conditions, individuals with NH, on average, achieve the maximum performance at the 30–40-dB sensation level (SL) above the SRT or average pure-tone thresholds (McArdle & Hnath-Chisolm, 2015; Ricketts et al., 2017). In speech audiometry testing in noise, when the presentation level of speech is constant, the addition of background noise (poor SNRs) negatively impacts the performance of people with NH (Beattie et al., 1997; Caldwell & Nittrouer, 2013; Carhart & Tillman, 1970; Dirks et al., 1982). However, if the presentation level is increased and the SNR is constant, the performance remains constant (Wilson, 2003). Researchers have suggested that people with NH require an SNR of at least +6 dB for satisfactory communication (Moore, B. C. J., 2012).

2.2. Binaural Hearing and Binaural Benefits

The evolution of the auditory system in most vertebrates with two ears, instead of one ear, suggests that there could be significant disadvantages in extracting important information about a listener's environment with only one ear (Fay & Popper, 2000). For humans, Cherry (1953) described an interesting phenomenon in noisy environments whereby, even if individuals have difficulties in understanding speech, they can focus on one talker and ignore the background noise. The author called the phenomenon a 'cocktail-party problem' (CPP). One of the most important observations in this study was that binaural hearing separates sounds more easily than monaural hearing does. The auditory system in people with NH is binaural hearing, which allows people to receive binaural sound information. In the horizontal plane, when the sounds are directly present from the front or rear of the head, the sounds reach the two ears simultaneously with the same intensity. However, when the sounds are outside the median plan, the position of the ears on either side of the head allows the individual to receive the sounds in the near ear first, which results in inter-aural time differences (ITD) between both ears (Blauert, 1997; Bronkhorst, 2000; Kuhn, 1977; Shaw, 1974). ITD cues can be better conveyed at low frequencies (i.e. below 1500 Hz) because the time delay at high frequency imparted by the head can exceed half the wavelength, resulting in ambiguous timing information (Litovsky, 2012; Van Hoesel, 2012). Furthermore, when the sounds are outside the median plan, the physical size of the head can block high-frequency sounds with short wavelengths from reaching the farther ear, which is known as the head-shadow (HS) effect. Thus, the intensity of sound at the farther ear is lower than that at the near one, which results in inter-aural level differences (ILDs) between the both ears. ILD cues are especially significant at higher frequencies with shorter wavelengths than at lower frequencies with longer wavelengths, and they can be negligible at 500 Hz (Litovsky, 2012; Van Hoesel, 2012). Thus, it is difficult for individuals who can only access low-frequency sounds to receive significant ILD cues. Individuals with binaural hearing can perceive and integrate ITD and ILD cues to separate target signals from noise, which facilitates the understanding of speech in noise (Bronkhorst & Plomp, 1988; Bronkhorst & Plomp, 1992; Dubno et al., 2008). A better SRiN performance with binaural compared to monaural hearing is identified as binaural benefits or advantages primarily attributed to binaural redundancy (BR), binaural squelch (SQ), and the HS effect (Dillon, 2001; Durlach & Colburn, 1978).

2.2.1 Binaural Redundancy.

When speech signal and noise come from the same direction (that is, the 0° azimuth), the signals received by both ears are identical. Thus, the same copy of the signal at both ears is likened to be listened to ‘twice’ by the binaural auditory system, which implies that the auditory system has a repeated opportunity to recognize the speech in noise, once for each ear (Dillon, 2001; MacKeith & Coles, 1971; Van Hoesel, 2012). The redundancies can result in improved auditory sensitivity to the signals with nuanced intensity and frequency, which can translate into improved SRiN performance (Sammeth et al., 2011). Compared to monaural hearing, listening utilising both ears under the signal and noise co-located condition generates BR of approximately a 1 to 2-dB SNR improvement (Bronkhorst & Plomp, 1988; Cox, Robyn et al., 1981). BR is typically measured under conditions where signals and noise both originate from a frontal loudspeaker, and the results for monaural versus binaural hearing are subsequently compared. Any measured performance increment obtained by adding the second ear is assumed to represent the primary benefit attributed to BR (e.g. Ching et al., 2006a).

2.2.2 Binaural Squelch

When speech signal and noise arrive from different directions, the binaural auditory system can combine the signals from each ear to generate an internal noise reduction that representation of the signals with a higher SNR (Dillon, 2001). In this process, the central auditory system can process the inter-aural timing, amplitude, and spectral differences in signals and noise arriving at two ears, and the central auditory system uses these differences to suppress the noise and enhance the signals (Sammeth et al., 2011). SQ is the most significant for low-frequency sounds up to 15 dB (below 2.5 kHz) and reduces to 2–3 dB

SNR for high-frequency sounds (above 2.5 kHz) (Carhart, 1965). Compared to monaural hearing, listening with both ears under the spatially separated condition where speech and noise arrives from different directions usually generates SQ of approximately a 2 to 3-dB improvement in the SNR (Bronkhorst & Plomp, 1988; Carhart, 1965; Zurek, 1993a). SQ is typically measured under conditions where speech is presented from a 0° azimuth and noise from the side (that is, a +90 or −90° azimuth). Thereafter, when the noise is at the monaural unaided side, the outcome with monaural hearing is compared to that with binaural hearing. Any measured performance increment obtained by adding the second ear is assumed to represent the primary benefit from SQ (e.g. Dincer D'Alessandro et al., 2015). Although the additional input ear has a poorer SNR, binaural hearing can utilise ITD and ILD cues to separate target signals from noise (Dillon, 2001; Sammeth et al., 2011). In addition to the SQ benefit, adding a second ear with a lower SNR can supply redundant information. However, this effect is often ignored in the discussion of SQ benefits (Dieudonné & Francart, 2019; Van Deun et al., 2010).

2.2.3 Head-Shadow Effect

When speech is presented from the front and noise is presented from the lateral side, the noise is diffracted by the head, which can attenuate the intensity of the noise in the ear farther away from the noise, thereby resulting in a higher SNR in one ear than in the other (Dillon, 2001; Litovsky et al., 2002). Thus, individuals with binaural hearing could selectively attend to the ear with a better SNR. However, unlike BR and SQ resulting from binaural input processing by the central auditory integration of sounds reaching both ears, HS is a purely physical phenomenon (Dieudonné & Francart, 2019; Durlach & Colburn, 1978; Sammeth et al., 2011). Thus, the amount of HS is dependent on the absolute and relative direction of the speech and noise. A better HS-induced SNR of the side contralateral to the noise could also be demonstrated under monaural hearing conditions. Furthermore, HS is typically measured for signals originating from the 0° azimuth and noise from one side (e.g. the +90 or −90° azimuth), and the outcomes are compared for monaural hearing ipsilateral to the noise versus binaural hearing, where any measured improvement is contributed by HS (e.g. Yuen et al., 2009). It should be noted that this approach measuring the HS by adding the ear with a better SNR can supply some redundant information. However, this effect is ignored in the discussion of HS benefits (Dieudonné & Francart, 2019; Van Deun et al., 2010). Since the current noise configuration only includes a single noise source, effects such as better-ear glimpsing are not considered.

2.3 Auditory Stream Segregation

People are exposed to various types of noises in daily life; for noisy environments, all listeners find it more difficult to recognize speech signal compared to quiet environments (Bronkhorst, 2015; Pittman & Wiley, 2001). Interference is typical challenges for children who usually study and stay in noisy environments such as classrooms and playgrounds where multiple competing sounds, including the voices of adults and children, environmental sounds, and reverberation, are simultaneously presented in different directions (Mok et al., 2007; Yuen & Yuan, 2014). The capacity of selecting and segregating multiple acoustic streams from different directions is called auditory stream segregation, which requires complex computations involving monaural and binaural hearing processes and is important for the speech and language development of children (Bregman, 1994; Yuen & Yuan, 2014).

2.3.1 Spatial Release from Masking (SRM)

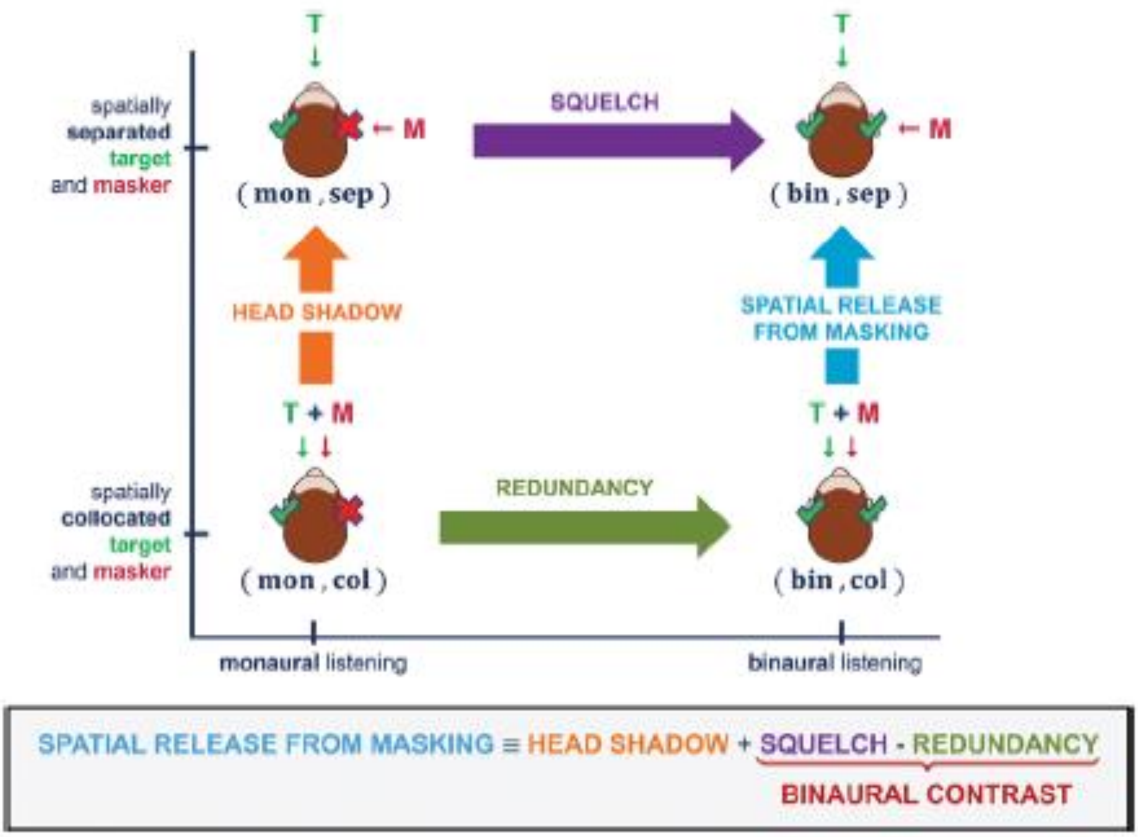
One method of measuring the auditory stream segregation ability is to evaluate the improvement in the SRiN performance obtained under co-located conditions (for example, speech and noise are both at the 0° azimuth) to that obtained under spatially separated conditions (for example, speech is at the 0° azimuth while noise is at the 90° one) (Bronkhorst & Plomp, 1988; Cullington & Zeng, 2008; Dirks & Wilson, 1969; Misurelli & Litovsky, 2012; Murphy et al., 2011). When the speech and noise both arrive from the frontal direction, the ITD and ILD cues are zero. Under the speech-and-noise-separated conditions, ITD and ILD cues may both contribute to demonstrating the SRM, which renders it easier for people to de-correlate speech from noise (Bronkhorst, 2000; Edmonds & Culling, 2005; Hawley et al., 2004; Litovsky, Goupell et al., 2012b; Zurek, 1993b). The improvement in speech recognition performance in the speech-and-noise-separated conditions is referred to as 'spatial release from masking' (SRM).

Considering the analysis of acoustic sounds under speech-and-noise-separated conditions, the auditory mechanisms either process inputs from each ear separately (monaural) or compare inputs arriving at two ears using inter-aural ITD and ILD cues (binaural) (Litovsky, 2012). In other words, the SRM is mainly dependent on both the monaural and binaural components. The monaural component is predominantly the result of the change in the SNR at each ear owing to the HS effect, while the binaural component is related to the binaural squelch (Plomp, 1976; Van Deun et al., 2010; Van Hoesel, 2012) (Plomp, 1976; Van Deun et al., 2010; Van Hoesel, R. J. M., 2012). Dieudonné and Francart (2019) established a framework to disentangle the SRM for adults with NH (

Figure 1), which unambiguously defines and relates the different effects (BR, HS, and SQ) in the SRM. In the framework, monaural processing is investigated by measuring the HS of monaural hearing when the noise moves from the front to the right. As reviewed in Section 2.2.2, ITD and ILD cues are supplied to the individual by adding the ear with a worse SNR (SQ), while the ear with the worse SNR can also supply redundant information to reduce noise (BR). Thus, the ability of true binaural cue processing in this framework owing to the inter-aural differences should be investigated by measuring the difference between SQ and BR, which is referred to as 'binaural contrast' (BC). According to these definitions, SRM is the sum of HS and BC. In the present study, the framework in

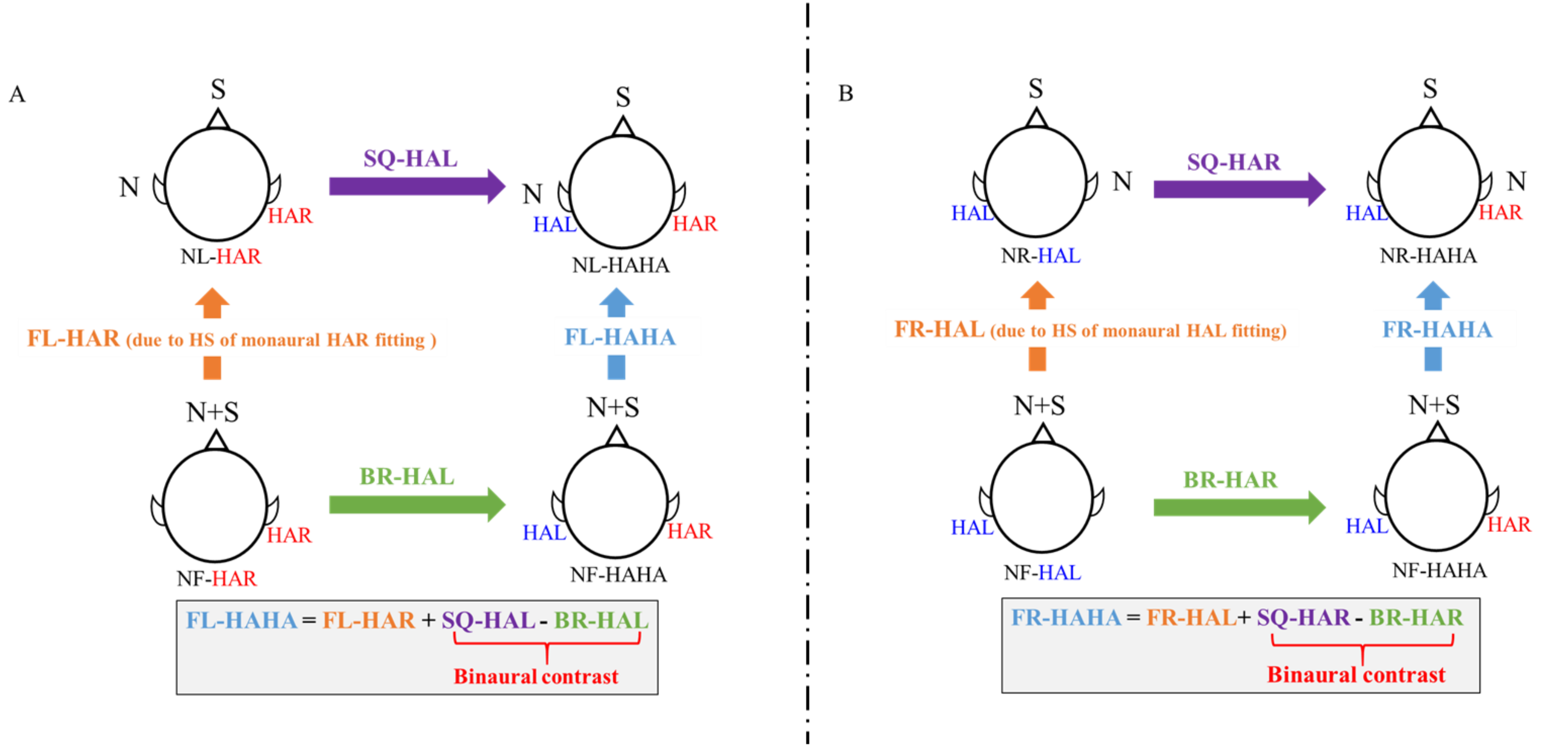
Figure 1 was modified and adopted to disentangle the binaural processing and SRM for children with HAHA fittings (Figure 2). When the noise moves from the front to one side, the monaural processing is measured by the HS of the individual with the monaural HA fitting, which is referred to as FL-HAR (panel A) or FR-HAL (panel B). Compared to individuals with monaural hearing, the SQ and BR of those with HAHA fittings were measured and are referred to as ‘SQ-HAL’ and ‘BR-HAL’ (panel A) or ‘SQ-HAR’ and ‘BR-HAR’ (panel B), respectively. Thus, the BC in the SRM equation for individuals with HAHA fittings also represents the difference between SQ and BR.

Figure 1 Framework of Disentangled SRM



Note. mon = monaural listening; bin = binaural listening; col = target and masker co-located condition; sep = target and masker separated condition; T = target; M = masker. From 'Redundant information is sometimes more beneficial than spatial information to understand speech in noise' by B. Dieudonné and T. Francart, 2019, Ear & Hearing, 40(3), p. 546 (https://doi.org/10.1097/AUD.0000000000000660). Copyright 2020 by the authors.

Figure 2 Framework of Disentangled SRM for Children with the HAHA Fitting in the Present Study



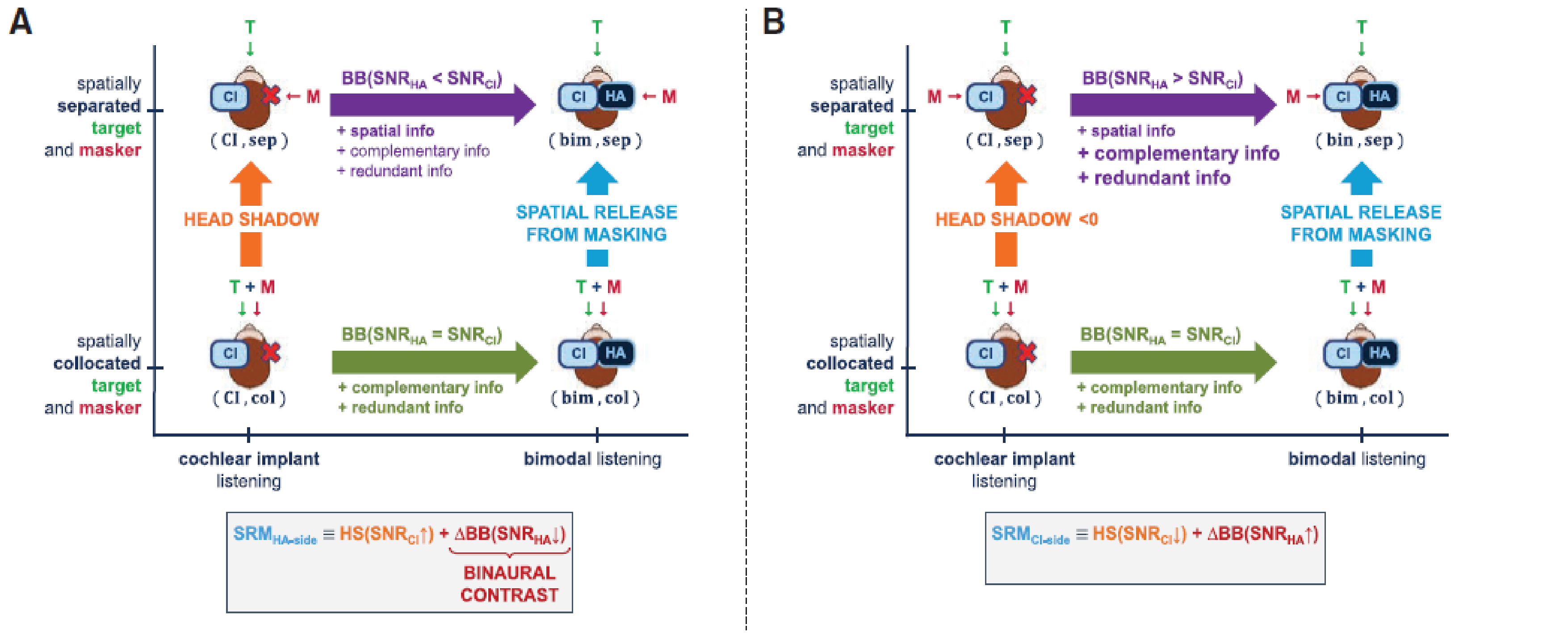
Note. HAHA = binaural-fitted hearing aid; HAL = monaural-fitted left hearing aid; HAR = monaural-fitted right hearing aid; N+S = noise and speech; N = noise; S = speech; NF = both speech and noise are presented from the front; NL = speech is presented from the front and noise is presented at -90° azimuth on the left; NR = speech is presented from the front and noise is presented at +90° azimuth on the right; BR-HAL =

binaural redundancy after adding a hearing aid on the right ear; SQ-HAL = binaural squelch after adding a hearing aid on the left ear; FL-HAHA = spatial release from masking of the participant fitted with binaural hearing aids when the noise source is moved from the front to the left side; BR-HAR = binaural redundancy after adding a hearing aid on the right ear; SQ-HAR = binaural squelch after adding a hearing aid on the right ear; FR-HAHA = spatial release from masking of the participant with binaural hearing aid fitting when the noise source is moved from the front to the right side.

Dieudonné and Francart (2020) transformed the framework in

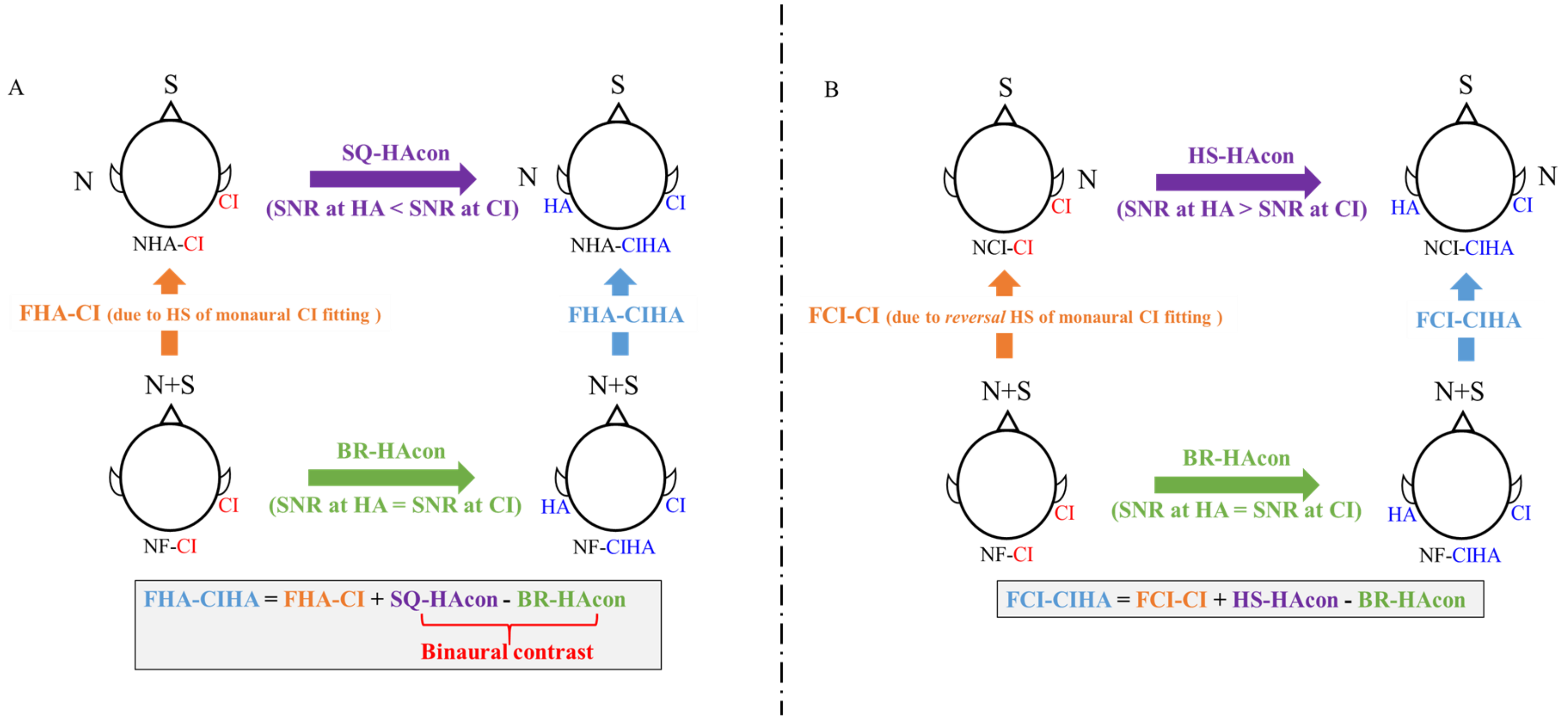
Figure 1 for individuals with the CIHA-fitted hearing aid (Figure 3). The functional hearing ability of each ear is asymmetric for most participants with CIHA; that is, the ear with the CI is usually dominant (i.e. the better-hearing ear), which mostly contributes to the SRiN performance. The ear with the HA is a complementary ear, which could provide extra benefits compared to listening with only the monaural-fitted CI fitting (Gifford et al., 2014; Mok et al., 2007; Van Hoesel, 2012). Therefore, in both frameworks for the participants with the CIHA, the monaural hearing component is usually due to the HS of the CI side because it is difficult for the participants to understand speech with only the HA (Dieudonné & Francart, 2020). For the left panel (A) in Figure 3, when the noise moves from the front to the HA side, the framework is directly translated from that for the listeners with NH. Subsequently, the binaural hearing component can be quantified by the difference in the bimodal benefit when the SNR decreases at the HA side. In contrast, for the right panel (B) in Figure 3, when the noise moves from the front to the CI side, a worse SNR at the CI side results in an HS disadvantage (i.e. the HS of the monaural CI is negative). Subsequently, the binaural hearing component can be quantified by the difference in the bimodal benefit when the SNR increases at the HA side. The framework in Figure 3 was adopted for adults with NH using a simulated bimodal hearing vocoder in the study of Dieudonné and Francart, so the present study tried to adopt the framework for children with the CIHA fitting (Figure 4). For the participant with the monaural CI fitting, when the noise moves from the front to the HA side (panel A), the result is referred to as the SRM for FHA-CI. This calculation is the monaural processing, which is measured by the HS of the monaural CI aided side. When the noise moves from the front to the CI side (panel B), the result is the SRM for FCI-CI, which also can be regarded as the result of a *reversal* HS of the monaural CI aided side. Thereafter, comparing the monaural-fitted CI and CIHA, the SQ and BR due to the additional HA near the noise direction were measured and are referred to as ‘SQ-HAcon’ and ‘BR-HAcon’ (panel A). The additional HA is far away from the noise direction, resulting in a higher SNR at the HA side, which does not exist in the individual with NH or the HAHA fitting (panel B). Thus, when the noise is at the CI side (NCI), the difference between the monaural-fitted CI and CIHA is also used to represent the HS of the HA side of individuals with the CIHA fitting (Schafer et al., 2011) and is referred to as ‘HS-HAcon’ (panel B).

Figure 3 Framework of Disentangled SRM for Individual with the CIHA Fitting



Note. CI = cochlear implant; HA = hearing aid; col = target and masker co-located condition; sep = target and masker separated condition; T = target; M = masker; HS = head-shadow effect; BB = bimodal benefit; SNR = signal-to-noise ratio; SRM = spatial release from masking. From 'Speech understanding with bimodal stimulation is determined by monaural signal to noise ratios = no binaural cue processing involve' by B. Dieudonné and T. Francart, 2020, Ear & Hearing, 41(5), p. 1160 (https =//doi.org/ 10.1097/AUD.0000000000000834). Copyright 2020 by the authors.

Figure 4 Framework of Disentangled SRM for Children with the CIHA Fitting in the Present Study



Note. CIHA = bimodal fitting; HA = hearing aid; CI = cochlear implant; N+S = noise and speech; N = noise; S = speech; NF = both speech and noise are presented from the front; NHA = speech is presented from the front and noise is presented at 90° azimuth from the hearing aid side; NCI = speech is presented from the front and noise is presented at 90° azimuth from the cochlear implant side; HS = head-shadow effect; BR-HAcon = binaural redundancy after adding a hearing aid on contralateral ear with an existing monaural cochlear implant fitting; SQ-HAcon =

binaural squelch after adding hearing aid on contralateral ear in addition to monaural cochlear implant fitting; FHA-CIHA = spatial release from masking of the participant with bimodal fitting when the noise source is moved from the front to the hearing aid side; HS-HAcon = head-shadow effect of adding hearing aid on contralateral ear in a monaural cochlear implant fitting; FCI-CIHA = spatial release from masking of the participant with bimodal fitting when the noise source is moved from the front to the cochlear implant side; SNR = signal-to-noise ratio.

2.3.2 SRM for Individuals With NH

The auditory stream segregation ability of children develops during adolescence. Researchers have found that children cannot achieve the same performance as adults until they are 13–15 years old; thus, the ability reflects a long-term maturational process of peripheral and central auditory pathways, which starts from infancy and continues through early childhood (Crandell & Smaldino, 2000; Sussman et al., 2007; Winkler et al., 2003). Litovsky (2005) reported that 4.5–7-year-old children with NH could take advantage of binaural benefits to segregate the speech targets from background noise and achieve an SRM in the range 3.5–7.5 dB SNR when the speech was from the front while competing sounds moved from the front to the right. Garadat and Litovsky (2007) revealed that the SRMs of 3-year-old children were similar to those of 4–5-year-old children, and Cameron et al. (2009) found that the SRMs of 11-year-old children were up to 12.9 dB SNR. Many studies have attempted to track the developmental process using SRM measurements; however, the results of the maturational timing of SRM obtained from children are not consistent. Some researchers have reported that children can completely acquire adult-like SRM in the early years (such as 3–6 years old) and that the SRM did not increase with age (Ching et al., 2011; Garadat & Litovsky, 2007; Litovsky, Goupell et al., 2012a; Lovett et al., 2012; Misurelli & Litovsky, 2012). In contrast, other researchers have suggested that it takes longer for children to develop SRM (Cameron et al., 2006; Vaillancourt et al., 2008; Van Deun et al., 2010; Yuen & Yuan, 2014). For adults with NH, the magnitudes of the obtained SRMs were in the range 3–12 dB SNR, depending on the number of competing sounds (Bronkhorst & Plomp, 1988; Bronkhorst & Plomp, 1992; Koehnke & Besing, 1996; Nilsson et al., 1994; Peissig & Kollmeier, 1997; Shinn-Cunningham et al., 2001)

2.4 SRiN Performance of Individuals with Hearing Loss

2.4.1 Binaural-Aided Hearing of Individuals with Hearing Loss

Although noise negatively impacts the speech recognition performance of people with NH, understanding speech in noisy environments is a much more complex and difficult task for people with hearing loss (Hopkins et al., 2008; Plomp, 1986). For example, researchers have found that children with HA or CI usually requires a significantly higher SNR to achieve an SRiN performance similar to their peers with NH (Goldsworthy Raymond & Markle, 2019; McCreery et al., 2015; McCreery et al., 2019). Based on the previous review (Section 2.2-2.3), the SRiN performance of people with NH can be improved from monaural to binaural hearing owing to the binaural benefits or improved from co-located conditions to spatially separated ones owing to SRM. However, if the individual has hearing loss in one ear, the diminished functional hearing ability of that ear could impact the normal binaural hearing development. Therefore, the lack of normal binaural input due to hearing loss can lead to considerable long-term hearing deficits in sound localisation, SRiN performance, and spatial cognition (Colletti et al., 1988; Corbin, 2019; Van Wieringen et al., 2019). Similarly, if an individual has hearing loss in both ears but uses only one hearing prosthesis, the long-term hearing deficits remain (Dillon, 2001). Furthermore, for individuals with monaural hearing (monaural input in one ear), the auditory nerves and central speech processing region related to the opposite ear may atrophy, thereby resulting in a progressively deteriorated speech recognition performance of the opposite ear. This phenomenon is termed ‘auditory deprivation’ (Gelfand & Silman, 1993; Silman et al., 1984). Given the negative impact of auditory deprivation, it is reasonable to assume that bilateral fitting with a hearing prosthesis not only provides binaural hearing for patients with bilateral hearing loss but also preserves the ability of the central auditory system to efficiently process inputs from each ear as far as possible. Therefore, restoring binaural hearing in people with hearing loss is critical for better speech understanding in noise and protecting the unaided ear from auditory deprivation.

For people with fitted hearing aids, wearing two hearing aids instead of one makes binaural hearing possible (Dillon, 2001), which is a standard practice in acoustic amplification for people with bilateral hearing loss (Litovsky & Madell, 2009). For CI recipients, two common methods help recipients obtain binaural hearing: the use of one CI on each ear (CICI) or the use of a CI in one ear and an HA on the contralateral ear (CIHA) (Potts et al., 2009; Waltzman et al., 1992). Children traditionally receive CI in one side owing to many factors, including limited financial resources in government-funded programs, relatively good hearing level in the non-implanted ear, clinical considerations, and personal preference (Nilakantan et al., 2018). Currently in China, the financial aid policy grants each child with bilateral hearing loss access to monaural CI only once in their lifetime (Program Office of China Rehabilitation Research Center for Hearing and Speech Impairment, 2012). For these monaural CI recipients, fitting a HA on the non-implant ear is a more affordable and less invasive approach compared to a second CI (Ching et al., 2006b). Currently, HAHA and CIHA fittings make binaural hearing available to individuals with bilateral hearing loss. The obtained binaural and spatial advantages could be less than those obtained with NH, and the magnitude of the benefits varies among people with hearing loss (Ching et al., 2011; Misurelli & Litovsky, 2015; Mok et al., 2007; Van Deun et al., 2010). Bilateral fitting is recommended for the most individuals with bilateral hearing loss (American Academy of Audiology, 2013; Valente et al., 2006). Thus, it is necessary to evaluate the potential benefits that help to improve SRiN performance when listening with two ears relative to only one ear.

2.4.2 Studies for Individuals with HAHA

As shown in Table 1, the SRiN performance for adults and children with HAHA fittings were evaluated in previous studies and will be addressed in the following sections. The binaural benefit was investigated under different device fitting conditions, and the SRM was investigated in different noise directions.

Table 1 ***SRiN and SRM of Individuals with HAHA from Previous Studies.***

Study	Participant			Outcome measure					Binaural benefit (HAHA fitting versus monaural HA fitting)		SRM (co-located condition versus spatial separated condition)		Comment
	N	Age (mean, years)	Pure-tone threshold (mean, dB hearing loss)	Stimuli presented from front (Language)	Noise	SNR	device fitting condition	Noise direction	Average group result (mean difference, dB SNR)	Individual result (*n*)	Average group result (mean difference, dB SNR)	Individual result (*n*)	
Festen and Plomp (1986)	12	30-71	Unaided threshold: 3FA<50	Sentence (Dutch)	SSN	Adaptive	Unaided, HAR, HAL, HAHA	NF, NR, NL	NL: HAR=HAL=HAHA; NF: HAR=HAL=HAHA; NR: HAR=HAL=HAHA; NL: unaided>HAR/HAL/HAHA (2); NR: unaided>HAR/HAL/HAHA (2)	NIP (HS): +1, -1 NCO (SQ): +1	Unaided: NL>NF (6.5), NR>NF (6.5); HAR: NL>NF (4.5[a]), NR>NF (4.5[a]); HAL: NL>NF (4.5[a]), NR>NF (4.5[a]); HAHA: NL>NF (4.5[a]), NR>NF (4.5[a]);		Binaural benefits are insignificant among participants with mild to moderate hearing loss, but are significant among participants with severe hearing loss.
	12	30-77	Unaided threshold: 3FA>50						NL: HAHA=HAR, HAHA>HAL (3); NF: unaided=HAR=HAL=HAHA; NR: HAHA>HAL (2), HAHA>HAR (3);	NF (BR): +1 NIP (HS): +7 NCO (SQ): +3	Unaided: NL>NF (5.5), NR>NF (5.5); HAR: NL>NF (3[a]), NR=NF; HAL: NL=NF, NR>NF (3[a]); HAHA: NL>NF (3.5[a]), NR>NF (4[a])		
van Schoonhoven et al. (2016)	19	Netherland: 23-68 (55); Germany: 54-84 (70);	Unaided threshold: 4FA<40	Sentence (Dutch or German)	SSN	Adaptive	HAB, HAHA	NF, NIP, NCO	NF (BR): HAB=HAHA; NCO (SQ): HAB=HAHA; NIP (HS): HAB=HAHA;				Binaural benefits are insignificant among participants with mild to moderate hearing loss, but are significant among participants with severe hearing loss.
	21		Unaided threshold: 4FA>40						NF (BR): HAB=HAHA; NCO (SQ): HAHA=HAB; NIP (HS): HAHA>HAB (4.1, *SD*=3.4);	NCO (SQ): +2			
Walden and Walden (2005)	28	50-90 (75.1)	Unaided threshold: 3FA=41.6[a]	Sentence (English)	4BN	Descending, from +25 dB to 0 dB in 5 dB step	Unaided, HAR, HAL, HAHA	NF	HAR>HAHA (**3**[a]); HAL>HAHA (1.5[a]) Monaural aided ear with better performing>HAHA (4[a]); Monaural aided ear with poorer performing=HAHA (1[a]);	NF (BR): +3, =2, -23			The study only tested NF direction, thus it only investigated the binaural redundancy benefit. For the individual data, the authors did not provide a clear criterion to classify differences among conditions and binaural disadvantages.

McArdle, Killion, Mennite, and Chisolm (2012)	20	59-85 (75.5)	Unaided threshold: 3FA=34.5, *SD*=8	Sentence (English)	4BN	Descending, from +25 dB to 0 dB in 5 dB step	Unaided, HAR, HAL, HAHA, HAR with left ear plugged	NF	HAHA>HAR (2.7) HAHA>HAL (3.4) HAHA>HAR with left ear plugged (4.4)	NF (BR): +16, -4			The study only tested NF direction, thus it only investigated the binaural redundancy benefit. For the individual data, the mean improvement of 1.5 dB in a single pairwise comparison was regarded as significant at the 95% CI. This study replicated the Walden and Walden (2005), but the results contrasted with those obtained by Walden and Walden (2005).
Marrone, Mason, and Kidd (2008a)	20	younger: 19-42, older: 57-80	Mild to moderately severe symmetric sensorineural hearing loss	Sentence (English)	Sentences from CRM corpus	Adaptive	HAR, HAL, HAHA	NF, NS±90	NF (BR): younger: HAHA=monaural HA fitting; older: HAHA=monaural HA fitting;		Monaural HA fitting: younger: 3.2, *SD*=2.9; older: 1.3, *SD*=2.8; HAHA fitting: younger: 4.4, *SD*=2.3; older: 1.8, *SD*=2.9; SRM with HAHA>SRM with monaural HA		Some participants can obtain a small amount of SRM with monaural HA, but the inter-individual variability was considerable (ranging from -2.6 to 7.9 dB). SRM obtained from HAHA was significantly better than from monaural HA fitting, even though the size of difference was small (1 dB, on average).
Dawes, Munro, Kalluri, and Edwards (2013)	48	new-monaural users: 48-84 (69), new-binaural users: 45-84 (67), experienced users: 64-90 (73)	Unaided threshold: new-monaural users: 4FA=27-43 (39), new-binaural users: 4FA=32-45 (39), experienced users: 4FA=29-61 (46)	Sentence (English)	Sentences from CRM corpus	Adaptive	HAR, HAL, HAHA	NF, NS±90			Monaural HA fitting: (4.1, *SD*=4.5); HAHA fitting: (6.0, *SD*=4.4); SRM with HAHA>SRM with monaural HA (1.4, 95% CI 0.4-2.5);		The results were in line with those obtained by Marrone, Mason, and Kidd (2008a).
Nittrouer et al. (2013)	18	99 months, *SD*=5	Unaided threshold: 3FA>50 in the better ear	Phoneme; Monosyllabic word (English)	Noise with a flat spectrum	0 dB, +3dB	HAHA	NF, NL			SRM (phoneme)=3.4%, *SD*=6.3; SRM (word)=5.6%, *SD*=7.8		The authors used SRM to enamine the head-shadow effect. SRM obtained from HAHA was significantly poorer than from NH on phoneme (6%) and word (10%) recognition
Ching, van Wanrooy, Dillon, and Carter (2011)	27	3.2-11.9 (7.0)	Unaided threshold: 4FA: 25-104	Monosyllabic words; Sentence (English)	8BN	Adaptive	HAHA	NF, NS±90			SRM (word)=0.63, *SD*=3.27; NF=NS90; SRM (sentence)=0.17, *SD*=2.35; NF=NS90	9 individuals with HAHA performed 2 dB or greater SRM	SRM obtained from children with HAHA was, on average, effectively zero. Children with HAHA had, on average, a 3 dB deficit in SRM on both word and sentence compared to the children with NH

Note. In the 'Individual result' column, the number of participants who obtained significant binaural benefits or SRM is indicated by '+', who obtained insignificant binaural benefits or SRM is indicated by '=', and who obtained significantly negative binaural benefits (i.e. binaural disadvantages) or negative SRM is indicated by '−'. 3FA = average hearing threshold for 500, 1000, and 2000 Hz; 4BN = four-talker babble noise; 4FA = average hearing threshold for 500, 1000, 2000, and 4000 Hz; 8BN = eight-talker babble noise; 95% CI = 95% confidence interval; BR = binaural redundancy; CRM = coordinate response measure; HAB = monaural HA-aided ear with the better pure-tone threshold; HAHA = binaural-fitted hearing aids; HAL = monaural-fitted hearing aid on the left ear; HAR = monaural-fitted hearing aid on the right ear; HS = head-shadow effect; NCO = speech presented from the front and noise contralateral to the ear with the monaural hearing aid; NF = speech and noise both presented from the front; NH = normal hearing; NIP = speech presented from the front and noise ipsilateral to the monaural HA ear; NL = speech presented from the front and noise presented at the −90° azimuth on the left; NR = speech presented from the front and noise presented at +90° azimuth on the right; NS±90 = speech presented from the front and noise presented at both +90 and −90° azimuths; SSN = Speech spectrum-weighted noise; SQ = binaural squelch; SRM = spatial release from masking.

[a] estimated data from the figure.

2.4.2.1 Studies for Adults with HAHA

In comparison with monaural-fitted HA, binaural-fitted HAHA could be advantageous for improving the SRiN performance. However, findings from studies on the benefits of HAHA fitting do not always align, and some are even contradictory.

When speech and noise both arrive from the same frontal direction (NF), it is expected that people with binaural hearing can perform binaural redundancy. Festen and Plomp (1986) found that the SNR50 was negligibly better with HAHA than with monaural HAL or HAR for listeners with moderate to severe hearing loss. A later study (Van Schoonhoven et al., 2016) showed similar results. The researchers reported that insignificant benefits were observed for listeners with HAHA fittings versus monaural HA fittings in the ear with a better pure-tone threshold. Other researchers (Walden & Walden, 2005) have suggested that people with HAHA fittings could perform a binaural disadvantage (binaural interference) compared to people with monaural HA fittings. A study using the Quick Speech-in-Noise Test (QuickSIN) evaluated the performance of people with HAHA versus monaural HA fittings and found that 23 of the 28 participants showed better SRiN performance with monaural hearing than with binaural hearing. In contrast, other researchers (McArdle et al., 2012) repeated the study conducted by Walden and Walden with listeners of similar age range and found that most listeners showed better performance with HAHA as compared to monaural HA fittings. One possible reason for the absence of binaural redundancy in the study by Walden and Walden (2005) is that the speech and noise co-located condition limits the role of binaural hearing owing to deficient spatial cues (Kalluri, 2014).

When speech and noise arrive from the front and one lateral side (0° and +90 or −90° azimuths), respectively, individuals with HAHA fittings could obtain some binaural benefits of binaural squelch and HS compared to individuals with monaural-fitted HAs. Festen and Plomp (1986) found that for listeners with unaided thresholds over 50 dB HL, when the speech was at the front and noise was ipsilateral to the monaural-fitted HA, the SRiN performance of the HAHA fitting was 3 dB SNR better than that of the monaural-fitted HA, which indicated the HS binaural benefit. Similar results were also found in a later study (Van Schoonhoven et al., 2016), wherein the researchers suggested that adding a second HA contralateral to the noise could improve the performance but only for listeners with 40 dB HL or worse. Furthermore, these studies (Festen & Plomp, 1986; Van Schoonhoven et al., 2016) mentioned that HS was insignificant for listeners with mild hearing loss in this noise direction because the speech signal was sufficiently audible in the unaided ear; that is, there was little room for improvement for listeners with relatively good unaided hearing thresholds in the ear contralateral to the noise. When the noise was presented contralateral to the monaural-fitted HA, van Schoonhoven et al. (2016) found that the binaural squelch benefit was insignificant; although Festen and Plomp (1986) found that when the noise was on the right side, the listeners achieved a slight but significant binaural squelch benefit (approximately 2 dB SNR) owing to the addition of the second HA on the right ear, which restored the binaural hearing for 25% of the participants.

Moreover, several studies have investigated the effect of binaural hearing on SRM. To eliminate the complication of whether a monaural HA was an acoustically better or poorer ear for given noise positions, the researchers (Dawes et al., 2013; Marrone et al., 2008b) evaluated the SRM by symmetrically placed noises presented from the front along with two unrelated maskers from both the +90 and −90° azimuths simultaneously. In both studies, compared to the co-located condition (NF), the listener with the monaural-fitted HA achieved an SRM for approximately 4 dB SNR when the noise moved to both sides. In contrast, the SRM with the HAHA fitting was slightly but significantly improved (approximately 1 dB SNR). Although the HAHA fitting could improve the SRM from that achieved with the monaural-fitted HA, the SRM obtained for individuals with HAHA was different from that obtained for their peers with NH. When the noise moved from the front to one side, Plomp and Mimpen (1981) reported an average SRM for 10 dB SNR in listeners with NH; the average SRM for the listeners with the HAHA fitting diminished to 5.5–6.5 dB SNR (Festen & Plomp, 1986). Furthermore, when the noise moved from the front to both sides, Marrone et al. (2008b) found that listeners with the HAHA presented an SRM for 5.4 dB SNR on average, which was 7 dB SNR poorer than the SRM for listeners with NH. Some researchers (Festen & Plomp, 1986; Neher et al., 2009) believe that the deterioration of the SRM in individuals with the HAHA fitting could be due to the poor binaural cues between both ears with the HA fitting.

2.4.2.2 Studies for Children with HAHA

Considering the different maturational level of speech recognition ability in noisy environments between children and adults (Allen & Wightman, 1994; Kirk et al., 1997; Schneider et al., 1986), the literature on adults may not represent the SRiN performance of children. Nittrouer et al. (2013) compared the SRiN performance when the noise was co-located with speech and when it was moved to one side to investigate the SRM for children with the HAHA fitting. They found that the children with the HAHA fitting presented a lower SRM (3.4 and 5.6% differences in phoneme and word recognition, respectively). Compared to their peers with NH, the SRMs of children with the HAHA fitting were reduced (6 and

10% decreases in phoneme and word recognition, respectively), which is similar to the findings of a previous study (Ching et al., 2011). Furthermore, the researchers studied the SRM for 3–12-year-old children with HAHA fittings when the noise moved from the front to both sides and found that the children with the HAHA fittings showed a reduced SRM (decreased by approximately 3 dB SNR) compared to their peers with NH. However, Ching et al. (2011) could not determine whether the reduced SRM in children with HAHA was due to distorted inter-aural cues in the HA or deficient auditory processing capabilities. The HA can compensate for the auditory threshold; the different HA electronic components, algorithms, and microphone position could distort important spatial information, including ITD, ILD, and spectral cues (Brown, A. D. et al., 2016; Dillon et al., 2003; Udesen et al., 2013; Van den Bogaert et al., 2006). For example, when the microphone was at the entrance to the ear canal, the ILD distortion was < 10 dB, but when it was behind the pinna, the ILD distortion was up to 30 dB at 6–8 kHz (Udesen et al., 2013). The fixed directionality could also introduce approximately 20 dB ILD of distortion when the sound was presented at a 100°–150° azimuth. Individuals are sensitive to detecting 0.5-dB changes in the ILD (Hartmann, 1999); thus, an ILD distortion of 20–30 dB is noticeable to individuals listening to the noise. In addition, nonlinear frequency compression can distort the ITD envelope and reduce the spectral coherence above the cut-off frequency, which can impact the recognition of high-frequency speech containing few low-frequency ITD cues (Brown, A. D. et al., 2016). Thus, when the binaural auditory processing system interprets the distorted spatial information, it may result in degraded SRiN performance. Because the HA was individually well-matched to prescriptive targets in the study by Ching et al. (2011), the deficit SRM may not be related to audibility but instead to a reduced auditory processing ability of separating speech from noise (Bronkhorst & Plomp, 1989; Ching et al., 1998a). In addition, other studies on adults have found that increased audibility (Ahlstrom et al., 2009) or customising the HA amplification characteristics (Marrone et al., 2008b) could not increase the SRM.

In the literature on both adults and children with hearing aid fittings, the findings revealed considerable individual variability in the SRiN performance; that is, certain people indeed achieved significant binaural benefits and normal-like SRM, whereas others showed limited advantages or disadvantages of SRiN with HAHA fittings (Boymans, M. et al., 2009; Ching et al., 2011; Cox, Robyn M. et al., 2011; Haggard & Hall, 1982; Ricketts et al., 2019). Many researchers have found that some factors may limit the binaural benefits of individuals with HAHA fittings, including the degree of hearing loss (Ricketts et al., 2019), high-frequency hearing loss, loudspeaker configuration (Kalluri, 2014), hearing-aid sound-processing strategy (Kalluri & Edwards, 2007), and binaural interference (Jerger et al., 1993). Furthermore, non-optimal microphone positions, insufficient amplification, nonlinear frequency compression, and HA noise reduction (Brown, A. D. et al., 2016; Neher et al., 2009) could prevent individuals with HAHA fittings from perceiving the spatial information, resulting in poor SRiN and SRM. For example, inadequate gain above 4000 Hz in most hearing aids results in the disappearance of the high-frequency-related ILD cues. Furthermore, nonlinear amplitude compression, such as wide dynamic range compression (WDRC), amplifies less higher-level sound than lower-level sound, thereby reducing the ILD cues, and the independent noise reduction at different frequencies causes different gains, which also distorts the spectral cues (Keidser et al., 2006; Rana & Buchholz, 2016).

2.4.3 Studies for Individuals with CIHA

As shown in Table 2, the SRiN performance for adults and children with CIHA fittings were evaluated in previous studies and will be addressed in subsequent sections herein. The binaural benefit was investigated under different device fitting conditions, and the SRM was investigated in different noise directions.

Table 2 *SRiN and SRM for Individual with CIHA from Previous Studies*

Study	Participant			Outcome measure					Binaural benefit (CIHA fitting versus monaural CI fitting)		SRM (co-located condition versus spatial separated condition)		Comment
	N	Age (mean, years)	Pure-tone threshold (mean, dB hearing loss)	Stimuli presented from front (Language)	Noise	SNR	device fitting condition	Noise direction	Average group result (mean difference, dB SNR)	Individual result (*n*)	Average group result (mean difference, dB SNR)	Individual result (*n*)	
Ching, Incerti, and Hill (2004)	21	25-84	Mean unaided threshold of HA ear: 3FA=98-100	Sentence (English)	8BN	+10, +15	CI-only; HA-only; CIHA	NF, NS60	NF (BR): CIHA>CI-only (20%[a]); NS60 (HS): CIHA>CI-only (10-25%[a]);	NF (BR): +7, =14 NS60 (HS): +8, =5			Ceiling and floor effects for some participants. The CIHA fitting experience was not directly related to the binaural benefit on the SRiN performance.
Illg, Bojanowicz, Lesinski-Schiedat, Lenarz, and Buchner (2014)	141	16.27-88.20 (58.52)	Median of unaided threshold ranges from 60-80 dB HL between 125-1000 Hz for the non-implanted ear	Sentence (German)	SSN, 1BN	+10 dB	CI-only; CIHA	NF	NF (BR): SSN: CIHA>CI-only (12%[a]) 1BN: CIHA>CI-only (16%[a])	NF (BR): +106, -35			The study only tested NF direction, thus it only investigated the binaural redundancy benefit. The threshold difference between the group of participants without binaural benefit and the group with the benefit is not statistically significant, but the author cannot find any predictor indicating the degree of benefit.
Crew, Galvin III, Landsberger, and Fu (2015)	9	43-79	Not reported average results	Sentence (English)	Multi-talker speech babble	Adaptive	CI-only; HA-only; CIHA	NF	NF (BR): CIHA=CI-only				The SRiN difference between CIHA and CI-only was not significant with a low observed power (0.125), which could be due to a small sample size (8) in the analysis and considerable across-subject variability of the performance in the data.
Morera et al. (2005)	12	23-75	Mean aided threshold of CI ear: 30-40 dB SPL across the frequency (500/1000/2000/4000/6000); Mean aided threshold of HA ear: 49-64 dB SPL across the frequency (500/1000/2000/4000/6000); Mean unaided threshold of HA ear: 85-95 dB HL across the frequency (500/1000/2000/4000/6000);	Disyllabic word (Spanish)	4BN	+10 dB	CI-only; HA-only; CIHA	NF, NCI, NHA	NF (BR): CIHA=CI-only; NHA (SQ): CIHA>CI-only (17.0%±12%); NCI (HS): CIHA>CI-only (30%[a]);	NF (BR): +6, =5, -1; NHA (SQ): +4, =8; NCI (HS): +6, =6;			The participants who preoperatively performed >20% scores in quiet with the HA can obtain significantly greater binaural benefits postoperatively.

Iwaka et al. (2004)	6	48-84	Unaided 3FA of HA ear: 92.5-118.7 dB HL; Aided 3FA of HA ear: 59.3 dB HL; Aided 3FA of CI ear: 34.3 dB HL	Sentence (Japanese)	Multi-talker speech babble	Adaptive	CI-only; CIHA	NF, NCI, NHA	NF (BR): CIHA>CI-only (3.5[a]); NHA (SQ): CIHA=CI-only; NCI (HS): CIHA=CI-only;			Small sample size.
Dunn, Tyler, and Witt (2005)	12	48-83		Sentence (English)	Multi-talker speech babble	Fixed, and individually set	CI-only; HA-only; CIHA	NF, NCI, NHA	CIHA>CI-only ($F(1,19)=19.72$, $p<.001$)	NF: +7, =2, -2; NHA: +5, =5, -1;	CIHA: NF>NCI, (($F(2,20)=4.48$, $p<.05$))	Unaided or aided thresholds of both ears was not reported. Ceiling and floor effect were observed in the individual results. The group average results were not reported. Even though two-way ANOVA reported device fitting condition and noise direction were both significant factors, the pairwise comparison using post hoc analysis was not conducted.
Mok, Grayden, Dowell, and Lawrence (2006)	14	37-83	Not reported average results	Sentence (English) Spondee (English)	Sentence: 4BN, Spondee: constant broadband noise	Sentence: +10; Spondee: adaptive	CI-only; HA-only; CIHA	Sentence: NF, Spondee: NF, NCI, NHA	Sentence: NF (BR): CIHA>CI-only (10%[a]) Spondee: NF (BR): CIHA>CI-only (1.5[a]); NCI (HS): CIHA>CI-only (3[a]); NHA (SQ): CIHA=CI-only	Sentence: +4, =6; Spondee: NF: +3, =7; NHA: +1, =7, -1; NCI: +4, =6;		The aided threshold of HA ear could account for part of individual variability on binaural benefits. The mid-to-high frequency information from the HA could have adverse effects on the binaural benefits.
Morera et al. (2012)	15	21-71.5 (48.5)	Mean aided threshold of HA ear: 30 and 40 dB SPL for the frequencies between 250 and 2000 Hz, and 53 dB and lower for frequencies above 3000 Hz	Sentence (Spanish)	SSN	Adaptive	CI-only; HA-only; CIHA	NF, NCI, NHA	NF (BR): CIHA>CI-only (3); NHA (SQ): CIHA>CI-only (2.6); NCI (HS): CIHA=CI-only;	NF (BR): +3, =11, -1; NHA (SQ): +2, =13; NCI (HS): not reported		The head-shadow effect calculation equation for per individual in the study was different from the equation in the current study.
Veugen, Chalupper, Snik, Opstal, and Mens (2016)	15	42-79 (61)	Not reported average results	Sentence (Dutch)	SSN, 1BN	Adaptive	CI-only; CIHA	NF, NCI, NHA, NS±90	1BN: NF (BR): CIHA=CI-only; NHA (SQ): CIHA>CI-only (3.1±3.6); NCI (HS): CIHA>CI-only (3.0±4.2); NS90 (SQ): CIHA>CI-only (2.4±3.9);		CIHA: NHA>NF (4.4±3.5) NCI=NF	The time constants and the number of compression channels of the automatic gain control (AGC) of the HA was matched to the CI in the CIHA fitting. The binaural benefits were significant for the AGC-matched HA in CIHA, but not significant for the standard HA in CIHA.

Gifford, Dorman, Sheffield, Teece, and Olund (2014)	35	68.0, *SD*=13.5	Mean unaided threshold of HA ear: 47-107 (125-8000 Hz)[a];	Sentence (English)	Multi-talker speech babble	BKB-SIN: adaptive; AzBio: +5	CI-only; HA-only; CIHA	NF, NCI, NHA	NF (BR): 0.9 (BKB-SIN); 9.5% (AzBio); NHA (SQ): -0.7 (BKB-SIN); 0.2% (AzBio); NCI (HS): not reported		CI-only (NF versus NHA): 5.7 (BKB-SIN); 19.9% (AzBio); HA-only (NF versus NCI): 1.5 (BKB-SIN); 2.7% (AzBio); CIHA (NF versus NHA): 4.9 (BKB-SIN); 14.1% (AzBio);		The study reported the mean difference between two device fitting conditions (CIHA versus CI-only) or two noise directions (NF versus NHA/NCI), but the authors did not report the statistic results among different conditions, that is, they did not report whether the mean difference was statistically significant.
Ching et al. (2005)	18	6-18	Mean unaided threshold of HA ear: 3FA=81-115	Sentence (English)	8BN	+10, +15	CI-only; HA-only; CIHA	NF, NS60	NF (BR): CIHA>CI-only (10%[a]); NS±60 (HS): CIHA>CI-only (15-20%[a]);	NF (BR): +6, =7 NS60 (HS): +11, =7			The results of children with CIHA were consistent with those of adults with CIHA in Ching et al. (2004).
Dincer D'Alessandro, Sennaroğlu, Yücel, Belgin, and Mancini (2015)	19	3-14 (9)	Not reported average results	Phoneme	SSN	Fixed, and individually set	CI-only; CIHA	NCI, NHA	NHA (SQ): CIHA>CI-only (12%);	NHA (SQ): +13, =6			For the individual results, the authors did not provide a clear criterion to classify differences among conditions, and not take the test variability into account. They considered all difference scores larger than 0% to be a binaural benefit.
Mok, Galvin, Dowell, and McKay (2007)	9	9.2-14.9 (12.1)	Not reported average results	/baba/	SSN	Adaptive	CI-only; HA-only; CIHA	NF, NCI, NHA	NF (BR): CIHA>CI-only (1.3); NHA (SQ): CIHA=CI-only; NCI (HS): CIHA>CI-only (2.2);	NF (BR): +4, =5; NHA (SQ): +1, =5, -3; NCI (HS): +5, =4;	CIHA: NHA>NF (3.8); NF>NCI (-0.4); CI-only: NHA>NF (5.5);	CIHA: NF versus NHA: +8, =1; NF versus NCI: +2, =3, -4; CI-only: Not reported	The study did not use speech signal to investigate SRT in the noise, but they tested the sound detection threshold in the noise. The binaural benefits for speech recognition and speech detection may be different. The SRM obtained from CIHA group was significantly 1-2 dB less than the NH group when the noise moved to the HA side, and significantly 5-6 dB less than the NH group when the noise moved to the CI side.
Mok, Galvin, Dowell, and McKay (2010)	9	11.8, *SD*=2.1	Not reported average results	Monosyllabic word (English)	4BN	-10	CI-only; HA-only; CIHA	NF, NCI	NF (BR): CIHA>CI-only (6.3%); NCI (HS): CIHA>CI-only (8.1%);	NF (BR): +6, =3; NCI (HS): +8, =1;			The mechanisms underlying the binaural benefit provided by the HA may be due to the ability to combine the additional speech information contained in the acoustic signal with the electric signal.

Litovsky, Johnstone, and Godar (2006)	10	6-14	Not reported average results	Disyllabic word (English)	2BN	Adaptive	CI-only; CIHA	NF, NCI, NHA	The SRiN performance of CIHA was not overall better than that of CI-only fitting in any noise condition, so the binaural benefit in any noise condition was near or negative.	NF (BR): difference>0: 5, difference=0: 1, difference<0: 4; NHA (SQ): difference>0: 3, difference=0: 2, difference<0: 5; NCI (HS): difference>0: 5, difference<0: ;	CIHA: NF versus NHA: 2[a]	CIHA: NF versus NHA: difference>0: 6, difference<0: 4; NF versus NCI: difference>0: 4, difference=0: 1, difference<0: 5;	The study reported the mean difference between two device fitting conditions (CIHA versus CI-only) or two noise directions (NF versus NHA/NCI), but the authors did not report the statistic results among different conditions, that is, they did not report if the mean difference was statistically significant.
Nittrouer et al. (2013)	6	103 months, *SD*=5	3FA>50 in the better ear	Phoneme; Monosyllabic word (English)	Noise with a flat spectrum	0 dB; +3dB	CIHA	NF, NHA			CIHA: NF versus NHA phoneme: 0.2% *SD*=7.4; word: 0.7% SD=6.2;		The authors used SRM to examine the head-shadow effect of the CI. SRM obtained from CIHA was significantly poorer than from NH on phoneme (10%) and word (16%) reception. Children with CIHA did not show SRM, on average. Because of the small sample size, the authors cannot explain the lack of effect.

Note. Note. In the ‘Individual result’ column, the number of participants who obtained significant binaural benefits or SRM is indicated by ‘+’, who obtained insignificant binaural benefits or SRM is indicated by ‘=’, and who obtained significantly negative binaural benefits (binaural disadvantages) or negative SRM is indicated by ‘−’. 1BN = one-talker babble noise; 2BN = two-talker babble noise; 3FA = average hearing threshold for 500, 1000, and 2000 Hz; 4BN = four-talker babble noise; 8BN = eight-talker babble noise; ANOVA = Analysis of Variance; AzBio = Arizona Biomedical Institute sentence recognition test; BKB-SIN = Bamford-Kowal-Bench Speech-in-Noise test; BR = binaural redundancy; BKB-SIN = Bamford-Kowal-Bench Speech-in-Noise test; BR = binaural redundancy; CIHA = binaural bimodal fitting; CI-only = monaural-fitted CI; HA-only = bimodal users with monaural-fitted hearing aid; HS = head-shadow effect; NCI = speech presented from the front and noise at the 90° azimuth on the CI side; NF = speech and noise both presented from the front; NH = normal hearting; NHA = speech presented from the front and noise at the 90° azimuth on the hearing-aid side; NS60 = noise presented from the 60° azimuth on the CI side, and speech presented from the 60° azimuth on the hearing-aid side; SQ = binaural squelch; SRM = spatial release from masking; SRiN = speech recognition in noise; SSN = Speech spectrum-weighted noise.

[a] data estimated from the figure.

2.4.3.1 Studies for Adults with CIHA

Bimodal CIHA fittings provide binaural hearing for monaural CI recipients by combining a monaural CI with an HA on the contralateral ear. The SRiN performance of people with CIHA fittings relative to monaural CI ones were studied in adults and children.

When speech and noise arrive from the same location, several studies have reported that the speech recognition scores of adults were significantly improved (10–20%) from monaural CI to CIHA fittings (Ching et al., 2004; Mok et al., 2006). With the popularisation of CI, the results of wider scope research conducted in other countries and language environments have agreed with these results. Illg, Bojanowicz, Lesinski-Schiedat, Lenarz, and Buchner (2014) investigated 141 adult CI recipients with different degrees of residual hearing in Germany and found that 106 patients with residual hearing in the non-implanted ear (threshold < 80 dB HL) at low frequencies (125 and 250 Hz) using CIHA fittings showed significant improvement in SRiN scores compared to monaural-fitted CIs (approximately 12–16%). Blamey et al. (2015) conducted a retrospective multi-centre study involving 15 international centres in Europe with 2247 adult CI recipients and concluded that SRiN performance was significantly greater in the CIHA group than in the CI one (approximately 9% improvement). In contrast, Morera et al. (2005) investigated 12 adults with CIHA fittings and reported that although 6 participants showed significant binaural benefit with CIHA compared to the monaural CI fitting, the benefit was not significant for the whole group. Furthermore, Crew et al. (2015) stated that CIHA fitting slightly, but not significantly, improved the SRiN performance of CI fittings. The researchers inferred that the insignificant benefit was potentially owing to the small sample size (*N*=8) in the analysis and the considerable cross-subject variability of the SRiN performance in their data.

When speech and noise arrive separately from different directions, researchers also evaluated the binaural benefits of CIHA fittings. Iwaka et al. (2004) investigated the SRiN performance of participants with CIHA versus monaural CI fittings for the noise at 90° azimuths under both the HA (NHA) and CI (NCI) conditions, respectively. They reported that the SRiN performance was not significantly different for the CIHA and monaural CI fittings under either the NHA or NCI condition. The authors did not provide explanations for the observed binaural deficits. In contrast, Ching et al. (2004) used a different test configuration wherein the speech and noise were both at the 60° azimuth on the HA and CI sides (NS60) to assess the potential contribution of the HA on the non-implanted ear. The results showed a significant binaural benefit of the CIHA fitting compared to the monaural CI one (approximately 10–25%). Furthermore, the HA showing the better HS-induced SNR contributed to the binaural benefit (Ching et al., 2004). Several studies used the same test setup as Iwaka et al. (2004) and reported binaural benefits with the CIHA fitting under NHA or NCI conditions. For example, Mok et al. (2006) found that the SRiN performance of the CIHA fitting was significantly better than that of the monaural-fitted CI under the NCI condition (approximately 3-dB SNR improvement) but not under the NHA condition; in fact, one participant performed worse with the CIHA fitting than with monaural-fitted CI under the NHA condition. The authors stated that the binaural disadvantage obtained under the NHA condition with CIHA fitting could be due to the better audibility compensation from the HA side in the mid-to-high frequency range. In addition, the mid-to-high frequency information received from the HA may conflict or interfere with that received from the CI owing to the different positions in the cochlea excited by electric versus acoustic signals. Most of the participant apical electrodes were positioned in the region of the cochlea at 1000–2000 Hz characteristic frequencies. However, these electrodes convey low-frequency (100 Hz) information; therefore, they stimulate the auditory nerves with higher characteristic frequencies. Thus, if the participants have better hearing compensation above 1000 Hz, as provided by the HA, they can perceive the high-frequency information from the HA and low-frequency information from the CI in the same region of the auditory pathway. This could result in conflict and confusion between the information received from the HA and CI. In contrast, Morera et al. (2012) reported that the participants with CIHA fittings compared to the monaural-fitted CIs obtained an SQ of 2.6 dB SNR under the NHA condition but not HS under the NCI condition. The authors reported that, for most participants with CIHA, the CI side provided the primary auditory information; thus, the HS of the HA side under the NCI condition was negated by the dominant SRiN ability of the CI. Veugen et al. (2016) found a significant binaural benefit (approximately 3-dB SNR) for the SRiN performance with CIHA versus monaural-fitted CI under both the NHA and NCI conditions when the automatic gain control (AGC) characteristics of the HA were matched to the CI processor (dual AGC broadband compression with 3- and 240-ms attacks and 80- and 1500-ms releases). Compared to the non-AGC-matched HA (i.e. syllabic multi-channel compression with a 1-ms attack and a 50-ms release), the AGC-matched HA could support a balanced loudness for the dynamic speech signal and improve the binaural benefits.

Furthermore, some researchers have evaluated the SRM for adults with CIHA or monaural-fitted CIs. Gifford et al. (2014) found that when the noise moved from the front to the HA side (FHA), CI recipients could obtain (on average) a 4.9-dB SNR difference between CIHA and 5.7-dB SNR with monaural-fitted CIs. The authors did not report the statistical analysis of the mean difference and whether the SRM was significant. Veugen et al. (2016) reported that the participants with CIHA showed significant SRM (4.4 dB SNR) under the FHA condition, but a significant SRM was not obtained when the noise moved from the front to the CI side (FCI). To explain the absence of the SRM under the FCI condition, the authors inferred that the functional hearing abilities of the CI and HA were asymmetric and that the CI was the dominant device, which contributed mostly to the SRiN performance. Under the NCI condition, the CI was masked in a worse SNR situation, and the HA was in a better SNR situation owing to the HS. Furthermore, the HS could provide ILD cues between the CI and HA sides, and the ILD cues are significant in high-frequency sounds. However, the HA compensated for limited audible function at high frequencies, and it was difficult for the individual to obtain significant ILD cues in the HA. Thus, the HS of the HA was insignificant under the NCI condition and did not contribute to the SRM when the noise moved from the front to the CI side. This explanation was elaborated upon by disentangling the SRM format in the bimodal listeners, as reported by Dieudonné and Francart (2020) (see Section 2.3.1). According to their model (Figure 3), the SRM for the individual with CIHA is dependent on the HS of the CI side (i.e. monaural component) and the differences in binaural benefits (i.e. binaural component). They also found that the binaural component was always either zero or negative in bimodal listeners. Therefore, they concluded that the SRM was a trade-off between the change in the SNR at the CI side and the offset of the change in the SNR at the HA side. Under the FHA condition (panel A in Figure 3), the SNR at the CI side was higher than that at the HA side, resulting in a positive HS at the CI side. Under the FCI condition (panel B in Figure 3), the SNR at the CI side was lower than that at the HA side, resulting in a negative HS of the CI side. Thus, the sum of the monaural and binaural components could result in a significant SRM under the FHA condition but an insignificant SRM under the FCI one.

2.4.3.2 Studies for Children with CIHA

Most of the results in the literature for adult CI recipients were obtained through studies involving post-lingually deafened patients. This possibly enables them to have some experience of binaural hearing, and be able to use acoustic information provided by the HA. However, pre-lingually deafened child CI recipients do not have binaural hearing experience and language skills in the early years, so they may not obtain binaural benefits on the SRiN performance with CIHA fitting (Mok et al., 2007). Ching et al. (2005) evaluated the binaural benefits of children with CIHA and CI fittings in the same test configuration (NS60) as that used for assessing adult CI recipients (Ching et al., 2004). The results indicated that children showed consistent results like those in adults. The SRiN performance with CIHA was also significantly better than that with monaural CI fitting under both the NF (approximately 10% improvement) and NS60 conditions (approximately 15–20% improvement). The researchers explained that head diffraction was a major contributor to the binaural benefit under the speech and noise spatially separated condition. The binaural benefit under the speech and noise co-located condition could be due to the combination of redundant inputs from both ears and/or using the complementary information provided by the HA and CI. A later study (Mok et al., 2007) used the NF, NHA, and NCI conditions to investigate the binaural benefits of children with CIHA fittings and found that the children showed significantly better performance with CIHA than with CI under the NF (1.3 dB SNR) and NCI conditions (2.2 SNR) but not under the NHA condition. The authors also reported that a significant SRM (3.8 dB SNR) was obtained from children with CIHA under the FHA condition, but an insignificant SRM was obtained under the FCI condition. One possible reason for the absence of the SRM when the noise shifted to the CI side was that the children relied on the CI ear more heavily. Several other studies have reported contradictory findings. Litovsky, Johnstone, and Godar (2006) evaluated the speech recognition performance of children with

CIHA versus monaural-fitted CIs in the same setup as the Mok et al. study (i.e. NF, NHA, and NCI) and found that the children did not obtain positive binaural benefits under any noise condition. The authors also reported greater SRM obtained from children with the CIHA fitting under the FHA condition than under the FCI condition, which was in agreement with the study by Mok et al. However, Nittrouer et al. (2013) reported that the children with the CIHA fittings could not obtain significant SRM under the FHA condition, and they did not provide an explanation for the absence of SRM because of the limited data in the study.

From the review of the binaural benefits on the SRiN performance of adults and children with CIHA fittings, the findings indicated that speech recognition abilities in different loudspeaker configurations of the monaural CI recipients could be improved using the CIHA fittings. The binaural benefits on the SRiN performance could result from BR, SQ, and HS. Moreover, there is an alternative potential advantage resulting from using acoustic amplification in the HA-aided ear contralateral to the CI-aided ear. The CI and HA in bimodal fitting could provide different information. Low-frequency sounds transmitted by an HA and high-frequency sounds transmitted by a CI complement each other, which could also improve the SRiN performance. Thus, this advantage is referred to as binaural complementarity (Ching et al., 2006b; Ching et al., 2007). Individuals can use the difference in voice pitch or fundamental frequency (F0) (Drullman & Bronkhorst, 2004), and frequency and amplitude modulations in the F0 and harmonics (Binns & Culling, 2007) to discriminate and segregate speech in noise (Carroll et al., 2011). Current CI devices cannot convey F0 information very efficiently, leading to poor SRiN performance in CI recipients (Carroll & Zeng, 2007; Luo et al., 2009; Stickney et al., 2004). The electric stimulation of a CI is restricted to a limited number of effective frequency channels and a limited spread of electrode locations, which cannot sufficiently resolve F0 or its harmonics. Some studies have shown that combining low-frequency acoustic information with electric stimulation information could significantly improve SRiN performance (Brown, C. A. & Bacon, 2009; Carroll et al., 2011; Kong et al., 2005; Zhang et al., 2010). In tonal languages, such as Mandarin Chinese, F0 is also crucial for conveying the lexical tone information beneficial for speech intelligibility because the tonality of a monosyllabic word signifies the specific lexical meaning of the word (Fu et al., 1998; Liang, Z. A., 1963; Lin, 1988). While Mid-to high-frequency speech signal contain linguistic information of consonants in tonal and non-tonal languages (Hu, Xu Jun et al., 2019; Miller & Nicely, 1955). Therefore, the low-frequency information provided by the HA complements the mid-high-frequency information provided by the CI to enhance the speech recognition performance of individuals with CIHA fittings.

The aforementioned studies indicated a trend of significant individual differences among adult and child CI recipients (see individual results in Table 2). Although certain people with CIHA fittings could integrate acoustic and electrical information in the binaural hearing system to alleviate certain difficulties of understanding speech in noise, others performed worse than monaural people with CI fittings, suggesting ‘binaural interference’ (i.e. Dunn et al., 2005; Illg et al., 2014; Mok et al., 2006). HA and CI may somehow negatively interact in the central auditory system, which is a typical concern for the bimodal fitting (Sammeth et al., 2011). Owing to the independent processing strategies between the HA and CI regarding the pitch, dynamic range, and shape of iso-loudness curves of sound, certain inter-aural mismatches occur in the bimodal fitting, which could potentially lead to binaural interference (Blamey et al., 1996; Blamey et al., 2000; Warren & Dunbar, 2018). For example, hearing loss is typically more severe at high frequencies at the cochlear base. The current HA is often unable to provide adequate amplification at high-frequencies because of the limited bandwidth (Ching et al., 2007; Pittman & Stelmachowicz, 2003; Stelmachowicz et al., 2004).

In contrast, the high frequencies of the incoming signal can be analysed and represented in the CI (Stelmachowicz et al., 2004). Although high frequencies are conveyed by the basal electrodes while low frequencies by the apical electrodes are tonotopically conveyed, the stimulation representing a certain frequency region of the incoming signal will not necessarily occur in the respective tonotopic frequency regions in the cochlea (Polonenko, 2018; Reiss et al., 2014). The processor of the CI can analyse approximately 250 to 8000 Hz frequencies, but the electrode array can cover only the basal turn and not the entire cochlea length. Therefore, the frequency allocation is always shifted to the higher frequency tonotopic regions, resulting in a mismatch between the frequency-to-electrode allocation and the stimulation region along the cochlea. Furthermore, the negative effect of the spectral mismatch on auditory perception can be aggravated if the amplified acoustic inputs are presented in the non-implanted ear with HA fitting (Warren & Dunbar, 2018).

ITD is an important cue for binaural benefits (see Section 2.2). The normal human auditory system is sensitive to ITD cues and can detect a change as small as 10 μs (Yost, 1974). The largest ITD is approximately 700 μs for the normal head size when the sound is presented from the 90° azimuth of the individual (Zirn et al., 2015; Zirn et al., 2019). For individuals with CIHA, the HA side receives signals through a microphone and thereafter, compresses and amplifies them. Subsequently, the HA can deliver processed signals in the ear canal, following which the physiological hearing process starts. Compared to the ear with NH, the HA extends the entire acoustic pathway by adding a signal processing delay. In contrast, the CI side can bypass the outer and middle ear and directly stimulate the auditory nerves using electrodes (Zirn et al., 2015). Generally, sounds transmitted by the CI to the auditory system are faster than those transmitted by the HA with processing delays. Thus, ITD cues are superimposed by a constant inter-aural timing mismatch between the CI and HA, resulting in a ‘device delay mismatch’ (Zirn et al., 2019). The timing differences in signal processing and delivering between the current CI and HA (device delay mismatch) can be up to 7–9 ms, which is more than 10 times as large as the largest ITD. Thus, the central auditory system of individuals with CIHA needs to compensate for this large inter-aural temporal stimulation mismatch, which may increase listening effort and affect the sound localisation and SRiN performance (Zirn et al., 2015; Zirn et al., 2019).

In clinical practice, matching loudness between bimodal devices is another potential challenge for bimodal fitting, especially for young children, because it can be difficult to compare/judge the loudness level of sounds between the HA and CI (Dincer D’Alessandro et al., 2015; Litovsky et al., 2006). Nevertheless, loudness matching is critical for optimising CIHA fitting outcomes for SRiN performance, and abnormal loudness growth across a range of frequencies can lead to both within-ear and inter-aural sound perception problems (Warren & Dunbar, 2018). For example, Ching, Psarros, Hill, Dillon, and Incerti (2001) adjusted the HA using a systematic procedure to balance loudness between the HA and CI for children with CIHA fitting. The authors found that the SRiN score with the CIHA fitting was significantly better with the adjusted HA than with the non-adjusted HA (10% improvement). In addition, the SRiN score significantly improved by 10% from monaural CI to CIHA fitting with adjusted HA (binaural redundancy benefit), but BR was not observed between monaural CI and CIHA fittings with non-adjusted HA.

2.4.4 Studies for Mandarin Chinese-Speaking Populations

SRiN performance in most aforementioned studies (Table 1 and 2) is in English-speaking populations with hearing loss using HAHA or CIHA fitting. English is a non-tonal language belonging to the Indo-European language family. However, Mandarin Chinese is a tonal language that belongs to the Sino-Tibetan language family (Zhu et al., 2011). Mandarin Chinese has four lexical tones with different F0 contours: high-flat (lexical tone one), rising (lexical tone two), falling-rising (lexical tone three), and falling (lexical tone four). Different lexical tones can convey different meanings, even if the syllable is the same (Luo et al., 2009). For example, '花 (Hua, Lexical tone one)' means 'flower', and '画 (Hua, Lexical tone four)' means 'drawing'. Some researchers (Fu et al., 1998; Kong & Zeng, 2006; Zhu et al., 2011) found that, compared to the consonant and vowel portions, acoustic cues (the change in F0 during phonation, temporal envelope, amplitude contour cues, and periodicity cue) of lexical tones are not easily disturbed by external factors, such as filtering, infinite clipping, adding noise, or short distance. Thus, compared to signals without lexical tones, the signals with lexical tones can strongly contribute to the perception of words and sentences, which results in an improvement in the overall SRiN performance in lower SNR conditions. Li et al. (2019) reported that, for participants with mild to severe sensorineural hearing loss, the speech recognition score in noise with the flat-tone sentence, where the lexical tones were changed to lexical tone one within sentences, was significantly (approximately 20–25%) lower than the score with the natural-tone sentence, where no changes were made to lexical tones within sentences. In addition, Chen, Y. et al. (2020) also found that participants with HAHA fitting achieved significantly (approximately 40%) worse speech recognition scores in noise with flat-tone sentences than with natural-tone sentences. Thus, based on these benefits in the tonal language, the SRiN performance of Mandarin Chinese-speaking population with hearing loss may be different from that of non-tonal language speakers.

Chinese speech audiometry started in the 1950s, and it was not promoted until the twentieth century (Bu & Ni, 2008; Xi, 2008). In recent years, some researchers have started to focus on speech recognition and binaural hearing in Chinese-speaking populations. However, the number of studies focussing on Mandarin Chinese-speaking populations with NH or HL hearing loss is still limited. Earlier studies have observed listeners with normal hearing. Meng et al. (2013) investigated the development of SRiN performance in 174, 2–5-year-old children with NH using the Mandarin Paediatric Speech Intelligibility (MPSI) Test. The speech was presented from the front of the participant, while noise was presented from behind with five fixed SNR levels (+10, +5, 0, −5, and −10 dB SNR). The participants progressed to each noise condition from +10 to −10 dB SNR, and the SNR condition wherein a participant could not achieve a 41.7% score was defined as the final SNR reached by the participant. The study reported that the children developed the ability to understand speech in noise at a very early stage (approximately 2 years old), and the final SNR reached by the 4–5-year-old children was approximately −5 SNR, which was significantly lower than the final SNR reached by the 2–3-year-old children. Yuen et al. (2009b) studied SRM obtained from 4–9-year-old children with NH and found that the children could show an SRM of 5.9 dB SNR and a 5.0 dB SNR with disyllabic word and lexical tone recognition test, respectively. Later, these researchers studied adults with NH and reported that the performance improved with age, with an average of 0.1–0.15 dB per month until age 9 in the speech and noise spatially separated conditions but not for the NF condition (Yuen & Yuan, 2014). Yuen et al. (2019) used an adaptive procedure of speech-in-noise test with disyllabic words to measure the SRM of children with NH aged 4.83–5.25. They reported that the children could perform SRM of 6.66 (*SD*=1.53) dB SNR when the noise moved from the front to left, and an SRM of 6.77 (*SD*=4.23) dB SNR when the noise moved from the front to right.

Certain studies have investigated the SRiN performance of Mandarin Chinese (Table 3), but most of them only evaluated the performance in one loudspeaker configuration (for example, speech and noise co-located condition). Chen, Y., Wang, Wang, Chen, and Lin (2014) compared the SRiN performance of adults with HAHA and monaural HA in the co-located condition where the speech and noise were presented from a +45° or/and −45° azimuth at the aided side, and reported that scores of the HAHA group were significantly higher (7%) than those of the monaural HA group. Other researchers reported that the lexical tone recognition of adults with CIHA fitting was significantly (10–15%) better than with CI fitting in the NF condition (Li, Y. et al., 2014; Wei et al., 2017). In addition, studies involving children with CIHA fitting reported results similar to those of adults. Their results showed that the SRiN performance of children with CIHA fitting significantly improved from monaural CI fitting in the NF condition (Li, L. et al., 2016; Tao et al., 2018; Zhao, 2013). In contrast, Yuen et al. (2009) reported that the word and lexical tone recognition performance of children with CIHA fitting was not significantly better than that with CI fitting in the NF condition. However, in the NCI condition, the researchers found a significant HS on the word and lexical tone recognition performance of children with CIHA fitting when compared to monaural CI fitting. Thus, the authors suggested that the children with CIHA fitting could not develop central binaural processing abilities to improve SRiN performance when the speech and noise were mixed; and more data from the speech and noise separated condition were required to support this conclusion.

There is little scope to compare the findings of cross-linguistic studies using existing published research due to significant differences in participant characteristics, languages, assessment setups, and analysis methods. Moreover, in most of the aforementioned studies, the binaural benefit on the SRiN performance was only investigated under NF conditions. Therefore, more studies are necessary to measure the binaural benefit of Mandarin Chinese-speaking populations with HAHA or CIHA fittings, and to investigate how spatial cues play a role in the SRiN performance in other setup conditions, such as noise presented from one side. With more studies investigating binaural and spatial benefits in different HA or CI device fitting conditions, the empirical evidence can offer appropriate and specific fitting strategies and hearing rehabilitation approaches for young children in clinical practice.

Table 3 *SRiN and SRM for Mandarin-Speaking Individuals from Previous Studies*

Study	Participant			Outcome measure					Binaural benefit (bilateral fitting versus unilateral fitting)		SRM (co-located condition versus spatial separated condition)		Comment
	N	Age (mean, years; months)	Pure-tone threshold (mean, dB HL)	Stimuli presented from front	Noise	SNR	device fitting condition	Noise direction	Average group result (mean difference, dB SNR)	Individual result (*n*)	Average group result (mean difference, dB SNR)	Individual result (*n*)	
Chen, Yu, Wang, Wang, Chen, and Lin (2014)	HAHA group: 21 Monaural HA group: 26	55-89 (70.48) 55-77 (69.81)	Unaided 4FA:71.71 Unaided 4FA: 69.32	Sentence Sentence	4BN	+5	HAHA Monaural HA	NS45 NS+45/ NS-45	HAHA group>Monaural group (7%)				The study compared results from two groups, but did not compare within-participant results
Wei et al. (2017)	12	8-33	250-4000 Hz: Aided threshold of CI ear: 25-33 Aided threshold of HA ear: 41-57 Unaided threshold of HA ear: 75-95	Lexical tone	1BN	+10, +5, 0	CI-only; HA-only; CIHA	NF	CIHA>CI-only (10-15%) in all SNR level				There was only one child in the participants. The study only tested NF direction, thus it only investigated the binaural redundancy benefit.
Li, Y., Zhang, Galvin III, and Fu (2014)	12	16-24	250-2000 Hz: Aided threshold of HA ear: 38-75 Unaided threshold of HA ear: 54-101	Lexical tone, vowel, consonant	SSN	+5	CI-only; CIHA	NF	Lexical tone: CIHA>CI-only (13.4%); Vowel: CIHA=CI-only; Consonant: CIHA=CI-only;	Lexical tone: +3, -1; Vowel: +3; Consonant: +3, -2;			There were three 16 years old teenagers in the participants. The study only tested NF direction, thus it only investigated the binaural redundancy benefit. The study did not report the binaural benefit results of all individuals.
Li, L., Ye, Wang, Bai, and Zhu (2016)	18	1.9-7.0 (3.6)	Not reported average results	Sentence, disyllabic word, monosyllab ic word	SSN	+10	CI-only; CIHA	NF	Sentence: CIHA>CI-only (7%) Disyllabic word: CIHA>CI-only (9%) Monosyllabic word: CIHA>CI-only (1%)				The study only tested NF direction, thus it only investigated the binaural redundancy benefit.
Tao, Liu, Yang, Wilson, and Zhou (2018)	17	5.85-38.02	125-500Hz: Aided threshold of HA ear: 58-68 Unaided threshold of HA ear: 75-95	Sentence	SSN	+5	CI-only; HA-only; CIHA	NF	CIHA>CI-only (10%[a])	+4, =13			There were six adults with prelinguistic hearing loss in the participants. The results included children and adults. The study only tested NF direction, thus it only investigated the binaural redundancy benefit.
Zhao (2013)	39	3.5-6.5 (4.9)	Unaided 4FA of HA ear: 97	Sentence, disyllabic word	4BN (sentence), SSN (disyllabic word)	Adaptive	CI-only; CIHA	NF	Sentence: CIHA>CI-only (2.12) Disyllabic word: CIHA>CI-only (1.28)				The study only tested NF direction, thus it only investigated the binaural redundancy benefit.

Yuen et al. (2009a)	15	10; 2 (5; 1-14; 4)	Not reported average results	Lexical tone, disyllabic word	SSN	Fixed, and individually set	CI-only; CIHA	NF, NCI	NF (BR): Disyllabic word: CIHA=CI-only; Lexical tone: CIHA=CI-only; NCI (HS): Disyllabic word: CIHA>CI-only (23.4%); Lexical tone: CIHA>CI-only (16.5%)	NF (BR): Disyllabic word: =4; Lexical tone: +1, =3; NCI (HS): Disyllabic word: +7, =5; Lexical tone: +5, =7;		12 participants were assigned to finish NCI (HS) condition, and four participants to finish NF (BR) condition. One participant participated in both conditions. The sample size in The NF condition was small.

Note. 1BN = one-talker babble noise; 4BN = four-speaker bubble noise; 4FA = average hearing threshold for 500, 1000, 2000, and 4000 Hz; BR = binaural redundancy; CIHA = binaural bimodal fitting; CI-only = monaural cochlear implant fitting; HA = hearing aid; HAHA = binaural hearing aid fitting; HA-only = bimodal users with monaural hearing aid fitting; HS = head-shadow effect; NCI = speech presented from the front and noise at 90° azimuth on the cochlear implant side; NF = speech and noise both presented from the front; NS+45/NS−45 = speech presented from the front and noise at +45° or −45° azimuth on the monaural hearing aid side; NS±45 = speech presented from the front and noise at +45° and −45° azimuth both; SRM, spatial release from masking; SSN, speech spectrum-weighted noise.

[a] estimated data from the figure

2.5 Hearing Loss and SRiN Performance

Hearing and speech recognition are the two most important foundations of communication for individuals with NH. Hearing loss significantly impacts the ability to detect, discriminate, recognize, and comprehend speech, and hence affects the communication that one has in life. This ability of individuals with hearing loss is more impacted in noisy environments than that in quiet environments. Plomp (1978) classified speech hearing loss as attenuation (class A) loss which is a reduction in hearing levels of both speech and noise, and distortion (class D) loss, which is a decrease in the speech-to-noise ratio for recognising speech in noise. The author stated that the attenuation loss is more related to the recognition difficulty in quiet conditions, while the distortion loss is more related to the recognition difficulty in noise. Many researchers highly regard hearing, speech, and communication in noise performance of individuals with hearing loss, so they have tried to evaluate the SRiN performance and investigate the potential causes of the difficulty in recognising speech in noise. Previous studies have investigated the relationship between SRiN performance and the pure-tone threshold, and reported that the pure-tone threshold (hearing loss through 500–4000 Hz) could explain 70–85% of the variance in SRiN performance (Divenyi & Haupt, 1997b; Humes et al., 1994; Jerger et al., 1991). Thus, studies have revealed that hearing loss or hearing sensitivity is the primary factor for predicting the SRiN performance of individuals with hearing loss, especially in the elderly population (Divenyi & Haupt, 1997a; Humes & Roberts, 1990). Other researchers found that, although the SRiN performance of individuals with NH is homogeneous and has less variation (Festen & Plomp, 1981), the SRiN performance of individuals with hearing loss had large individual variations irrespective of their hearing threshold (Killion, 1997; Killion & Niquette, 2000). The hearing loss and SRiN performance are Furthermore discussed in Section 2.5.1 to investigate whether a relationship exists between them from the perspective of audibility.

2.5.1 Speech Intelligibility Index

To quantify the audibility proportion of long-term speech sounds, the American National Standards Institute (ANSI) proposed the Speech Intelligibility Index (SII) in 1997 (ANSI, 1997). Unlike pure-tone audiometry, which measures the level of hearing loss and describes the hearing sensitivity of pure-tone signals, SII was developed to calculate the weighted audibility of individual frequency regions of speech signal in a specified speech test, and represent the amounts of useful speech information for the individual (ANSI, 1997; French & Steinberg, 1947; Hornsby, 2004; Stiles et al., 2012).

2.5.1.1 SII Calculation

Speech articulation theory was developed in the 1950s at Bell Telephone Laboratories, and engineers in the laboratory used the articulation model (Articulation Index, AI) to predict speech intelligibility transmitted through different telecommunication devices under varying electroacoustic conditions (French & Steinberg, 1947). The basic procedures and parameters in the AI model computation were standardised in ANSI S3.5-1969 (ANSI, 1969; Pavlovic, 1987). In the audiology profession, this model was used to quantify the correlation between audible speech cues and speech intelligibility (Amlani et al., 2002). Considering the critical concept of predicting speech intelligibility, the SII was adopted to replace the AI in the new ANSI S3.5-1997 standard, which was a revision of the ANSI S3.5-1969. As AI and SII shared a common ancestry, there were many similarities between AI and SII. For example, they were both developed based on the underlying theory that AI and SII are quantitative ways to measure audible speech information for a listener and predict speech intelligibility (Hornsby, 2004). However, the AI and SII calculations were not identical, with the major difference being that the 1997 standard provides a more general framework for calculating SII, so researchers can flexibly determine input variables such as equivalent speech and noise levels and auditory threshold. In addition, the 1997 standard was extended to include new parameters and procedures in the calculation, such as the self-speech masking spectrum level (V_i), slope per octave of the upward spread of masking (*Ci*), and speech level distortion factor (L_i). SII is a proportional index based on the summed audibility of weighted speech bands in quiet and competing noise, and is defined in Equation 1 as follows:

$$SII = \Sigma I_i A_i \qquad (1)$$

To avoid confusion, the SII will be used throughout the remainder of this thesis to refer to the procedures described in the newer 1997 standard. In the formula, the frequency-importance function (I_i) represents the contribution of a given frequency band (i), and the relative frequency-importance function of various frequencies for different speech materials provided in the 1997 standard. The audible function (A_i) represents the amount of speech energy above the listener's hearing threshold and competing noise in each frequency band (i). The function also involves several modifications and variables that highlight the primary differences between the SII and AI calculations in the two standards, such as the spread of masking, standard speech spectrum level, and speech level distortion factor. The SII value ranges from zero to one, with a value of zero indicating that no speech cues are audible, while a value of 1 indicates that all speech cues are audible. In a noisy condition, the speech cues are mixed with competing noise, which are rendered certain parts of speech being masked by the noise, and thus, the speech audibility depends on the SNR in the frequency bands. In a quiet condition, the hearing threshold also limits audibility in the same manner as noise, and thus, the hearing threshold can be transferred to a hypothetical ‘internal noise’ using conversion factors in the 1997 standard to calculate the SII in quiet conditions (Hornsby, 2004).

2.5.1.2 SII and Speech Recognition Performance

SII can be used to predict speech recognition performance by a transfer function (TF) that was first expressed as an equation (Equation 2) by Fletcher and Galt (1950), and modified by Studebaker, McDaniel, and Sherbecoe (1995). The TF is a power function and is represented as an s-shaped curve, as follows:

$$S = (1-10^{-AP/Q})^{N} \qquad (2)$$

where S is the score in proportion correct, A is the SII value in the ANSI S3.5-1997 standard, P is a proficiency factor, and Q and N are the fitting constants depending on the speech material and listeners tested, respectively. The proficiency factor was first proposed by (Fletcher & Galt, 1950) to modify the predicted speech intelligibility and it explains variations in the enunciation of the speaker and the familiarity of the listener with the speaker; thus, the maximum value would be 1 if the listener has normal hearing and the speaker and listener use the same dialect. In addition, other researchers found that proficiency was also related to age and hearing loss in the listener (Scollie, 2008; Studebaker et al., 1997). Furthermore, as the proficiency factor influenced the overall SII performance, it was applied to the TF after the SII calculation where the values of Q and N determine the slope and curvature of the s-shaped curve, and speech recognition performance in percent-correct monotonically increases with the SII values for listeners with normal hearing (Scollie, 2008).

The use of the TF with SII value to predict SRiN performance has been proven to be valid for listeners with NH or mild to moderate hearing loss (French & Steinberg, 1947; Lee & Mendel, 2017; Pavlovic, 1984; Pavlovic et al., 1986). However, it is limited to using the TF with SII as a predictor for the SRiN performance of listeners with severe to profound hearing loss, such as CI recipients, because of the deterioration in auditory processing and large individual variability in speech recognition performance among CI recipients (Ching et al., 1998b; Lee et al., 2019; Pavlovic, 1984; Scollie, 2008). To improve the feasibility of using the SII to predict the speech recognition performance of listeners with hearing loss, some researchers have proposed various correction factors to modify the SII calculation, such as the proficiency factor, hearing loss desensitisation factor, duration of deafness, auditory processing factor, and cognitive function factor (Amlani et al., 2002; Lee et al., 2019; Pavlovic et al., 1986; Scollie, 2008; Sherbecoe & Studebaker, 2003). The modifications in these studies were developed from a particular group of participants of various ages and auditory capacities using different speech materials and procedures, which is difficult to generalise the modifications to other studies (Amlani et al., 2002; Scollie, 2008). Thus, the present study attempted to use a relatively simple prediction model without these modifications to investigate whether the aided

SII of HA or CI can predict the SRiN performance of children with HAHA and CIHA fitting.

2.6 Summary of Research Gaps

Binaural HAHA and CIHA fittings are both recommended methods in clinical fitting practice for individuals with bilateral hearing loss (American Academy of Audiology, 2013; Valente et al., 2006). However, many individuals with bilateral hearing loss use only one hearing device on one ear, possibly owing to uncertainty about the magnitude of bilateral fitting benefits and the additional cost of buying one more HA. Therefore, Furthermore evidence from research on the effectiveness of binaural versus monaural hearing is important to guide patient selection for hearing prosthesis fitting.

Previous studies have reported some results regarding the SRiN performance of individuals with HAHA or CIHA fitting. Many studies have measured the SRiN performance in only one simple noise configuration (that is, noise and speech both from the front), so only the co-located test condition may lead to under-predicted binaural benefits provided by a second hearing device. Furthermore, some researchers have only investigated the group binaural and spatial benefits, rather than the intra-participant binaural and spatial benefits on performance. Group results can provide a good argument for the standard fitting model (i.e., bilateral hearing device fitting), but cannot allow individual predictions (i.e., the second hearing device may be useful or detrimental for an individual). Moreover, though tonal languages (that is, Mandarin Chinese) are widely used in the world, with approximately 1.3 billion people speaking

Mandarin Chinese (Vandali et al., 2017), most sound processing strategies in the CI were designed based on non-tonal languages (English) (Liu et al., 2017). In addition, most studies have been conducted in the English-speaking population, but only a few studies have been conducted on the Mandarin Chinese-speaking population. In the case of young Mandarin Chinese-speaking children, there were less studies than that on adults. Therefore, it is unclear whether the binaural and spatial benefits on the SRiN performance of non-tonal languages-speaking population can be shared with the Mandarin Chinese-speaking population with hearing loss. Thus, these research gaps have been addressed in the present study. Mandarin Chinese-speaking preschool children (aged 3–7 years) with severe to profound hearing loss using HAHA or CIHA fitting were recruited and their SRiN performance was measured in different noise directions to investigate all binaural and spatial benefits on the performance. Although many previous studies (Table 1-3) have reported group statistics, none have reported individual statistics using an intra-participant statistical comparison. The SRiN performance in children with hearing loss may have great individual variability. For example, most children can obtain significant binaural benefits, but few can even perform binaural disadvantages, which may be excluded or covered in the group statistics. Thus, the intra-participant statistical comparison can report the individual statistics for each child and according to the individual results, clinicians can provide personalised suggestions for a fitting approach or hearing rehabilitation for individuals experiencing hearing loss.

2.7 Research Questions and Hypotheses

Given the problems in the previous studies stated in the last section, several research questions were formulated for this study. The SRiN performance was evaluated in two groups of participants, children with HAHA (HAHA group) and CIHA (CIHA group). The binaural hearing condition was fitted with the HAHA and CIHA. In the HAHA group, the monaural hearing condition referred to either a unilateral HA on the left ear (HAL) or a unilateral HA on the right ear (HAR); in the CIHA group, it referred to a unilateral CI in one ear and the other ear without obstruction/hearing device. The speech was presented from 0° azimuth while the noise was presented from 0°, +90°, or −90° azimuth. The specific questions addressed in both the HAHA and CIHA groups were as follows:

1. Is there any significant binaural benefits on SRiN performance of children listening in binaural versus monaural hearing condition in each of the three noise directions?
2. Is there any significant SRM for children listening in binaural and monaural hearing condition?
3. Is there any significantly different SRM for children listening in binaural hearing condition versus monaural hearing condition?
4. Can the speech intelligibility index (SII) obtained from either monaural hearing condition predict the SRiN performance of children in each of the three noise directions?

The hypotheses for the research questions were as follows:

1. According to the findings from individuals with different device fitting conditions in the previous studies, SRiN performance of children listening in binaural hearing condition will be significantly better than those

listening in monaural hearing condition, so significant binaural benefits on SRiN performance will be obtained by the participant listening in binaural hearing condition in each of the three noise directions.

2. According to the findings from individuals in different noise conditions in the previous studies, for the HAHA group, a positive SRM was shown in children with HAHA fitting. Furthermore, SRM will only be shown in children with monaural HA fitting when the noise moves from the front to the unaided side due to HS, but it will not be shown in children with monaural HA fitting when the noise moves from the front to the aided side. In addition, for the CIHA group, the positive SRM will only be shown in children with CIHA and CI when the noise moves from the front to the HA side, but will not be shown in children with CIHA and CI when the noise moves from the front to the CI side. The binaural component cannot contribute to the SRM in bimodal listeners, and the better SNR at the CI side due to HS (monaural component) is only involved in the SRM.
3. According to the disentangled SRM framework, the SRM for children listening in binaural hearing condition will be significantly better than those listening in monaural hearing condition when the noise moves from the front to the monaural aided side. However, the SRM for children listening in binaural hearing condition cannot be significantly different from those listening in monaural hearing condition when the noise moves from the front to the monaural unaided side.
4. According to the relationship between audibility and speech recognition, the aided SII obtained from the monaural HA ear predicts the SRiN

performance. For the CIHA group, the aided SII obtained from the monaural HA and CI ears is difficult to predict for the SRiN performance.

Chapter 3: Method

3.1 Participants

Native Mandarin Chinese-speaking children with binaural hearing aid fitting or bimodal fitting using an oral-only communication mode were recruited in one hearing and speech rehabilitation centre in Zhengzhou, China. The present study recruited 27 children in the HAHA group and 37 children in the CIHA group. All 64 children volunteered to participate in the study. Written consent forms were signed by their parents or guardians, adhering to the Human Research Ethics policy of The Education University of Hong Kong. This study was approved by the Human Research Ethics Committee (Ref. no. 2017-2018-0371).

This study had two participant recruitment criteria. First, the recruited children who could not score 100% in the familiarisation procedure of the speech recognition test in quiet conditions were excluded from the study (see Section 3.3.3.3). Four children (HAHA-F5, HAHA-F6, CIHA-F13, and CIHA-M14) were excluded following this procedure. Second, the children who completed the familiarisation task but could not finish one testing round in the speech recognition test in noise were also excluded from the study. Subsequently, four children (HAHA-F10, HAHA-M3, CIHA-M9, and CIHA-M11) were excluded after this procedure as when background noise was introduced to the speech recognition test, these four children were not willing to participate in the test or provide a response. Although non-compliance is typical in studies of children at a very young age, the remaining participants were able to complete all test conditions in noise, including some children younger than those four children, thus the age of participants may not be a factor that caused the four children to be unable to finish test conditions in noise. One reason was that these children rarely experienced very noisy (very worse SNR) auditory environments in daily life, as compared to the noisy environments in the present study. The noisy listening condition was too puzzling and difficult for them, hence, they refused to continue to finish the test in noise. In addition, HAHA-F10 and HAHA-M3 were fitted with HAHA fitting for less than six months, while CIHA-M9 and CIHA-M11 were fitted with CIHA fitting for six and eight months, respectively, but CIHA-M9 and CIHA-M11 were not fitted with HA on both ears before cochlear implantation. Therefore, compared to other participants, their limited binaural hearing experience could easily cause listening fatigue in noisy environments.

Finally, a total of 23 children (10 girls; 13 boys) in the HAHA group and 33 children (14 girls; 19 boys) in the CIHA group completed all test conditions in this study. According to the sample size estimation—24 children for each group—in G*Power 3.1.7 using an effect size of 0.6 (Faul et al., 2009) and a power level (1-β) of 0.8 with a significance level of 0.05 (α) for a paired t-test, the number of participants is sufficient for obtaining power suitable for the analysis of the group results. The mean age of the 23 participants with HAHA was 4.4 years, ranging from 2.9 to 7.5 years, and the mean age of the 33 participants with CIHA was 4.6 years, ranging from 3.1 to 6.6 years.

Most participants (91%) in the present study were diagnosed with hearing loss before age 3, and the rest were diagnosed after that. Nearly half of the participants (45%) underwent new-born hearing screening for the rest of participants, the results of which were unclear. Almost all the parents of these participants reported that their children were born at hospitals in non-urban places. Hospitals did not supply the new-born hearing screening program for the children, and thus children with hearing loss were not identified early. Some participants (10/13 in the HAHA group and 16/18 participants in the CIHA group) who did not receive the new-born hearing screening test were not diagnosed with hearing loss until the parents found that they had delayed speech and language development. Subsequently, the participants were fitted using different models of devices. Before they arrived in the lab, the hearing prostheses used in the present study were independently fitted and programmed by clinicians who were not involved in the study; therefore, information about specific signal processing was not available. The device settings were selected as per the participants' preference based on their daily lives and did not change during the data collection. The demographic information of the individual participants is presented in Appendix A.

All participants in the HAHA group were bi-laterally fitted simultaneously, except for one participant, HAHA-M11, who was fitted first on the left ear and was then fitted on the right ear within three months. The participants were full-time HAHA users (≥ 10 hours/day) for over six months. In the present study, only one participant, HAHA-F11, had binaural conductive hearing loss, and the rest had sensorineural hearing loss. For the CIHA group, the participants were fitted with CI for at least one year, and HA on the contralateral ear simultaneously or sequentially after the CI was fitted. Most of the participants (29/33) fitted the HA within the first year after CI surgery. The remaining participants (4/33) were fitted with HA in the second or third year after CI surgery. All the participants had been full-time postoperative bimodal users (≥ 10 hours/day) for over six months, except for three participants: CIHA-M10 and CIHA-M21 who had used bimodal fitting for three months, and CIHA-M22 who had used bimodal fitting for five months. Furthermore, before cochlear implantation, although most of the participants had experienced a bilateral hearing aid for over six months, in the audiology assessment, they had not received any benefits on the hearing and speech skills development from them. In the present study, the participants had severe to profound hearing loss in the non-implanted ear, and the monaural HA device fitting condition was too difficult for them to complete the speech test in noise; thus, the monaural HA device fitting condition was excluded.

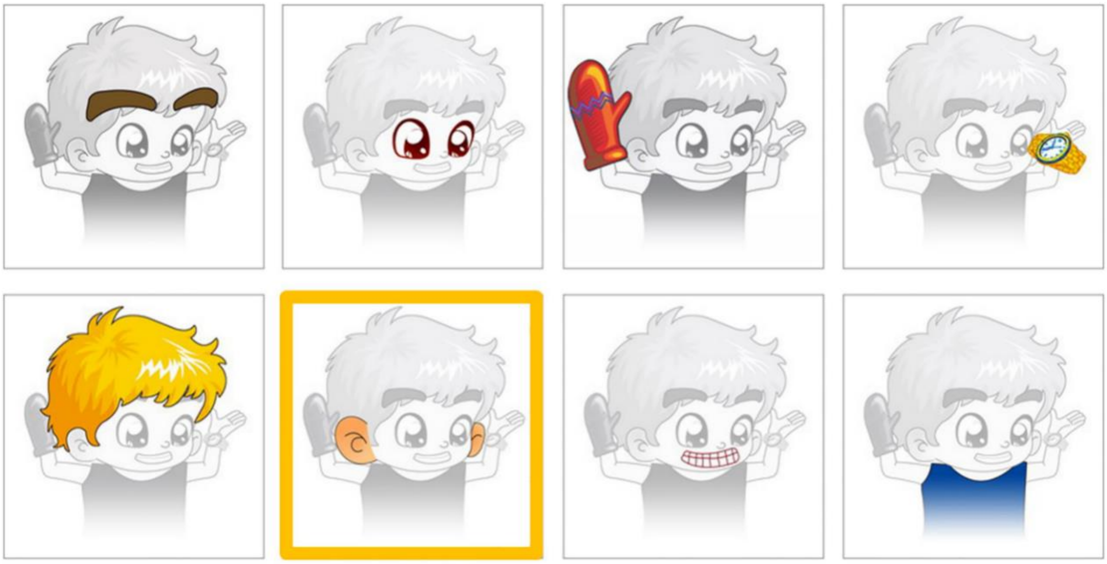
3.2 Materials

The study used the Mandarin Spoken Word-Picture IDentification Test (Adaptive version) custom software (MAPID-A) to yield an adaptive signal-to-noise ratio for a 50% correct score (aSNR-50%) as the outcome measure for the SRiN performance (Yuen et al., 2019). In the Mandarin Chinese-speaking population, the MAPID-A is the first objective assessment tool with paediatric speech materials to investigate SRiN performance using an adaptive method. The adaptive speech-in-noise test can provide the threshold level result (aSNR-50 %) and error estimates, such as *SD*, *SE*, and *99% confidence interval*, for the intra-participant comparison, which can detect any statistically significant changes in the SRiN performance under different test conditions. Therefore, the MAPID-A provides a valuable opportunity to track intra-participant changes in the SRiN performance of young children if they adopt new hearing prostheses, processing algorithms, or coding strategies, or participate in intervention or rehabilitation programs.

In MAPID-A, speech stimuli are spoken by an adult female native Chinese-Mandarin speaker. In the speech recognition test in quiet conditions, the targets were twenty-four disyllabic words (DI-WORD) divided into three sub-sets: animals, everyday objects, and body parts and clothing items. Eight pictures corresponding to the eight items in the respective sub-set were randomly distributed to appear in a display format of a four-column to two-row matrix on a touchscreen monitor, such that each sub-set offered an eight-alternative forced choice (eight-AFC). A sample testing screen from the 'animal' eight-AFC closed-set sub-set is shown in

Figure 5. In the study by Yuen et al. (2019), five items including ‘耳朵’ (Ear), ‘头发’ (Hair), ‘衣服’ (Cloth), ‘蝴蝶’ (Butterfly), and ‘手表’ (Watch) were removed from the speech recognition test in the adaptive noise procedure, such that a total of 19 equivalently homogeneous disyllabic words which had been adjusted to the same difficulty level after absolute intensity adjustments were used as speech targets. However, the same original pictures associated with the removed items were still shown on the touchscreen monitor; therefore, the response mode of the eight-AFC closed-set test was maintained in the adaptive testing procedure. The noise signal was a tailor-made speech-spectrum weighted noise (SSN), which was created based on the average speech spectrum of all 24 test items. Furthermore, the intensity level of the noise signal was root-mean-square (RMS) equalised to match the adjusted intensity level of all the homogenised items which had the same RMS level of the 24 items. In addition, the noise signal was also used to calibrate the presentation level of the test items. Furthermore, the speech stimuli and noise were saved and distributed in separate channels (Yuen et al., 2019).

Figure 5 Sample Screen from Body Parts and Clothing Items Sub-Test in MAPID-A v. 3.2 Software



Note. The picture corresponding to item '耳朵' (Ear), was selected and enclosed by a yellow frame. The Mandarin spoken word—Picture Identification test in noise—Adaptive (MAPID-A) measures subtle speech-recognition-in-noise changes and spatial release from masking in very young children' by K. C. P. Yuen, X. Y. Qiu, H. Y. Mou, and X. Xi, 2019, *PloS One*, *14*(1), p. 6 (http://doi.org/10.1371/journal.pone.0209768).

3.3 Procedures

3.3.1 Pure-Tone Audiometry

The pure-tone audiometry was conducted for the following SII calculation. The unaided thresholds of each ear were measured via a TDH-39 headphone for octave frequencies ranging between 250–8000 Hz, while the aided thresholds of each hearing device were measured in the sound field via loudspeakers placed at ±45° azimuth and 1 m from the participant. Furthermore, aided thresholds of HA were measured for octave frequencies ranging between 250–4000 Hz, and aided thresholds of CI were measured in the 250–8000-Hz range. Furthermore, the unaided and aided thresholds were used to calculate the speech intelligibility indices of hearing aids and cochlear implants.

3.3.2 Hearing Aid Measurement

The electroacoustic performance of the hearing aids was measured in a test box of Axiom® Audioscan when the hearing aid was connected to a 2-cc coupler and placed at the reference testing point in the test box. The hearing aid outputs in the 2-cc coupler for 65 (average) dB SPL were measured using standard speech (Speech-std 1) stimuli filtered to provide the long-term average speech spectrum (LTASS) in Axiom® Audioscan. Subsequently, the electroacoustic performance of the bilateral hearing aids of the HAHA group and the hearing aids fitted to the non-implanted ear of the CIHA group were measured. The hearing aid outputs produced in the ear canal are different from the output generated in the coupler, and this difference is called the real ear to coupler difference (RECD), which was measured to predict the hearing aid output in the ear canal (Ricketts et al., 2017). The RECD measurement was performed for both ears of participants in the HAHA group and the non-implanted ear of participants in the CIHA group. Thereafter, the hearing aid output in the coupler and the measured RECD were used to the SII derivation. However, the hearing aid measurement was not completed for participants HAHA-M1 and HAHA-M14 whose parents did not consent to the measurement, so the SII cannot be calculated for these two participants.

3.3.3 Speech Recognition Test

3.3.3.1 Set-up of Testing Environment.

The participants were seated at the centre of a sound-treated booth. Both the speech and noise stimuli were delivered using the MAPID-A software (Yuen et al., 2019) installed on a laptop with a touchscreen monitor, by a Creative Sound Blaster X-Fi surround 5.1 Pro USB sound card and two loudspeakers. One loudspeaker was placed at a distance of 1 m at a 0° azimuth, and another loudspeaker was placed at 1 m at a +90° azimuth or −90° azimuth from the participants' position. The loudspeaker height was at the same horizontal plane as that of the participant ear when seated (Figure 6). In addition, the participants were not allowed to rotate their head during each round of testing, and the chair was rotated 90° clockwise or anticlockwise for the left or right noise conditions, respectively.

Figure 6 Testing Environment and Equipment Setup

Note. The participant sat on a blue chair and faced a touchscreen that was connected to the laptop. One loudspeaker was in front of the participant, and the other was on the left side.

3.3.3.2 Calibration of Signals

According to the instructions of the calibration interface in the software, each loudspeaker was calibrated separately using a sound level meter. The calibration signal was a noise signal at 75 dB SPL. After the calibration, the presentation level of the noise was automatically adjusted to 65 dB SPL by the custom software.

3.3.3.3 Familiarisation and Speech Recognition Test in Quiet

A familiarisation trial was conducted for the participants with the HAHA or CIHA fittings in quiet conditions to familiarise the participants with the items and their corresponding pictures prior to testing SRiN performance. The present study aimed to evaluate the speech recognition ability of the participant in terms of noise, but not vocabulary knowledge. First, the test administrator informed the participant that a woman would talk from the frontal loudspeaker. Subsequently, the eight-AFC test plate of the corresponding item was presented on a touchscreen monitor. After this, the administrator introduced the correct response of the item associated with the picture on the test plate for the participant. All three sub-tests were presented to the participant for the purpose of familiarisation in the training procedure. Following the training procedure, a speech recognition test in quiet was conducted to verify that the participant could correctly identify all items with the corresponding pictures. One test item was presented randomly from the frontal loudspeaker, and the participant was required to select one picture representing the test item he/she had heard spoken from the loudspeaker and then touch the correct picture from among the eight choices. Participants did not have a time limit for the response. After the participant selected one picture on the touchscreen, a yellow frame quickly flashed around the picture following which the administrator pressed a hot key to log the selection in the software and display the next test plate of the corresponding item on the screen, and thereafter pressed the same hot key to present the next test item. This process was repeated until all 24 test items were randomly presented, which comprised one round of the speech recognition test in quiet conditions.

In a typical case, the participant was familiar with all testing items and achieved a 100% speech recognition score in the first testing round of the speech recognition test in quiet conditions. If the participant failed to achieve a 100% score in the first testing round of the speech recognition test in quiet conditions, the tester would retrain the participant with the items incorrectly identified, following which the participant underwent a second testing round of the speech recognition test in quiet. Consequently, the participants who could not achieve a 100% speech recognition score in the second testing round were excluded from the study. Two children each in the HAHA and CIHA groups could not meet this test criteria and, thus, could not participate in the noise testing. The familiarisation procedure took approximately 10–15 min to complete.

3.3.3.4 Adaptive Speech Recognition Testing in Noise.

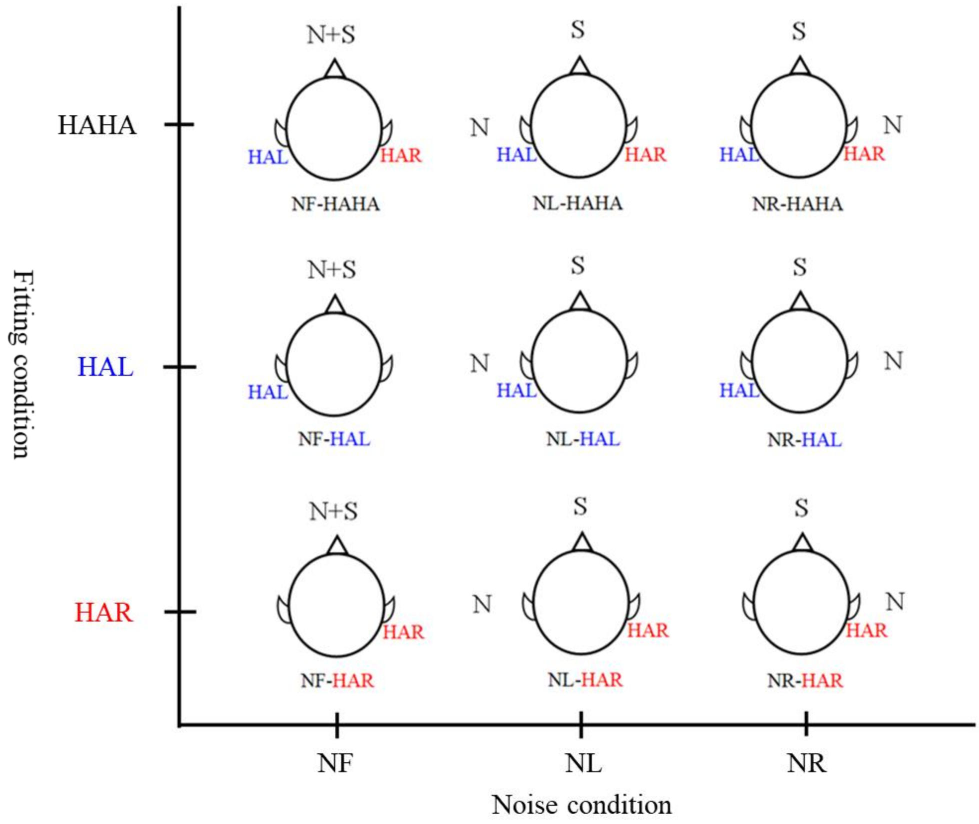
3.3.3.4.1 Test Conditions and Sequences

MAPID-A is a closed-set test, and the participant was familiarised with all test items using a quiet testing procedure. Thus, learning and memory effects were minimised in the test, although the participants were required to complete test conditions in different noise and device fitting conditions. Each participant was tested from an relatively easier condition to a more difficult one so that the effects of learning and presentation order could not overestimate test results of benefits.

HAHA group: The speech signal (S) was always presented from the front, and each participant was tested with noise from the front (NF), left side (NL), and right side (NR) of the participant. In each noise direction, the tests were conducted for the participant wearing bilateral hearing aids (HAHA), a monaural hearing aid on the left ear (HAL), and a monaural hearing aid on the right ear (HAR). Therefore, in total, 9 conditions (3 noise conditions × 3 device fitting conditions) were tested for each participant (

Figure 7). Moreover, to improve the test-retest reliability of the results obtained for each test condition within participants, the same test conditions were repeated for two rounds. Therefore, each participant underwent a total of 18 testing rounds (3 noise conditions × 3 device fitting conditions × twice repeated) in the speech recognition test with noise. The 18 testing rounds were completed in 2 sessions over 2 days, and each session lasted approximately 1 h, including 2 or 3 breaks to prevent fatigue. A total of 25 children completed all 18 testing rounds with noise.

Figure 7 Conditions in SRiN Test for Participants with HAHA, HAL, and HAR



Note. HAHA = binaural hearing aids fitting; HAL = left hearing aid fitting; HAR = right hearing aid fitting; N+S = noise and speech; N = noise; S = speech; NF = both speech and noise are presented from the front; NL = speech is presented from the front and noise is presented at -90° azimuth on the left; NR = speech is presented from the front and noise is presented at +90° azimuth on the right.

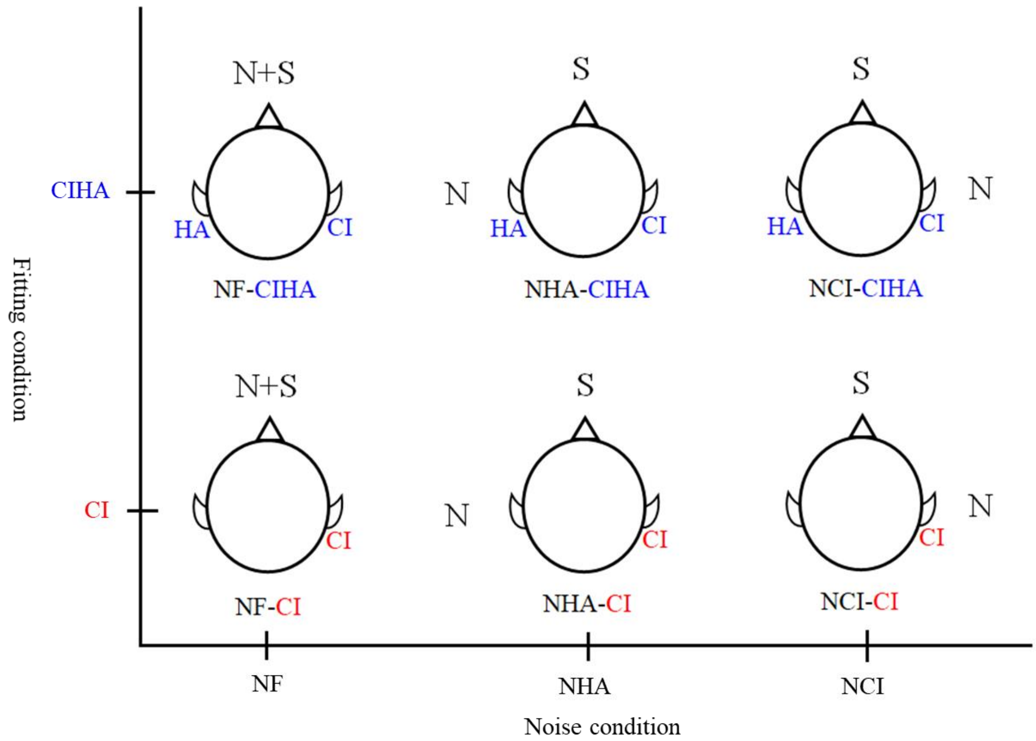
According to the literature review, the participant with HAHA may achieve the binaural benefit to improve their SRiN performance relative to HAL or HAR fitting (see Table 1 in Section 2.4.2); therefore, testing listening in binaural hearing condition was deemed to be an easier condition than monaural hearing condition. All the participants in the HAHA group were first tested with HAHA in different noise directions followed by the more difficult device fitting condition (HAL or HAR) in different noise directions (Appendix C1). In addition, the participants with HAHA may have better SRiN performance in spatially separated noise conditions than co-located noise conditions due to SRM (see Table 1 in Section 2.4.2); thus, the spatially separated noise condition was deemed easier than the co-located one. Therefore, the participants were first tested under NL-HAHA or NR-HAHA followed by under NF-HAHA. The order of NL-HAHA and NR-HAHA conditions was balanced between Sequences 1–8 and later Sequences 9–16 (Appendix C) for each of the participants in the HAHA.

When the participants were tested with monaural HA fitting, the participants with HAL were hypothesised to obtain better SRiN performance in the NR condition than in the NF or NL conditions due to HS. Thus, the participants with HAL were first tested in the NR-HAL condition, followed by NL-HAL or NF-HAL conditions, which was balanced between Sequences 1 and 2. In a similar manner, the participants with HAR were first tested in the NL-HAR condition, followed by NR-HAR or NF-HAR, which was balanced between Sequences 3 and 4.

To avoid potential impact of learning effect and improve the test-retest reliability of the SRiN performance for the participants, each test condition was tested twice with a reverse sequence. After the completion of three noise directions with one device fitting condition (e.g., in order of NL-HAHA, NR-HAHA, and NF-HAHA), the same test condition was repeated for the participant (e.g., in order of NF-HAHA, NR-HAHA, and NL-HAHA). The results from the same test condition were combined for the following statistics. In Sequences 1–8, the first six test conditions were identical while Sequences 9–16 mirrored Sequences 1–8. All test sequences were assigned to one participant and another to counterbalance potential testing-order effects across participants.

CIHA group: Each participant was tested from the front (NF), the HA side (NHA), and the CI side (NCI) of the participant. In each noise direction, the tests were conducted for the participant wearing bimodal fitting (CIHA) or monaural CI fitting (CI) hearing aids. Therefore, a total of 6 conditions (3 noise conditions × 2 device fitting conditions) were conducted for each participant (Figure 8). For other participants who were fitted with HA on the right ear and a CI on the left ear, the noise directions of NHA and NCI mirrored those of this participant, as shown in Figure 8. Like the HAHA group, the same test conditions were conducted for 2 rounds such that each participant underwent a total of 12 testing rounds (3 noise conditions × 2 device fitting conditions × twice repeated). The 12 testing rounds were completed in one session lasting approximately 1.5 h, including several breaks to prevent fatigue. Therefore, a total of 33 children completed all 12 rounds of noise testing.

Figure 8 Conditions in SRiN Test for Participants with CIHA and CI



Note. CIHA = bimodal fitting; HA = hearing aid; CI = cochlear implant; N+S = noise and speech; N = noise; S = speech; NF = both speech and noise are presented from the front t; NHA = speech is presented from front and noise is presented at 90° azimuth from the hearing aid side; NCI = speech is presented from front and noise is presented at 90° azimuth from cochlear implant side.

Like the HAHA group, the participant in the CIHA group was also tested from one condition regarded as an relatively easier condition to another condition regarded as a more difficult condition. The participants with CIHA may achieve binaural benefits to improve their SRiN performance relative to monaural CI fitting (see Table 2 in Section 2.4.3); thus, the CIHA device fitting condition was deemed easier than the monaural CI one. Therefore, all the participants in the CIHA group were first tested with CIHA in different noise directions followed by the monaural CI device fitting condition in different noise directions (Appendix C). In addition, the participants with CIHA may have better SRiN performance under spatially separated noise conditions than co-located ones owing to SRM (Table 2 in Section 2.4.3); hence, the spatially separated noise condition was deemed easier than the co-located one. Subsequently, the participants were first tested under NHA-CIHA or NCI-CIHA conditions followed by the NF-CIHA condition. The order of NHA-CIHA and NCI-CIHA was balanced between Sequences 1–2 and 3–4.

When the participants were tested with monaural CI fitting, they were hypothesised to obtain better SRiN performance in the NHA condition than in the NF or NCI conditions due to HS. Thus, the participants were first tested in the NHA-CI condition, followed by the NF-CI or NCI-CI conditions, which was balanced between Sequences 1 and 2.

After three noise directions with one device fitting condition were completed, the participant was retested under the same three noise conditions in a reverse sequence (in order of NHA-CIHA, NCI-CIHA, NF-CIHA, NF-CIHA, NCI-CIHA, and NHA-CIHA). In Sequences 1 and 2, the first 6 test conditions were identical, and Sequences 3 and 4 mirrored Sequences 1 and 2. The test sequences were assigned to one participant and another.

3.3.3.4.2 Adaptive Signal-to-Noise Ratio Estimation.

Before the tester started the speech recognition test in noise, the participants were instructed that they needed to ignore a noisy sound from the front or side loudspeaker and hear a disyllabic word produced by the female who previously spoke to them in quiet conditions from the front loudspeaker. Furthermore, MAPID-A did not have 'pass' or 'no response' selection, when the participant had difficulty in recognising the item, and the participants were encouraged to try their best to guess the target and select one. In addition, MAPID-A did not provide any feedback to the participants' responses, but the test administrator occasionally provided encouragements to reinforce the effort and attention of the participants. An adaptive SNR result (aSNR-disyllabic word 50 %) was estimated using an up-down adaptive procedure (Levitt, 1971), and the following steps were applied in the tracking procedure:

a) The intensity level of noise was fixed at 65 dB SPL, and the initial SNR of the first item in each test round was the mean SNR required for 50% correct identification (−13.34 dB SNR for NF condition and −17.11 dB SNR for noise presented at a 90° azimuth from one side (NS) condition) in the previous study (Yuen et al., 2019). The speech signal was presented after the noise with an onset delay of 0.5 s and the noise stopped after the speech signal with a delay of 0.5 s.

b) If the participant correctly identified the first item at the initial SNR level, the testing procedure would start from step (d) below; otherwise, the procedure would start from step (c).

c) If the participant incorrectly identified the first item at the initial SNR level, the first item was repeatedly presented with a 4 dB step increase in SNR. The procedure only proceeded to step (d) when the participant correctly identified the first item.

d) The second item was presented with a 4 dB decrease in SNR presentation level.

e) If the participant correctly identified the second item, the third item was presented with a further decrement of 4 dB SNR; otherwise, the third item was presented with a 4 dB SNR increment. This step was repeated until the first 6 items were presented.

f) After the sixth item was presented, the step size increment or decrement of the presentation SNR was changed to 2 dB for the remaining items in the adaptive procedure; that is, if the participant correctly identified the sixth item, the seventh item was presented with a 2 dB SNR decrement in presentation level; otherwise, it was presented with a 2 dB SNR increment. This step was repeated until the end of the adaptive testing procedure.

The presentation SNR of the sixth item was the starting point of the first reversal. If the adjustment direction of the presentation SNR changed, such as from decrement to increment or *vice versa*, the reversal point was an endpoint of the first reversal and the starting point of the second reversal (

Figure 9). For example, the presentation SNR level of the sixth item in

g) Figure 9 was the starting point of the first reversal. An incorrect identification of the sixth item resulted in an increase in the presentation SNR level of the seventh item. Thereafter, a correct identification of the seventh item resulted in a change in the adjustment direction—a decrement in the presentation SNR level of the eighth item. Thus, the presentation SNR level of the seventh item was the endpoint of the first reversal and the starting point of the second reversal. The adaptive testing procedure was terminated after 12 reversals were obtained.

h) If all 19 items were randomly presented before the 12 reversals were obtained, a second round of these items was randomly presented until the 12 reversals were obtained. Thus, all 19 items were presented twice (a maximum of 38 items) in one adaptive procedure for noise. However, if the 12 reversals were not completed before 38 items were presented, the procedure was terminated by the software.

i) The midpoint was the intermediate value between the SNR of two adjacent reversals. A total of 12 midpoints of all completed reversals from the SNR presentation level of the sixth to the last item were averaged to estimate the *M* and *SD* of the aSNR-50%. The lower (smaller or more negative) aSNR-50% represents a better SRiN performance.

j) Thereafter, *SE* was calculated using Equation 3, where $N = 12$ is the total number of completed reversals.

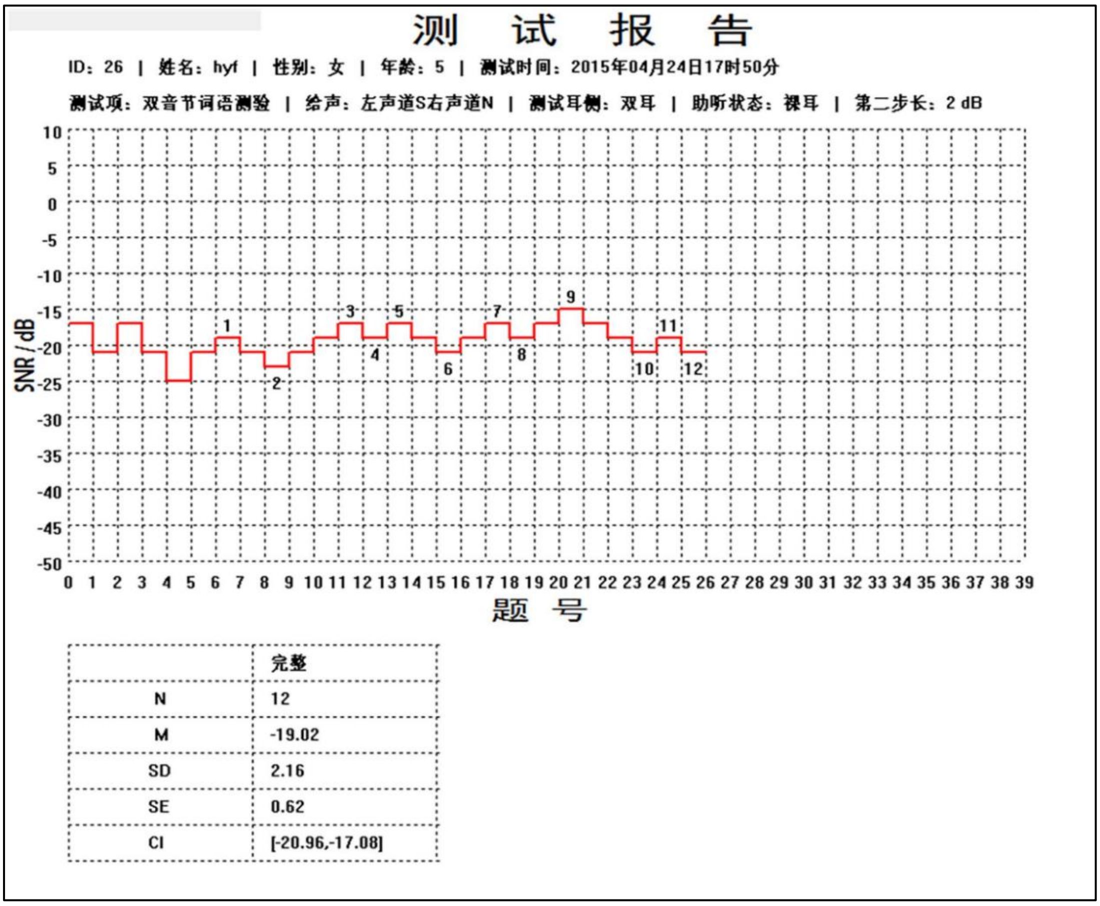
$$SE = SD / \sqrt{N} \tag{3}$$

k) Furthermore, the 99% confidence interval (*99% confidence interval*) was computed using Equation 4, where *t* is the *t*-value in a two-tailed test for the degrees of freedom (= $N - 1 = 11$) in Equation 3:

$$99\%\ confidence\ interval = [(M - t \times SE), (M + t \times SE)] \tag{4}$$

l) Finally, *M*, *SD*, *SE*, and *99% confidence interval* for the aSNR-50% results were automatically calculated for subsequent analyses.

Figure 9 Sample Adaptive Test Result from Speech-in-Noise Test in MAPID-A



Note. The results were generated using a computer. The red line represents the SNR of each testing item. Twenty-six items were presented to obtain the 12 reversals and the *M* and *99% confidence interval* of the aSNR-50% score. The Mandarin spoken word—Picture IDentification test in noise—Adaptive (MAPID-A) measures subtle speech-recognition-in-noise changes and spatial release from masking in very young children' by K. C. P. Yuen, X. Y. Qiu, H. Y. Mou, and X. Xi, 2019, *PloS One*, *14*(1), p. 6 (http://doi.org/10.1371/journal.pone.0209768).

3.4 Data Analysis

3.4.1 Analysis of SII Obtained from HA and CI

3.4.1.1 Hearing Threshold of Pure-Tone Audiometry.

Descriptive statistics were derived for the unaided and aided hearing thresholds of participants in the HAHA and CIHA groups, including the *M* and *SD* of the groups. Furthermore, the hearing thresholds of individual participants were used in the SII calculation, such that interpolation or extrapolation was used to generate one-third octave thresholds that could not be obtained from pure-tone audiometry. In addition, to process missing values when the participant had no response (NR) to the maximum output level of a test frequency, the hearing threshold was estimated to be 5 dB above the maximum output level at that frequency.

3.4.1.2 Hearing Aid Output in Real-Ear.

Descriptive statistics were derived for measured RECD values and HA outputs in the 2-cc coupler of participants in the HAHA and CIHA groups, including *M* and *SD*. Subsequently, the measured RECD values and hearing aid outputs in the 2-cc coupler of individual participants were used in the speech audibility evaluation, such that interpolation or extrapolation was used to generate a one-third octave RECD that could not be obtained from the real ear measurement.

3.4.1.3 SII Calculation.

The SII was calculated for each HA and CI using a spreadsheet application in Excel (https://doi.org/10.13140/RG.2.2.10105.83044) (Hornsby, 2019), which was developed according to the ANSI S3.5-1997 standard (ANSI, 1997). The entire calculation procedure considered various factors including the spread of masking, standard speech spectrum level, and speech level distortion factor. However, to calculate the SII obtained from the hearing aid (SII-HA) and cochlear implant (SII-CI), some additional parameters (discussed as follows) had to be entered into the spreadsheet. The other parameters in the spreadsheet were automatically calculated based on the previous parameters that were entered in the spreadsheet, and the calculation functions were provided by the ANSI S3.5-1997 standard.

The SII obtained from the HAL and HAR of the participants in the HAHA group (SII-HAL and SII-HAR), and from the non-implanted ear with the HA contralateral to the CI side (SII-HAcon) of the participants in the CIHA group were calculated in steps 1 to 7 described below, while the SII obtained from the CI side (SII-CI) was calculated using steps 8 to 10. For example, the SII obtained from an HA (for example, HA of the right ear of HAHA-F11) and a CI (for example, CI on the right ear of CIHA-F3) are shown in Figure 10 and 11, respectively. Thus, descriptive statistics were derived for the monaural SII of participants in the two groups, including *M* and *SD*.

SII-HA

1. The spreadsheet required entry of pure-tone thresholds (Ti’, in dB HL) at one-third octave centre frequencies, which could not be obtained from the pure-tone audiometry, such that the measured audiometric thresholds (dB HL) were

interpolated or extrapolated to yield one-third octave thresholds (Table 4). The unaided thresholds at one-third octave centre frequencies were entered as Ti' in the spreadsheet. The interpolation or extrapolation was calculated using the following steps:

a) unaided threshold at 160 Hz = unaided threshold at 200 Hz = unaided threshold at 250 Hz = 40.00 dB HL

b) unaided threshold at 315 Hz = unaided threshold at 250 Hz + (unaided threshold at 500 Hz - unaided threshold at 250 Hz)/3 = 40 + (35 – 40)/3 = 38.33 dB HL

c) unaided threshold at 400 Hz = unaided threshold at 315 Hz + (unaided threshold at 500 Hz - unaided threshold at 250 Hz)/3 = 38.33 + (35 – 40)/3 = 36.67 dB HL

2. Measured RECD results (dB SPL) (Table 5) were interpolated or extrapolated to yield one-third octave by the following steps:

a) RECD at 160 Hz = RECD at 200 Hz = RECD at 250 Hz = – 4.00 dB SPL

b) RECD at 315 Hz = RECD at 250 Hz + (RECD at 500 Hz – RECD at 250 Hz)/3 = – 4 (2 – (–4))/3 = –2.00 dB SPL

c) RECD at 400 Hz = RECD at 315 Hz + (RECD at 500 Hz – RECD at 250 Hz)/3 = – 2 (2 – (–4))/3 = 0.00 dB SPL

d) RECD at 630 Hz = (RECD at 500 Hz + RECD at 750 Hz)/2 = (2 + 7)/2 = 4.50 dB SPL

e) RECD at 800 Hz = (RECD at 750 Hz + RECD at 1000 Hz)/2 = (7 + 10)/2 = 8.50 dB SPL

3. Hearing aid outputs in the 2-cc coupler (dB SPL) for 65 dB SPL input were measured at one-third octave except for 160 Hz, thus, the outputs at 160 Hz were extrapolated and were equal to the outputs at 200 Hz.
   a) 2-cc output at 160 Hz = 2-cc output at 200 Hz = 85.02 dB SPL
4. The interpolated or extrapolated RECD (dB SPL) in step 3 and hearing aid outputs in the 2-cc coupler (dB SPL) were used to calculate outputs in the real ear (RE-output, dB SPL) at one-third octave by the following step (315 Hz as an example):
   a) RE-output at 315 Hz = RECD at 315 Hz + 2-cc output at 315 Hz = –2 + 88.90 = 86.90 dB SPL
5. RE output, the overall level of the amplified speech input, was measured at the output of a band-pass filter wider than 1 Hz (ANSI, 1997). Thus, the overall level was converted into the speech spectrum level at one-third octave-centred frequencies according to Equation (3) in clause 3.6 in the ANSI S3.5-1997. Subsequently, the real ear to free field transfer function in the ANSI S3.5-1997 was used to estimate the speech spectrum level in the free field, which was entered as equivalent speech spectrum level (Ei', in dB SPL) in the spreadsheet. The calculation procedure was as follows (315 Hz as an example):
   a) Ei' at 315 Hz = RE-output at 315 Hz – $10\lg[\Delta(f)/\Delta_0(f)]$ – real-ear to free field transfer function = 86.90 – 18.65 – 1.4 = 66.85 dB SPL

   where $\Delta(f)$ is the filter bandwidth, and $\Delta_0(f)$ is the reference bandwidth of 1 Hz. Furthermore, $10\lg[\Delta(f)/\Delta_0(f)]$ is the bandwidth adjustment column in ANSI S3.5-1997.

6. According to the ANSI S3.5-1997 standard, as the measures in quiet was desired, the equivalent noise spectrum levels (Ni') at all one-third octaves was entered as -80 dB SPL (Hornsby, 2019).
7. In addition, the frequency importance factor (FIF) of the band is significantly different among languages (Chen, J. et al., 2016; Kuo, 2013; Wong et al., 2007). For example, the FIF derived from the English monosyllabic PB words at 1600 Hz is 0.0902 (ANSI S3.5-1997), however, that derived from Mandarin monosyllabic PB words at 1600 Hz is 0.1087, and the differences between the FIF values of English and Mandarin are larger than 1.5% at 160, 1600, 2000, 2500, and 4000 Hz (Chen, J. et al., 2016). Therefore, the FIF values of the Mandarin Chinese materials from the study by Chen et al. were entered into the spreadsheet.

SII-CI

8. The aided threshold of the CI side (dB HL) was interpolated or extrapolated to yield a one-third octave threshold and entered as Ti' in the spreadsheet. The interpolation or extrapolation was the same as in Step 1 in the SII-HA calculation.
9. The Ei' (dB SPL) in the spreadsheet was entered using values of universal long-term average spectrum of speech (LTASS) (Byrne et al., 1994).
10. The Ni and FIF values were the same as those used in the SII-HA calculation.

Table 4 ***Unaided Threshold (dB HL) of Right Ear of HAHA-F11***

Frequency (Hz)																	
(160)	(200)	250	(315)	(400)	500	(630)	(800)	1000	(1250)	(1600)	2000	(2500)	(3150)	4000	(5000)	(6300)	8000
40.00	40.00	40.00	38.33	36.67	35.00	30.00	25.00	20.00	25.00	30.00	35.00	36.67	38.33	40.00	61.67	83.33	105.00

Note. The frequencies in brackets were interpolated or extrapolated according to the measured audiometric thresholds.

Table 5 ***RECD (dB SPL) of Right Ear of HAHA-F11***

Frequency (Hz)																	
(160)	(200)	250	(315)	(400)	500	(630)	(800)	1000	(1250)	(1600)	2000	(2500)	(3150)	4000	(5000)	(6300)	8000
-4.00	-4.00	-4.00	-2.00	0.00	2.00	4.50	8.50	10.00	11.00	11.00	12.00	12.00	12.50	13.00	16.50	23.50	27.00

Note. The frequencies in brackets were interpolated or extrapolated according to the measured RECD.

Table 6 ***Hearing Aid Outputs in the 2-cc Coupler (dB SPL) of Right Ear With HA of HAHA-F11***

Frequency (Hz)																	
(160)	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000
85.02	85.02	87.11	88.90	93.09	92.49	90.70	91.29	91.89	91.29	95.18	97.57	95.78	97.27	95.78	93.39	88.01	82.03

Note. The frequencies in brackets were interpolated or extrapolated according to the measured outputs.

Figure 10 SII Obtained from Right Ear with HA of HAHA-F11

SII ANSI S3.5 1997

Enter the following in the yellow squares:

1) (Ti') Eqivalent Hearing Threshold Levels (in dB HL) at 1/3rd octave band center frequencies

2) (Ei') Equivalent Speech Spectrum Levels (in dB SPL) at 1/3rd octave band center frequencies

3) (Ni') Equivalent Noise spectrum levels(in dB SPL) at 1/3rd octave band center frequencies

SII Total **0.739**

Fi (1/3 octave band center freq)	**Ti' (Eq. Hearing Thresh. Lvl.)**	**Ei' (Eq. Sp. Spec. Level)***	**Ni' (Eq. Noise Spec. Lvl)***	**Ii (Band import. func.)**	Ui (St. Sp. spec.normal effort)	Xi (Ref. Int. Noise spec. lvl.)	Vi (Self Sp. Mask. Lvl)	Bi (Larger of Ni or Vi)	Ci (Spread of Masking Slope)	Zi (Eq.Masking Spec. Lvl)	Xi' (Eq. Int. Noise Spec. Lvl.)	Di (Eq. Dist. Spec. Lvl.)	Li (Level Distortion factor)	Ki (temporary variable)	Ai (band audibility function	**Band SII values**
160	40.00	65.37	**-80.00**	0.0546	32.41	0.60	41.37	41.37	-45.77	41.37	40.60	41.37	0.86	1.00	0.86	**0.0467649**
200	40.00	63.87	**-80.00**	0.0269	34.48	-1.70	39.87	39.87	-46.08	34.34	38.30	38.30	0.88	1.00	0.88	**0.0236401**
250	40.00	64.46	**-80.00**	0.0323	34.75	-3.90	40.46	40.46	-45.15	32.99	36.10	36.10	0.88	1.00	0.88	**0.0283207**
315	38.33	66.85	**-80.00**	0.0362	33.98	-6.10	42.85	42.85	-43.11	33.13	32.23	33.13	0.86	1.00	0.86	**0.0310247**
400	36.67	71.94	**-80.00**	0.0546	34.59	-8.20	47.94	47.94	-39.44	35.32	28.47	35.32	0.83	1.00	0.83	**0.0452676**
500	35.00	72.04	**-80.00**	0.0473	34.27	-9.70	48.04	48.04	-38.79	41.91	25.30	41.91	0.83	1.00	0.83	**0.0390905**
630	30.00	71.15	**-80.00**	0.0608	32.06	-10.80	47.15	47.15	-38.73	41.85	19.20	41.85	0.82	1.00	0.82	**0.0497469**
800	25.00	74.04	**-80.00**	0.0626	28.30	-11.90	50.04	50.04	-36.37	40.59	13.10	40.59	0.78	1.00	0.78	**0.0486148**
1000	20.00	75.64	**-80.00**	0.0761	25.01	-12.50	51.64	51.64	-34.83	44.55	7.50	44.55	0.75	1.00	0.75	**0.0567742**
1250	25.00	74.64	**-80.00**	0.0746	23.00	-13.50	50.64	50.64	-34.84	46.48	11.50	46.48	0.74	1.00	0.74	**0.0551831**
1600	30.00	74.43	**-80.00**	0.1087	20.15	-15.40	50.43	50.43	-34.33	44.51	14.60	44.51	0.72	1.00	0.72	**0.0786178**
2000	35.00	70.92	**-80.00**	0.1113	17.32	-17.70	46.92	46.92	-35.85	45.43	17.30	45.43	0.73	1.00	0.73	**0.080971**
2500	36.67	63.33	**-80.00**	0.0738	13.18	-21.20	39.33	39.33	-39.83	42.19	15.47	42.19	0.75	1.00	0.75	**0.0552822**
3150	38.33	66.12	**-80.00**	0.0624	11.55	-24.20	42.12	42.12	-37.55	34.72	14.13	34.72	0.72	1.00	0.72	**0.0450173**
4000	40.00	64.83	**-80.00**	0.0303	9.33	-25.90	40.83	40.83	-37.70	35.67	14.10	35.67	0.72	1.00	0.72	**0.021684**
5000	61.67	68.54	**-80.00**	0.0351	5.31	-23.60	44.54	44.54	-34.90	35.33	38.07	38.07	0.67	1.00	0.67	**0.0234234**
6300	83.33	73.46	**-80.00**	0.0218	2.59	-15.80	49.46	49.46	-31.34	38.88	67.53	67.53	0.62	0.70	0.43	**0.0094208**
8000	105.00	74.58	**-80.00**	0.0306	1.13	-7.10	50.58	50.58	-30.04	44.01	97.90	97.90	0.60	0.00	0.00	**0**

Note. This is for speech in quiet. Data in the Ti', Ei', Ni', and Ii columns were entered into the spreadsheet, and data in the remaining columns were calculated according to data in these four columns and functions provided in the ANSI S3.5-1997 standard. Fi = Centre frequency of an SII band; i = Individual band number used in calculation of SII; Ti'= equivalent hearing threshold level; Ei'= spectrum level of equivalent speech; Ni'= spectrum level of equivalent noise; Ii= band importance function; Ui = spectrum level of standard speech for normal vocal effort; Xi =

reference internal noise spectrum level; Vi = spectrum level for self-speech masking; Bi = larger spectrum levels for equivalent noise and self-speech masking; Ci = Slope per octave (doubling of frequency) of the upward spread of masking; Zi = spectrum level for equivalent masking; Xi'= spectrum level of equivalent internal noise; di = spectrum level for equivalent disturbance; Li = speech level distortion factor; Ki = temporary variable used in the calculation of the band audibility function; Ai = band audibility function.

Figure 11 SII Obtained from Right Ear with CI of CIHA-F3

SII ANSI S3.5 1997																**SII Total**
Enter the following in the yellow squares:																**0.870**
1) (Ti') Eqivalent Hearing Threshold Levels (in dB HL) at 1/3rd octave band center frequencies																
2) (Ei') Equivalent Speech Spectrum Levels (in dB SPL) at 1/3rd octave band center frequencies																
3) (Ni') Equivalent Noise spectrum levels(in dB SPL) at 1/3rd octave band center frequencies																
Fi (1/3 octave band center freq)	**Ti' (Eq. Hearing Thresh. Lvl.)**	**Ei' (Eq. Sp. Spec. Level)***	**Ni' (Eq. Noise Spec. Lvl)***	**Ii (Band import. func.)**	Ui (St. Sp. spec.normal effort)	Xi (Ref. Int. Noise spec. lvl.)	Vi (Self Sp. Mask. Lvl)	Bi (Larger of Ni or Vi)	Ci (Spread of Masking Slope)	Zi (Eq.Masking Spec. Lvl)	Xi' (Eq. Int. Noise Spec. Lvl.)	Di (Eq. Dist. Spec. Lvl.)	Li (Level Distortion factor)	Ki (temporary variable)	Ai (band audibility function	**Band SII values**
160	25.00	56.80	**-80.00**	0.0546	32.41	0.60	32.80	32.80	-50.91	32.80	25.60	32.80	0.91	1.00	0.91	**0.0496894**
200	25.00	60.20	**-80.00**	0.0269	34.48	-1.70	36.20	36.20	-48.29	24.97	23.30	24.97	0.90	1.00	0.90	**0.0242571**
250	25.00	60.30	**-80.00**	0.0323	34.75	-3.90	36.30	36.30	-47.64	28.82	21.10	28.82	0.90	1.00	0.90	**0.0291608**
315	28.33	59.00	**-80.00**	0.0362	33.98	-6.10	35.00	35.00	-47.82	28.54	22.23	28.54	0.91	1.00	0.91	**0.0328017**
400	31.67	62.10	**-80.00**	0.0546	34.59	-8.20	38.10	38.10	-45.34	26.72	23.47	26.72	0.89	1.00	0.89	**0.0486247**
500	35.00	62.10	**-80.00**	0.0473	34.27	-9.70	38.10	38.10	-44.76	31.18	25.30	31.18	0.89	1.00	0.89	**0.042029**
630	33.33	60.50	**-80.00**	0.0608	32.06	-10.80	36.50	36.50	-45.12	30.85	22.53	30.85	0.88	1.00	0.88	**0.0537928**
800	31.67	53.70	**-80.00**	0.0626	28.30	-11.90	29.70	29.70	-48.57	28.75	19.77	28.75	0.90	1.00	0.90	**0.0565748**
1000	30.00	53.70	**-80.00**	0.0761	25.01	-12.50	29.70	29.70	-47.99	22.87	17.50	22.87	0.88	1.00	0.88	**0.0672106**
1250	30.00	53.00	**-80.00**	0.0746	23.00	-13.50	29.00	29.00	-47.83	22.46	16.50	22.46	0.88	1.00	0.88	**0.065275**
1600	30.00	52.00	**-80.00**	0.1087	20.15	-15.40	28.00	28.00	-47.79	20.16	14.60	20.16	0.86	1.00	0.86	**0.0938557**
2000	30.00	48.70	**-80.00**	0.1113	17.32	-17.70	24.70	24.70	-49.19	20.76	12.30	20.76	0.87	1.00	0.87	**0.0964275**
2500	30.00	48.70	**-80.00**	0.0738	13.18	-21.20	24.70	24.70	-48.60	17.42	8.80	17.42	0.84	1.00	0.84	**0.0620289**
3150	30.00	46.80	**-80.00**	0.0624	11.55	-24.20	22.80	22.80	-49.14	16.79	5.80	16.79	0.84	1.00	0.84	**0.0525525**
4000	30.00	45.60	**-80.00**	0.0303	9.33	-25.90	21.60	21.60	-49.24	14.30	4.10	14.30	0.84	1.00	0.84	**0.0253251**
5000	31.67	44.50	**-80.00**	0.0351	5.31	-23.60	20.50	20.50	-49.32	14.15	8.07	14.15	0.82	1.00	0.82	**0.0286964**
6300	33.33	44.30	**-80.00**	0.0218	2.59	-15.80	20.30	20.30	-48.84	12.50	17.53	17.53	0.80	1.00	0.80	**0.0174795**
8000	35.00	43.70	**-80.00**	0.0306	1.13	-7.10	19.70	19.70	-48.57	11.79	27.90	27.90	0.80	1.00	0.80	**0.024371**

Note. This is for speech in quiet. Data in the Ti’, Ei’, Ni’, and Ii columns were entered into the spreadsheet, and data in the remaining columns were calculated according to data in these four columns and functions provided in the ANSI S3.5-1997 standard. Fi = Centre frequency of an SII band, i = Individual band number used in calculation of SII, Ti’= equivalent hearing threshold level, Ei’= spectrum level of equivalent speech; Ni’= spectrum level of equivalent noise; Ii= band importance function; Ui = spectrum level of standard speech for normal vocal effort; Xi =

reference internal noise spectrum level; Vi = spectrum level for self-speech masking; Bi = larger spectrum levels for equivalent noise and self-speech masking; Ci = Slope per octave (doubling of frequency) of the upward spread of masking; Zi = spectrum level for equivalent masking; Xi'= spectrum level of equivalent internal noise; di = spectrum level for equivalent disturbance; Li = speech level distortion factor; Ki = temporary variable used in the calculation of the band audibility function; Ai = band audibility function.

3.4.2 Analysis of SRiN Performance

3.4.2.1 aSNR-50% Scores of Group Results.

3.4.2.1.1 Combined aSNR-50% Scores from the Same Condition.

The *N*, *M*, *SD*, and *SE* of aSNR-50% results from two testing rounds of the same test condition were combined using the formulae from (Higgins et al., 2019) to generate the combined *N*, *M*, *SD* and *SE* of aSNR-50% results (Table 7), which were used in the following statistical analysis of binaural benefit, SRM, and regression analysis.

Table 7 ***Formulae for Calculating Combined N, M, SD, and SE of aSNR-50% Results***

	First testing round	Second testing round	Combined first and second testing round
Completed reversals	N_1	N_2	$N_{12} = N_1 + N_2$
M	M_1	M_2	$M_{12} = \frac{N_1 M_1 + N_2 M_2}{N_1 + N_2}$
SD	SD_1	SD_2	$SD_{12} = \sqrt{\frac{(N_1 - 1)SD_1^2 + (N_2 - 1)SD_2^2 + \frac{N_1 N_2}{N_1 + N_2}(M_1^2 + M_2^2 - 2M_1 M_2)}{N_1 + N_2 - 1}}$
SE	SE_1	SE_2	$SE_{12} = \frac{SD_{12}}{\sqrt{N_{12}}}$

Note. Adapted from ‘Chapter 6: Choosing effect measures and computing estimates of effect’ by JPT. Higgins, T. Li, and JJ. Deeks (editors) in the JPT Higgins, J. Thomas, J. Chandler, M. Cumpston, and T. Li, MJ. Page, VA. Welch (editors), 2019, *Cochrane Handbook for Systematic Reviews of Interventions version 6.0 (updated July 2019).* Retrieved from www.training.cochrane. org/handbook. Copyright 2020 by the authors.

3.4.2.1.2 Analysis of Variance (ANOVA) and Post Hoc Analyses of Combined aSNR-50% Scores

The combined aSNR-50% scores of different test conditions in the speech recognition test in noise were analysed using Statistica v. 11 (Statsoft Inc., 2011). Thereafter, descriptive statistics were derived for the combined aSNR-50%, including *M*, *SD*, *SE*, and *95% confidence interval*. Furthermore, a two-way repeated measures ANOVA was used to evaluate the primary effect of the device fitting condition and noise direction, and the interaction effect between the device fitting condition and noise direction on aSNR-50%. Post hoc analyses using honestly significant difference (HSD) proposed by Turkey were used to evaluate different pairwise comparisons among the test conditions. The mean difference of the aSNR-50% score between conditions A and B in the pairwise comparison (Table 8 and 9) was calculated to quantify the magnitude of each binaural benefit and SRM. In addition, for all the analyses, the level of statistical significance was set at $\alpha < .05$.

HAHA Group: In the ANOVA of the aSNR-50% scores, the two repeated measure primary effects were device fitting condition (HAHA, HAL, and HAR) and noise direction (NF, NL, and NR). In the post hoc analyses of aSNR-50% scores, the pairwise score comparisons between binaural HAHA and monaural HA fitting demonstrated binaural benefits of adding the second HA to the monaural HA fitting: BR with HAR (BR-HAR) and HAL (BR-HAL) in the NF condition, SQ with HAR (SQ-HAR) and HAL (SQ-HAL) near the noise, and HS with HAR (HS-HAR) and HAL (HS-HAL) contralateral to the noise (Table 8). If Condition A was better or worse than or identical to Condition B then there were positive, negative, or no binaural benefits of BR, SQ, or HS, respectively. In addition, when the noise moved from the front to the left or right side, the aSNR-50% scores of pairwise comparisons between the NF condition and spatially separated (NL or NR) condition were regarded as the SRM (FL or FR) of the participant with HAHA (FL-HAHA or FR-HAHA), HAL (FL-HAL or FR-HAR), and HAR (FL-HAR or FR-HAR) (Table 8). Furthermore, if Condition A was better, worse, or equal to condition B, it implied there was positive, negative, or no SRM, respectively. Moreover, if the aSNR-50% scores of pairwise comparison in NL-HAHA and NR-HAHA were significantly different, it indicated the DA of the two ear sides with HA (Table 8). DA is a collective measure of how well 1) the aided ear contralateral to the noise functions in the more favourable SNR condition due to HS, and 2) the aided ear ipsilateral to the noise functions in the less favourable SNR condition due to SQ. Thus, if Condition A was better, worse, or equal to Condition B, it implied there was DA-HAL, DA-HAR, or no DA, respectively.

Table 8 ***Post Hoc Analyses of Pairwise Comparisons Among test conditions in the HAHA Group***

Outcome			Condition A	Condition B	Result: A is better than B	Result: A is worse than B	Result: A is the same as B	Figure number
Binaural benefit	BR	BR-HAR	NF-HAL	NF-HAHA	+ve	-ve	no difference	12
		BR-HAL	NF-HAR	NF-HAHA	+ve	-ve	no difference	
	SQ	SQ-HAR	NR-HAL	NR-HAHA	+ve	-ve	no difference	13
		SQ-HAL	NL-HAR	NL-HAHA	+ve	-ve	no difference	
	HS	HS-HAR	NL-HAL	NL-HAHA	+ve	-ve	no difference	14
		HS-HAL	NR-HAR	NR-HAHA	+ve	-ve	no difference	
SRM	HAHA	FL-HAHA	NF-HAHA	NL-HAHA	+ve	-ve	no difference	15
		FR-HAHA	NF-HAHA	NR-HAHA	+ve	-ve	no difference	
	HAL	FL-HAL	NF-HAL	NL-HAL	+ve	-ve	no difference	16
		FR-HAL	NF-HAL	NR-HAL	+ve	-ve	no difference	
	HAR	FL-HAR	NF-HAR	NL-HAR	+ve	-ve	no difference	17
		FR-HAR	NF-HAR	NR-HAR	+ve	-ve	no difference	
DA			NL-HAHA	NR-HAHA	DA-HAL	DA-HAR	no difference	18

Note. +ve = positive value of binaural benefits or SRM; -ve = negative value of binaural benefits or SRM.

Figure 12 Monaural HA Versus HAHA for BR of HAR and HAL (BR-HAR and BR-HAL)

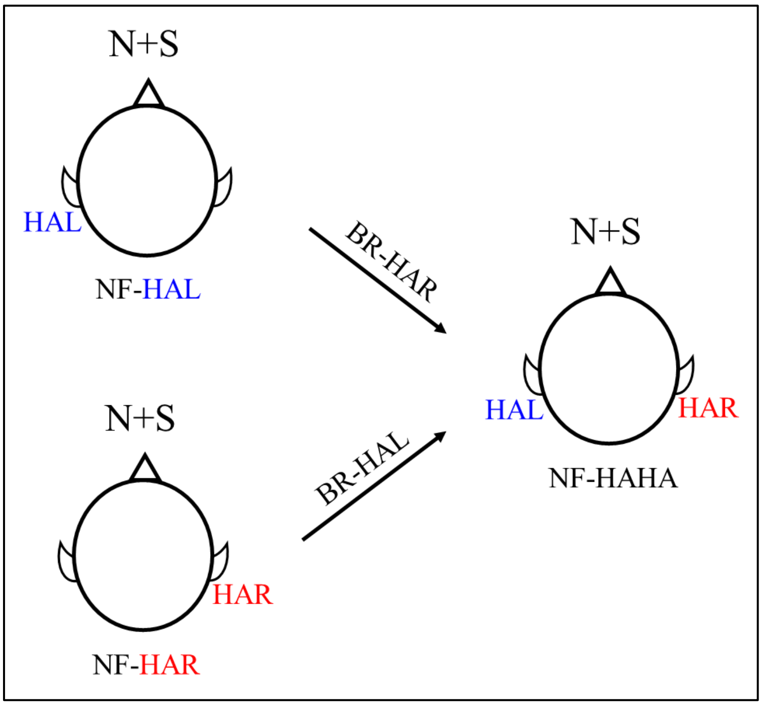


Figure 13 Monaural HA Versus HAHA for SQ of HAR and HAL (SQ-HAR and SQ-HAL)

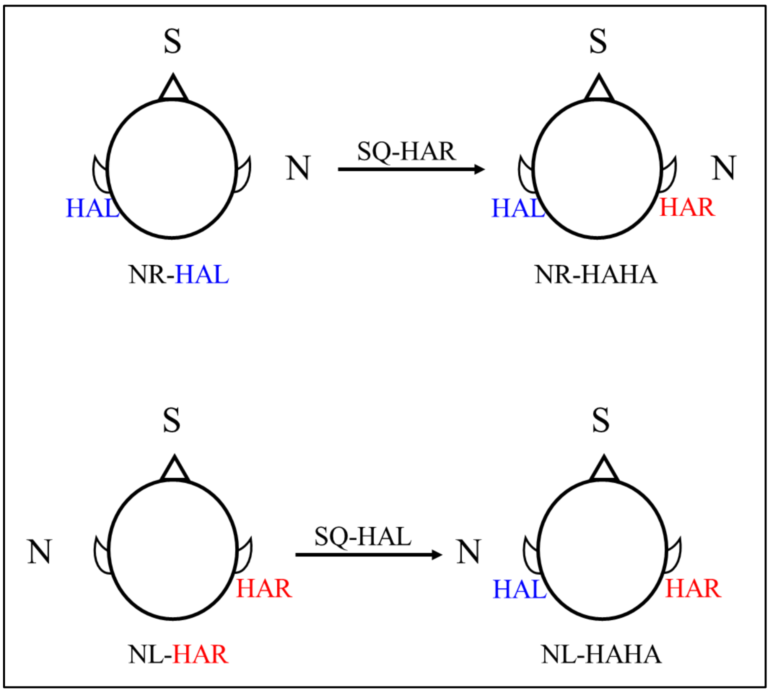


Figure 14 Monaural HA Versus HAHA for HS of HAR and HAL (HS-HAR and HS-HAL)

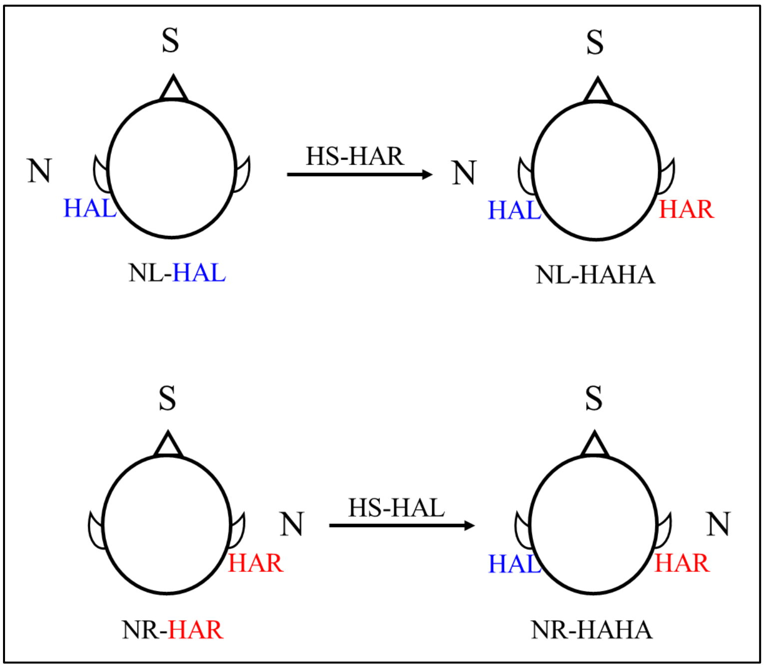


Figure 15 NF vs. NL or NR for Participants with HAHA (SRM for FL-HAHA and FR-HAHA)

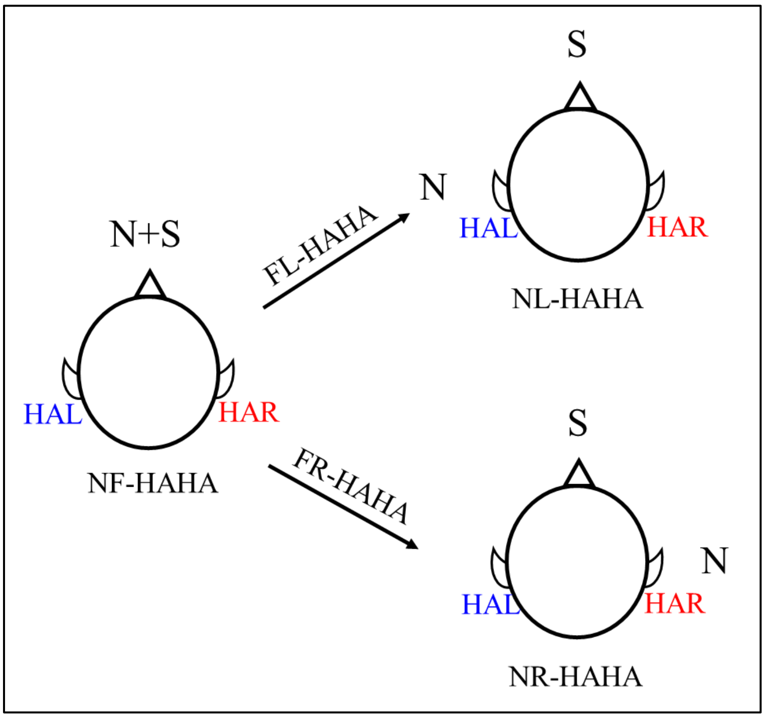


Figure 16 NF vs. NL or NR for Participants with HAL (SRM for FL-HAL and FR-HAL)

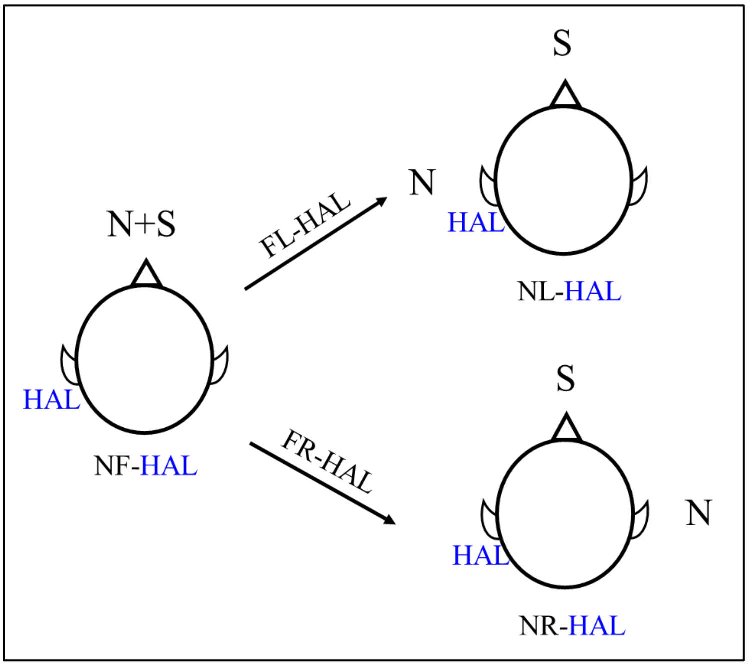


Figure 17 NF vs. NL or NR for Participants with HAR (SRM for FL-HAR and FR-HAR)

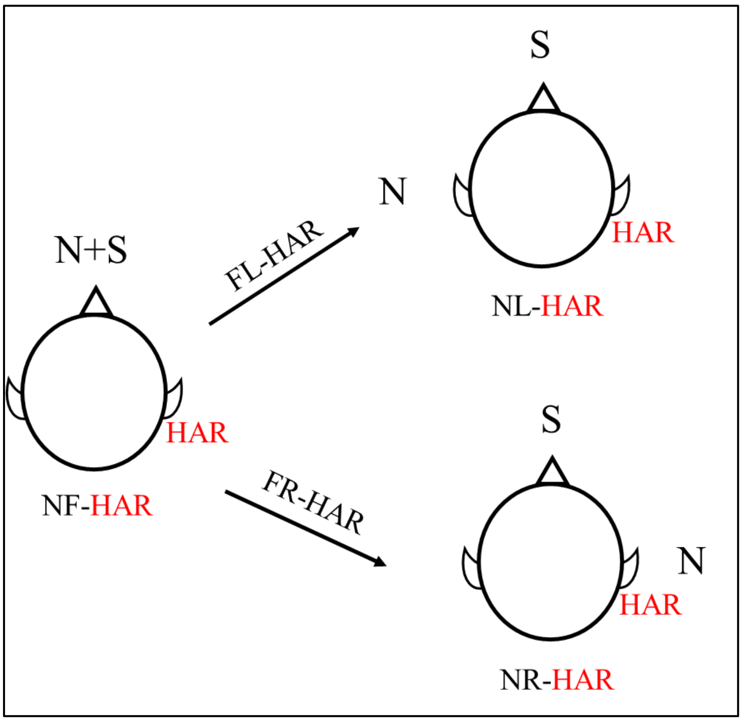
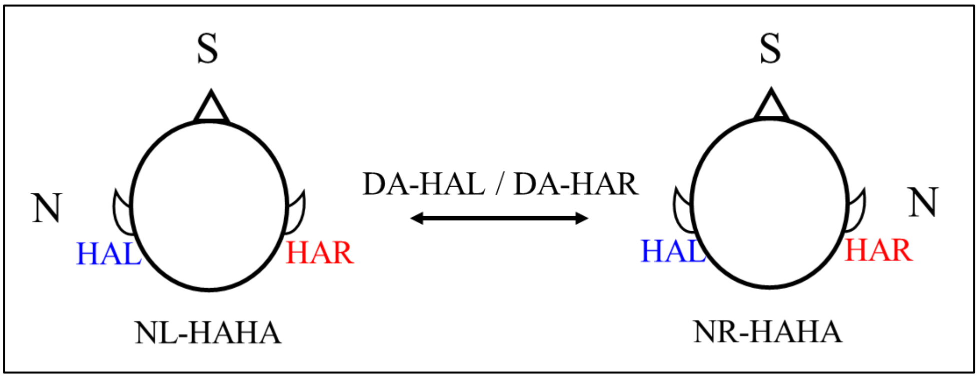


Figure 18 NL vs. NR for DA of HAL or HAR (DA-HAL or DA-HAR)



CIHA Group: In the ANOVA, the two repeated measure primary effects were device fitting condition (CIHA and CI) and noise direction (NF, NHA, and NCI). Furthermore, in the post hoc analyses of aSNR-50% scores, the pairwise comparisons between CIHA fitting and monaural CI fitting demonstrated the combined benefits of adding a contralateral HA to the monaural CI fitting: BR of the contralateral HA in the NF condition (BR-HAcon), SQ of the contralateral HA in the NHA condition (SQ-HAcon), and HS of the contralateral HA in the NCI condition (HS-HAcon) (Table 9). If Condition A was better, worse, or equal to Condition B, it implied there were positive, negative, or no binaural benefits of BR-HAcon, SQ-HAcon, and HS-HAcon, respectively. In addition, when the noise moved from the front to the HA CI sides, the aSNR-50% scores of pairwise comparisons between the NF condition and spatially separated (NHA or NCI) conditions were regarded as SRM (FHA or FCI) of the participant with CIHA (FHA-CIHA or FCI-CIHA), and monaural CI (FHA-CI or FCI-CI) (Table 9). Furthermore, if Condition A was better, worse, or equal to condition B, it implied there was positive, negative, or no SRM, respectively. Moreover, if the aSNR-50% scores of pairwise comparison in NHA-CIHA and NCI-CIHA were significantly different, it indicated the DA of the two ear sides with CI and HA (Table 9). Thus, if Condition A was better, worse, or equal to Condition B, it implied there was DA-HAcon, DA-CI, or no DA, respectively. Furthermore, for test conditions in the pairwise comparisons for the participant who was fitted with an HA on the right ear and a CI on the left ear mirrored the conditions in Figure 19 to 24.

Table 9 ***Post Hoc Analyses of Pairwise Comparisons Among test conditions in the CIHA Group***

Outcome			Condition A	Condition B	Result: A is better than B	Result: A is worse than B	Result: A is the same as B	Figure number
Binaural benefit	BR	BR-HAcon	NF-CI	NF-CIHA	+ve	-ve	no difference	19
	SQ	SQ-HAcon	NHA-CI	NHA-CIHA	+ve	-ve	no difference	20
	HS	HS-HAcon	NCI-CI	NCI-CIHA	+ve	-ve	no difference	21
SRM	CIHA	FHA-CIHA	NF-CIHA	NHA-CIHA	+ve	-ve	no difference	22
		FCI-CIHA	NF-CIHA	NCI-CIHA	+ve	-ve	no difference	
	CI	FHA-CI	NF-CI	NHA-CI	+ve	-ve	no difference	23
		FCI-CI	NF-CI	NCI-CI	+ve	-ve	no difference	
DA			NHA-CIHA	NCI-CIHA	DA-HAcon	DA-CI	no difference	24

Note. +ve = positive value of binaural benefits or SRM; -ve = negative value of binaural benefits or SRM.

Figure 19 CI Versus CIHA for BR of HA on the Contralateral Ear (BR-HAcon)

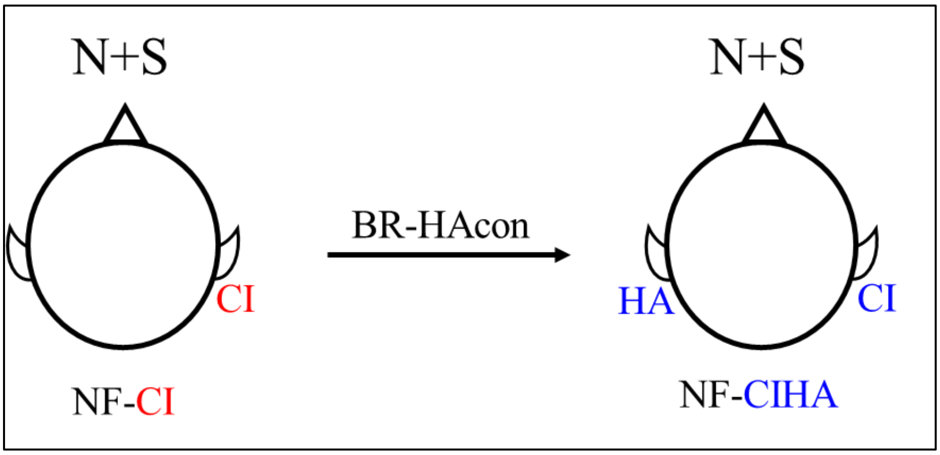


Figure 20 CI Versus CIHA for SQ of HA on the Contralateral Ear (SQ-HAcon)

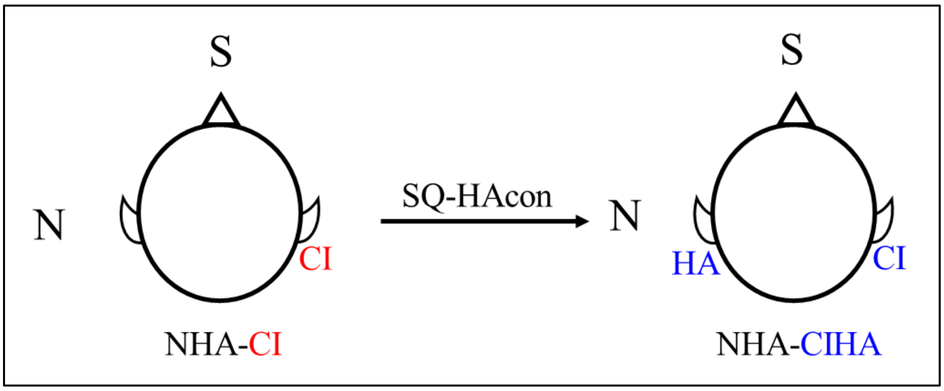


Figure 21 CI Versus CIHA for HS of HA on the Contralateral Ear (HS-HAcon)

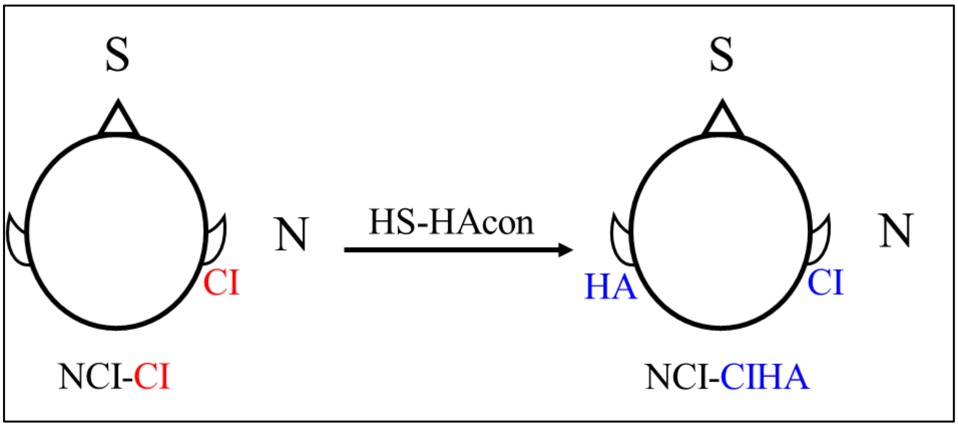


Figure 22 NF vs. NHA or NCI for Participants with CIHA (SRM for FHA-CIHA and FCI-CIHA)

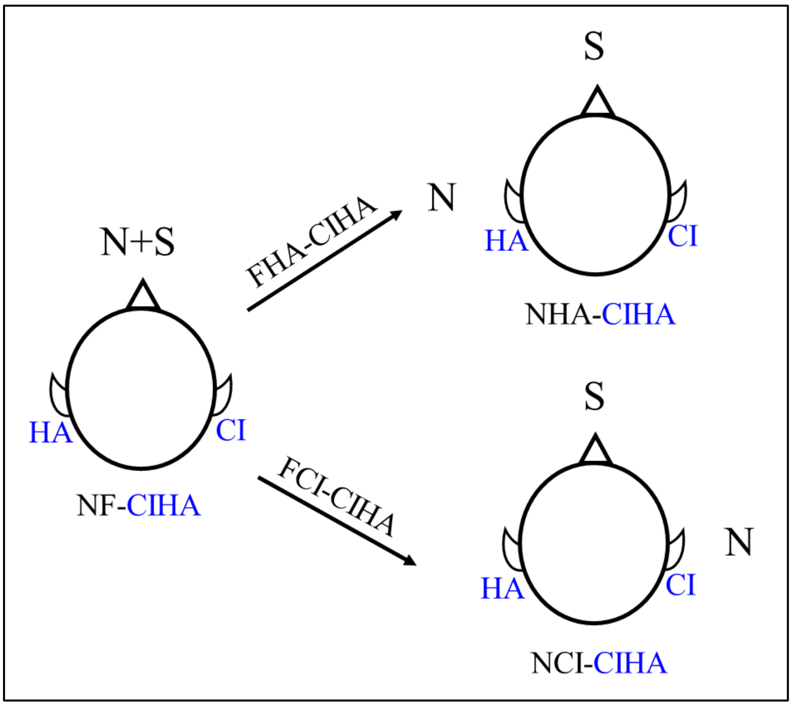


Figure 23 NF vs. NHA or NCI for Participants with Monaural CI (SRM for FHA-CI and FCI-CI)

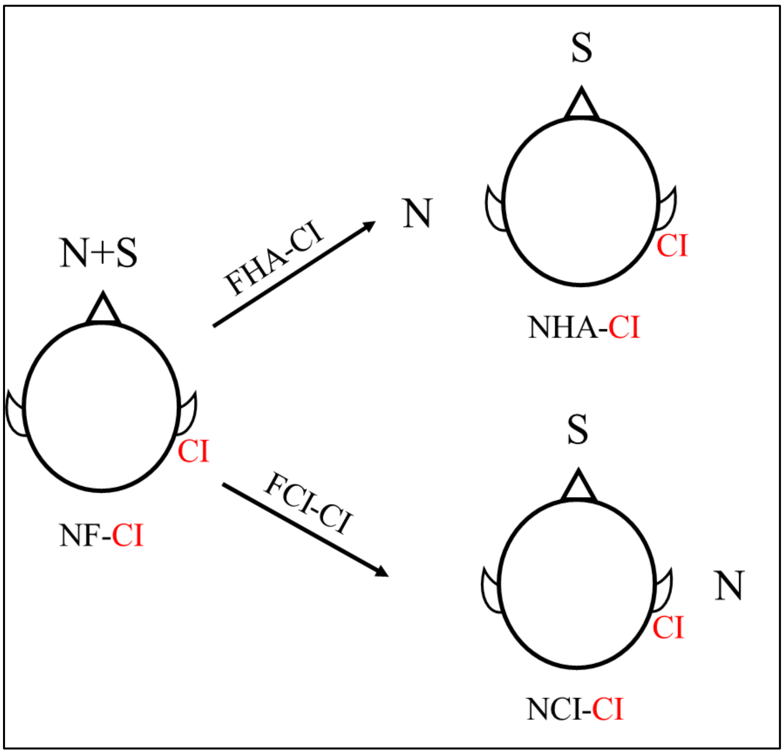
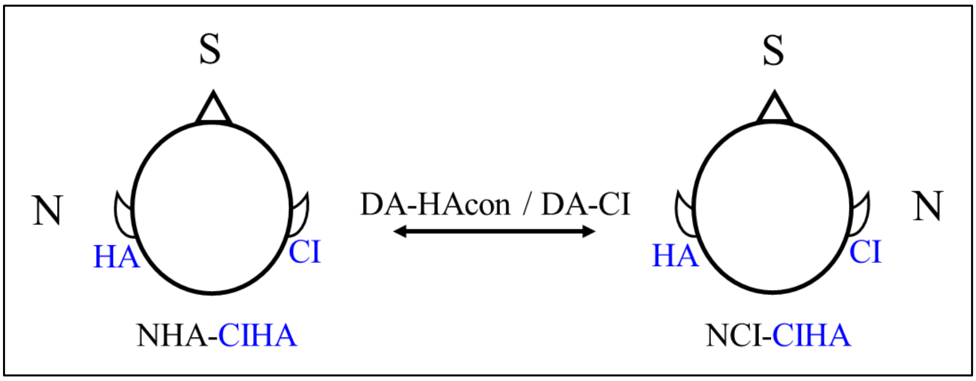


Figure 24 NHA vs. NCI for DA of CI or HA on the Contralateral Ear (DA-CI or DA-HAcon)



3.4.2.1.3 ANOVA and Post Hoc Analyses of SRM Results.

Descriptive statistics were derived for the SRM results of each group, including *M*, *SD*, *SE*, and *95% confidence interval*. A two-way repeated measures ANOVA was used to evaluate the primary effect of the device fitting condition (HAHA, HAL, and HAR in the HAHA group; CIHA and CI in the CIHA group) and noise direction (FL and FR in the HAHA group; FHA and FCI in the CIHA group), and interactions between the device fitting condition and noise direction. Post hoc analyses using honest significant difference (HSD) proposed by Turkey evaluated different pairwise comparisons. In addition, for all analyses, the level of statistical significance was set at $p < .05$.

3.4.2.2 aSNR-50% Scores of Individual Results.

The aSNR-50% scores data of individual participants under different test conditions in the speech recognition test in noise were analysed using confidence interval analysis. The *99% confidence interval* was obtained using the individual combined aSNR-50% scores from each test condition. Subsequently, two non-overlapping *99% confidence intervals* confirmed statistically significant differences in scores, that is, if the *99% confidence intervals* of scores from the two test conditions were non-overlapping, the speech recognition performances of these two conditions were deemed significantly different. This stringent criterion is a powerful and efficient measure to determine any subtle differences among the outcomes from different test conditions.

Furthermore, for each participant in the two groups, outcomes from the aforementioned pairwise comparisons (Table 8 and 9) were compared by intra-participant comparison. It was conducted using the result of the participant as a baseline (that is, their own control variables), such that the intra-participant comparison can minimise other interfering factors among the group of participants due to individual variability, such as language competence, attention, and intelligence. Because the mean aSNR-50% and *99% confidence interval* were obtained from each participant, it is possible for a researcher or clinician to interpret the result without having to first collect data from a control group, which substantially reduces the time and resources needed.

3.4.3 Regression Analysis of SII and SRiN Performance

A correlation analysis was conducted to examine the relationships among variables, including aSNR-50% results under different device fitting conditions for different noise directions, binaural benefits, SRM, and DA. A single linear regression analysis with a forced enter was adopted to examine the causal relationships among variables.

These analyses both used SPSS Statistics v.26 (IBM Corp., 2019).

For the HAHA group, SII-HAL was a predictor, and the aSNR-50% results of the HAHA fitting in all the noise directions (NF-HAL, NL-HAL, NR-HAL, NF-HAHA, NL-HAHA, and NR-HAHA) were dependent variables. Similarly, when SII-HAR was a predictor, the aSNR-50% results in all the noise directions (NF-HAR, NL-HAR, NR-HAR, NF-HAHA, NL-HAHA, and NR-HAHA) were dependent variables.

For the CIHA group, SII-CI was a predictor, and the aSNR-50% results of the CIHA fitting in all noise directions (NF-CI, NHA-CI, NCI-CI, NF-CIHA, NHA-CIHA, and NCI-CIHA) were dependent variables. In addition, when SII-HA was a predictor, the aSNR-5-% results of the CIHA fitting in all the noise directions (NF-CIHA, NHA-CIHA, and NCI-CIHA) were dependent variables. Moreover, considering that for most individuals with the CIHA fitting, the SRiN performance of the CI side was better than that of the HA side (Gifford et al., 2014; Mok et al., 2007; Van Hoesel, R. J. M., 2012), the SII-HAcon was a predictor for the binaural-benefit dependent variables (BR-HAcon, SQ-HAcon, and HS-HAcon).

Chapter 4: Results

4.1 Hearing Ability

4.1.1 Hearing Threshold Results

The descriptive statistics of the unaided and aided hearing thresholds are listed in Table 10. Figure 25 and 26 show the values of *M* and *SD* of the unaided and aided thresholds for the HAHA and CIHA groups at all frequencies, respectively. The thresholds of each participant are shown in Appendix C.

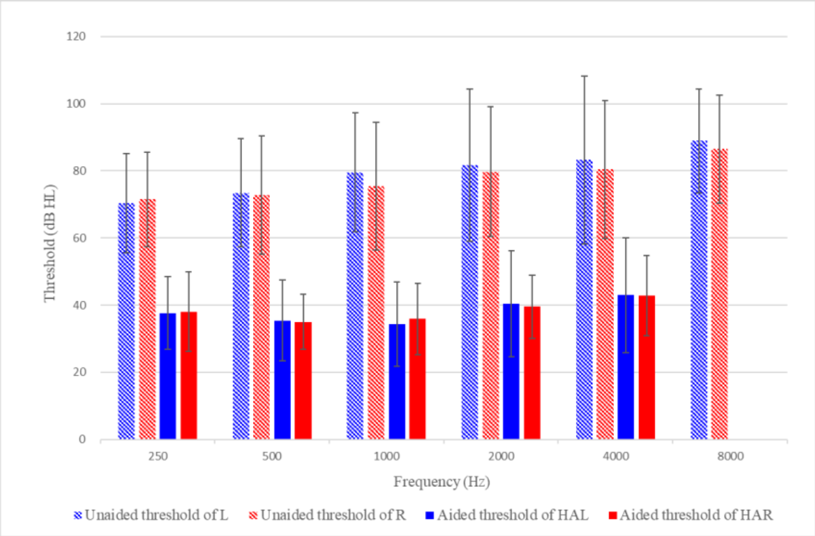
4.1.2 Hearing Aid Performance

Two participants (HAHA-M1 and HAHA-M14) in the HAHA group could not complete the real-ear measurement. Figure 27 and 28 show the measured RECD and hearing aid output in the 2 cc coupler for the two groups, respectively. The descriptive statistics of the RECD and hearing aid outputs in the 2 cc coupler are listed in Table 11 and 12, respectively.

4.1.3 SII Results

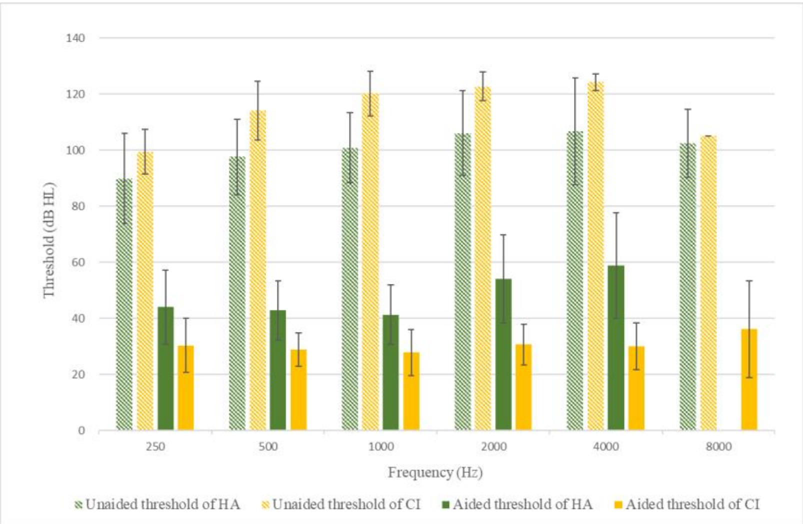
The descriptive statistics of the monaural SII for the two groups are listed in Table 13.

Figure 25 Mean Unaided and Aided Pure-Tone Thresholds (dB HL) of the Participants with the HAHA Fitting



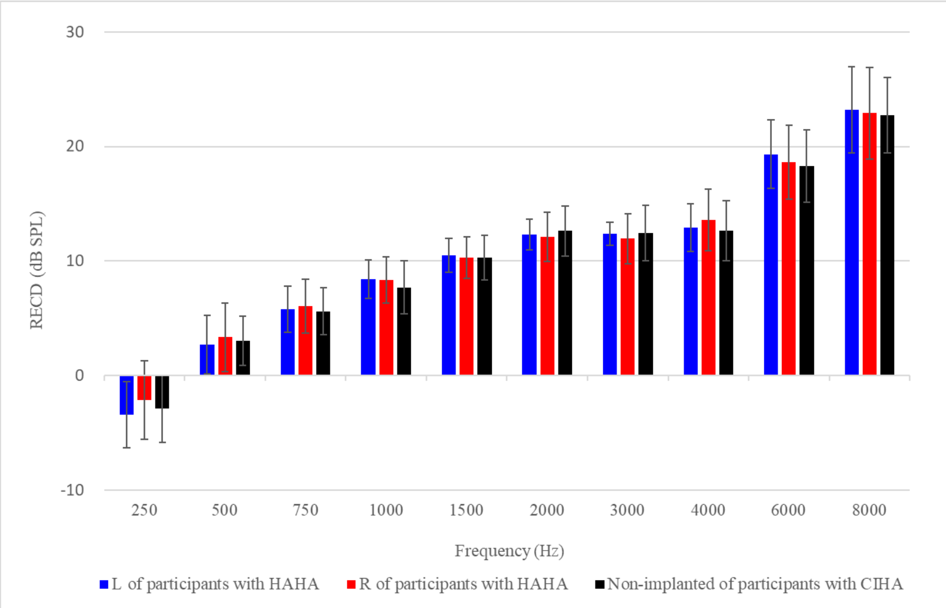
Note. Error bars represent *SD*. *N* = 23 for the HAHA group. L = left; R = right; HAL = monaural hearing aid fitting on the left ear; HAR = monaural hearing aid fitting on the right ear.

Figure 26 Mean Unaided and Aided Pure-Tone Thresholds (dB HL) of the Participants with the CIHA Fitting



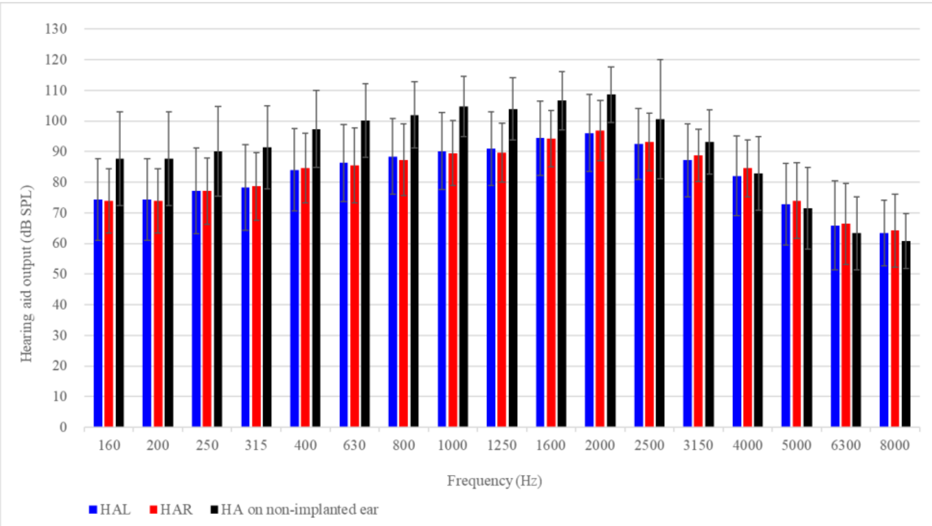
Note. Error bars represent *SD*. *N* = 33 for the CIHA group. CI = cochlear implant; HA = hearing aid.

Figure 27 Mean RECD (dB SPL) Measured in the Participants



Note. Error bars represent *SD*. *N* = 21 for the HAHA group, and *N* = 33 for the CIHA group. L = left; R = right.

Figure 28 Mean Hearing Aid Output (dB SPL) of the Participants for Speech as Input



Note. Error bars represent *SD*. *N* = 21 for the HAHA group, and *N* = 33 for the CIHA group. HA = hearing aid; HAL = monaural hearing aid fitting on the left ear; HAR = monaural hearing aid fitting on the right ear.

Table 10 ***Unaided and Aided Pure-Tone Thresholds (dB HL) of the Participants***

Group	Ear		250 *M*	250 *SD*	500 *M*	500 *SD*	1000 *M*	1000 *SD*	2000 *M*	2000 *SD*	4000 *M*	4000 *SD*	8000 *M*	8000 *SD*
HAHA	L	Unaided	70.43	15.14	73.48	16.41	79.57	18.02	81.74	23.24	83.26	25.61	88.91	15.88
		Aided	37.61	11.06	35.43	12.33	34.35	12.82	40.43	16.23	43.04	17.50	NA	NA
	R	Unaided	71.52	14.42	72.83	17.95	75.43	19.42	79.78	19.80	80.43	20.5	86.52	16.48
		Aided	38.04	12.13	35.00	8.39	35.87	10.83	39.57	9.64	42.83	12.23	NA	NA
CIHA	HA	Unaided	89.85	16.32	97.58	13.70	100.91	12.78	106.06	15.35	106.82	19.36	102.42	11.71
		Aided	44.09	13.43	42.88	10.83	41.36	10.70	54.07	15.88	58.94	19.07	NA	NA
	CI	Unaided	99.39	8.08	114.09	10.64	120.30	8.10	122.73	5.17	124.24	3.09	105.00	0.00
		Aided	30.45	9.79	28.94	5.96	27.88	8.39	30.76	7.41	30.00	8.48	36.21	17.50

Note. *M* and *SD* represent the results of all the participants from each group. *N* = 23 for the HAHA group and *N* = 33 for the CIHA group. HA = hearing aid; CI = cochlear implant; L = left; R = right; NA = not applicable.

Table 11 ***Measured RECD (dB SPL) of the Participants***

Group	Ear	250 *M*	250 *SD*	500 *M*	500 *SD*	750 *M*	750 *SD*	1000 *M*	1000 *SD*	1500 *M*	1500 *SD*	2000 *M*	2000 *SD*	3000 *M*	3000 *SD*	4000 *M*	4000 *SD*	6000 *M*	6000 *SD*	8000 *M*	8000 *SD*
HAHA	L	-3.43	2.90	2.67	2.55	5.76	2.02	8.38	1.68	10.48	1.50	12.29	1.35	12.38	1.00	12.90	2.07	19.33	2.98	23.19	3.79
	R	-2.14	3.41	3.33	3.01	6.05	2.38	8.33	2.03	10.29	1.83	12.10	2.16	11.95	2.17	13.57	2.70	18.62	3.20	22.90	3.99
CIHA	Non-implanted	-2.91	2.94	3.03	2.15	5.61	2.06	7.67	2.32	10.30	1.93	12.61	2.17	12.42	2.41	12.61	2.62	18.30	3.16	22.73	3.32

Note. *M* and *SD* represent the results of all the participants from each group. *N* = 23 for the HAHA group and *N* = 33 for the CIHA group. L = left; R = right.

Table 12 ***Hearing Aid Output (dB SPL) of the Participants***

Frequency (Hz)	HAHA				CIHA	
	HAL		HAR		HA on non-implanted ear	
	M	*SD*	*M*	*SD*	*M*	*SD*
160	74.32	13.28	73.95	10.51	87.67	15.23
200	74.32	13.28	73.95	10.51	87.67	15.23
250	77.18	13.95	77.08	10.87	90.12	14.59
315	78.33	13.95	78.62	11.12	91.45	13.56
400	84.05	13.37	84.57	11.33	97.33	12.55
500	86.94	12.60	86.93	11.50	100.55	12.03
630	86.33	12.59	85.45	12.26	100.18	11.99
800	88.41	12.37	87.31	11.70	101.97	10.77
1000	90.18	12.66	89.52	10.58	104.70	9.87
1250	90.91	12.04	89.62	9.60	103.91	10.19
1600	94.38	12.09	94.30	9.14	106.64	9.52
2000	96.05	12.52	96.90	9.82	108.58	9.11
2500	92.45	11.61	93.12	9.37	100.48	19.46
3150	87.14	11.96	88.75	8.59	93.09	10.44
4000	82.03	12.98	84.53	9.20	82.94	12.05
5000	72.81	13.30	73.98	12.30	71.58	13.34
6300	65.92	14.58	66.42	13.18	63.39	11.91
8000	63.49	10.68	64.20	11.85	60.76	8.92

Note. *M* and *SD* represent the results of all the participants from each group. *N* = 21 for the HAHA group and *N* = 33 for the CIHA group. HAL = monaural HA fitting on the left ear; HAR = monaural HA fitting on the right ear.

Table 13 ***Monaural SII of the Participants***

Group	Hearing prosthesis	SII	
		M	*SD*
HAHA	HAL	0.39	0.18
	HAR	0.41	0.21
CIHA	HA on non-implanted ear	0.19	0.15
	CI	0.86	0.01

Note. *N* = 21 for the HAHA group, and *N* = 33 for the CIHA group. HAL = monaural HA fitting on the left ear; HAR = monaural HA fitting on the right ear; CI = cochlear implant

4.2 SRiN Performance

4.2.1 ANOVA and Post Hoc Analyses of Group Results

4.2.1.1 aSNR-50% Scores and SRM Results in the HAHA Group

Table 14 lists the descriptive statistics of the average aSNR-50% scores in nine test conditions of the HAHA group. Differences between two aSNR-50% scores were calculated from each pairwise comparison for each participant with HAHA, and the results were averaged to obtain the group results that are listed in Table 15.

For all aSNR-50% scores from each test condition of the HAHA group, the two-way repeated ANOVA yielded a significant main effect for the device fitting condition with $F(2, 44) = 7.96$, $p = .001$, $\eta_p^2 = .27$. The main effect of noise direction was non-significant with $F(2, 44) = 2.38$, $p = .104$, $\eta_p^2 = .10$. However, the interaction effect was significant with $F(4, 88) = 37.42$, $p < .001$, $\eta_p^2 = .63$. Table 15 lists the *p* value of the post hoc analyses of the aforementioned pairwise comparisons (refer to Table 8) for the HAHA group. The results revealed that the participants showed a significantly positive BR-HAR, HS-HAR, HS-HAL, and FR-HAL, and a significantly negative FL-HAL and FR-HAR (Figure 29). However, the participants showed a non-significant BR-HAL, SQ-HAR, SQ-HAL, FL-HAHA, FR-HAHA, FL-HAR, and DA with hearing aids.

Table 14 ***Descriptive Statistics of Group Average aSNR-50% Scores (dB SNR)***

under ***Nine test conditions for the Participants in the HAHA Group***

device fitting condition	Noise direction	test conditions	*M*	*SD*	*SE*	95 % CI	
						LL	*UL*
HAHA	NF	NF-HAHA	-3.50	3.44	0.72	-4.99	-2.01
	NL	NL-HAHA	-3.57	4.29	0.90	-5.43	-1.72
	NR	NR-HAHA	-2.78	4.90	1.02	-4.90	-0.66
HAL	NF	NF-HAL	-1.12	4.68	0.98	-3.14	0.91
	NL	NL-HAL	1.33	5.97	1.24	-1.25	3.91
	NR	NR-HAL	-3.72	4.57	0.95	-5.69	-1.74
HAR	NF	NF-HAR	-2.06	4.61	0.96	-4.06	-0.07
	NL	NL-HAR	-3.71	4.60	0.96	-5.70	-1.72
	NR	NR-HAR	2.24	5.73	1.19	-0.23	4.72

Note. *N* = 23; *95% confidence interval* = 95% confidence interval; *LL* = lower limit, *UL* = upper limit; HAHA = binaural hearing aids fitting; HAL = monaural HA fitting on the left ear; HAR = monaural HA fitting on the right ear; NF = both speech and noise are presented from the front; NL = speech is presented from the front and noise is presented at -90° azimuth on the left; NR = speech is presented from the front and noise is presented at +90° azimuth on the right.

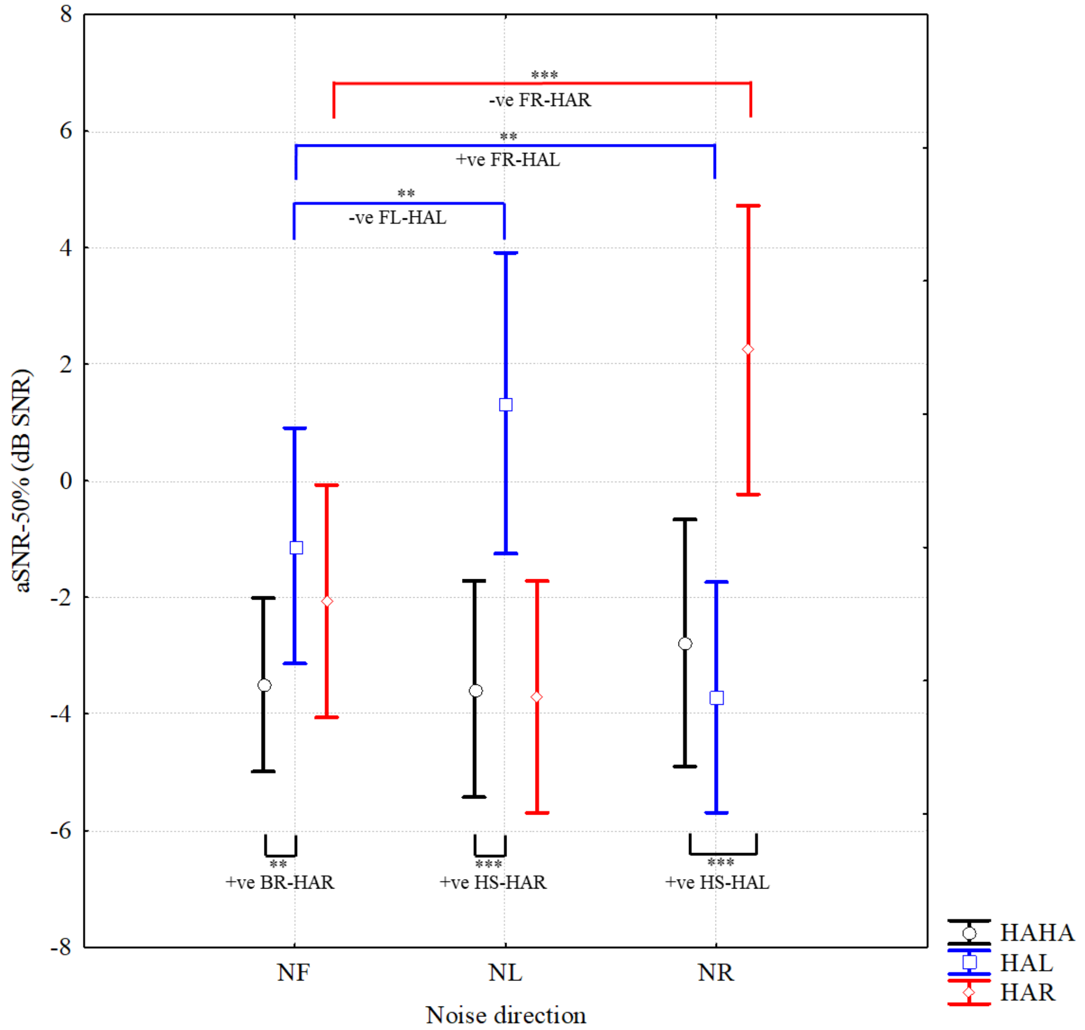
Table 15 ***Outcome (dB SNR) for Each Pairwise Comparison in the HAHA Group***

Outcome (A - B)			Condition A	Condition B	*M*	*SD*	*p* value	Result
Binaural benefit	BR	BR-HAR	NF-HAL	NF-HAHA	2.38	2.77	.005	+ve
		BR-HAL	NF-HAR	NF-HAHA	1.43	3.69	.317	Non-significant
	SQ	SQ-HAR	NR-HAL	NR-HAHA	-0.93	3.78	.834	Non-significant
		SQ-HAL	NL-HAR	NL-HAHA	-0.13	2.64	>.99	Non-significant
	HS	HS-HAR	NL-HAL	NL-HAHA	4.90	3.53	<.001	+ve
		HS-HAL	NR-HAR	NR-HAHA	5.02	3.86	<.001	+ve
SRM	HAHA	FL-HAHA	NF-HAHA	NL-HAHA	0.07	3.73	>.99	Non-significant
		FR-HAHA	NF-HAHA	NR-HAHA	-0.72	4.85	>.958	Non-significant
	HAL	FL-HAL	NF-HAL	NL-HAL	-2.45	3.05	.004	-ve
		FR-HAL	NF-HAL	NR-HAL	2.60	2.85	.002	+ve
	HAR	FL-HAR	NF-HAR	NL-HAR	1.64	3.02	.317	Non-significant
		FR-HAR	NF-HAR	NR-HAR	-4.31	4.08	<.001	-ve
DA	DA-HAL / DA-HAR		NL-HAHA	NR-HAHA	-0.79	3.43	.928	Non-significant

Note. *N* = 23. DA was quantified as the difference between NL-HAHA and NR-HAHA. BR = binaural redundancy; SQ = binaural squelch; HS = head-shadow effect; SRM = spatial release from masking; HAHA = binaural hearing aid fitting; HAL = monaural HA fitting on the left ear; HAR = monaural HA fitting on the right ear; DA = device advantage; +ve = positive value of binaural benefits or SRM; -ve = negative value of binaural benefits or SRM.

figure

Figure 29 Group Average aSNR-50% Scores of the Participants in the HAHA Group



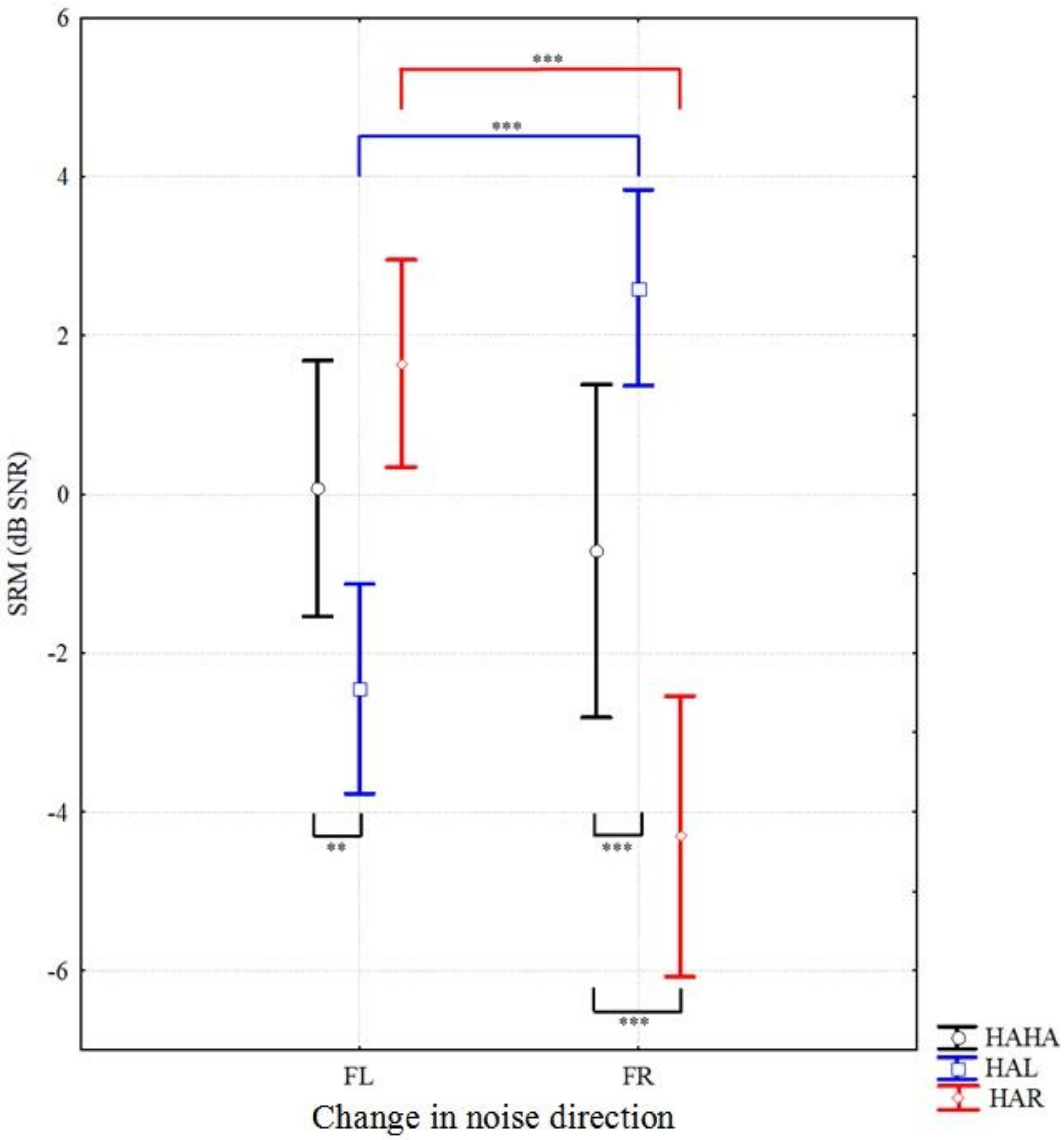
Note. The mean aSNR-50% of participants with HAHA (black, circles), HAL (blue, squares), and HAR (red, rhombuses) are shown for NF (left), NL (middle), and NR (right). Statistical significance across conditions is indicated using brackets and asterisks above the symbols. Error bars represent a *95% confidence interval*.

$^{**}p < .01$. $^{***}p < .001$.

For the six SRM results, the two-way repeated ANOVA showed that the main effect of the device fitting condition was not significant with $F(2, 44) = 1.88$, $p = .164$, η_p^2

= .08; moreover, the main effect of noise direction showed a similar result and $F(1, 22) = 1.27$, $p = .273$, $\eta_p^2 = .05$. However, the interaction between the device fitting condition and noise direction was significant and $F(2, 44) = 83.34$, $p < .001$, $\eta_p^2 = .79$. In the FL condition, FL-HAHA was not significantly better than FL-HAR ($p = .118$), but it was significantly better than FL-HAL ($p = .002$) (Figure 30). The results revealed that even though the binaural HAHA fitting cannot significantly improve the SRM when compared to that with the monaural HAR fitting, it can significantly improve the performance when compared to that with the monaural HAL fitting. In the FR condition, FR-HAHA was significantly worse than FR-HAL ($p <.001$); however, it was significantly better than FR-HAR ($p <.001$). The results indicate that the binaural HAHA fitting significantly decreased the SRM when compared to that with the monaural HAL fitting, but it can significantly increase when compared to that with monaural HAR fitting. In addition, FR-HAL was significantly better than FL-HAL ($p <.001$), and FL-HAR was significantly better than FR-HAR ($p <.001$) (Figure 30). The results indicate that the noise that was contralateral to the monaural HA fitting significantly increased the SRM from that where the noise was ipsilateral to the monaural HA fitting. However, FL-HAHA was not better than FR-HAHA ($p =.778$), indicating that the SRM with binaural HAHA fitting was not significantly different regardless of the direction of the noise.

Figure 30 Group Average SRM Results of the Participants in the HAHA Group



Note. The mean SRM for participants with HAHA (black, circles), HAL (blue, squares), and HAR (red, rhombuses) are shown for the FL (left) and FR (right) noise directions. Statistical significance across conditions is indicated by brackets and asterisks above the symbols. Error bars represent *95% confidence interval*.

$^{**}p < .01$. $^{***}p < .001$.

4.2.1.2 aSNR-50% Scores and SRM Results in the CIHA Group

Table 16 lists the descriptive statistics of the average aSNR-50% scores in six conditions of the CIHA group. The differences between two aSNR-50% scores were calculated from each pairwise comparison for each participant with CIHA, and the results were averaged to obtain the group results that are listed in Table 17.

For all aSNR-50% scores from each test condition of the CIHA group, the two-way repeated ANOVA yielded a significant main effect for the device fitting condition and $F(1, 32) = 31.64$, $p < .001$, $\eta_p^2 = .50$. The main effect of noise direction was significant with $F(2, 64) = 19.24$, $p < .001$, $\eta_p^2 = .38$. The interaction effect was non-significant with $F(2,64) = 1.42$, $p = .250$, $\eta_p^2 = .04$. Table 17 lists the *p* values of the post hoc analyses of the aforementioned pairwise comparisons (refer to Table 9) for the CIHA group. The results revealed that the participants showed a significantly positive BR-HAcon, SQ-HAcon, HS-HAcon, FHA-CIHA, and FHA-CI, a significantly negative FCI-CI, and a significant DA-CI (Figure 31). However, the participants showed a non-significant FCI-CIHA.

Table 16 ***Descriptive Statistics of Group Average aSNR-50% Scores (dB SNR) under Six test conditions for the Participants in the CIHA Group***

device fitting condition	Noise direction	test conditions	*M*	*SD*	*SE*	*95% confidence interval*	
						LL	*UL*
CIHA	NF	NF-CIHA	-5.41	2.63	0.46	-6.34	-4.48
	NHA	NHA-CIHA	-7.30	3.33	0.58	-8.48	-6.12
	NCI	NCI-CIHA	-4.19	3.55	0.62	-5.45	-2.93
Monaural CI	NF	NF-CI	-1.87	4.70	0.82	-3.54	-0.20
	NHA	NHA-CI	-3.67	5.62	0.98	-5.66	-1.67
	NCI	NCI-CI	0.30	5.63	0.98	-1.69	2.30

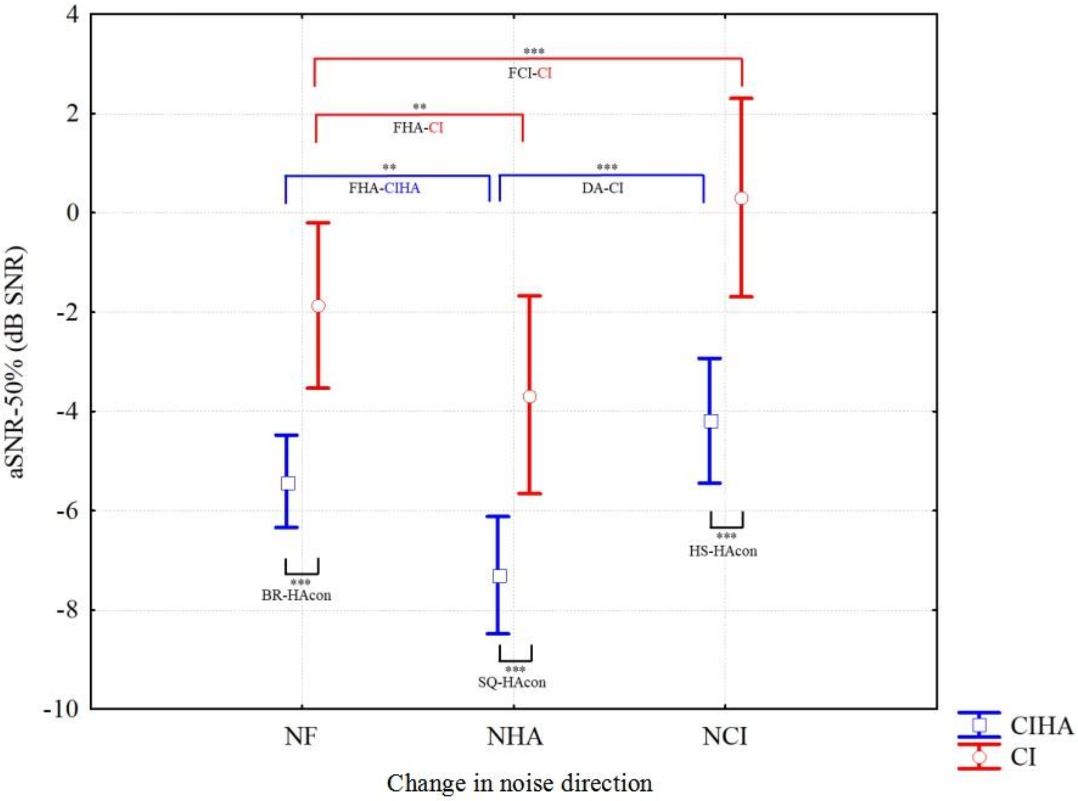
Note. N = 33; *95% confidence interval* = 95% confidence interval; *LL* = lower limit, *UL* = upper limit; CIHA = bimodal fitting; CI = cochlear implant; NF = both speech and noise are presented from the front; NHA = speech is presented from front and noise is presented at 90° azimuth from the hearing aid side; NCI = speech is presented from front and noise is presented at 90° azimuth from cochlear implant side.

Table 17 ***Outcome (dB SNR) for Each Pairwise Comparison in the CIHA Group***

Outcome (A - B)			Condition A	Condition B	*M*	*SD*	*p* value	Result
Binaural benefit	BR	BR-HAcon	NF-CI	NF-CIHA	3.54	4.08	<.001	+ve
	SQ	SQ-HAcon	NHA-CI	NHA-CIHA	3.63	4.08	<.001	+ve
	HS	HS-HAcon	NCI-CI	NCI-CIHA	4.49	5.01	<.001	+ve
SRM	CIHA	FHA-CIHA	NF-CIHA	NHA-CIHA	1.89	3.36	.001	+ve
		FCI-CIHA	NF-CIHA	NCI-CIHA	-1.22	3.03	.075	Non-significant
	Monaural CI	FHA-CI	NF-CI	NHA-CI	1.80	3.41	.002	+ve
		FCI-CI	NF-CI	NCI-CI	-2.17	3.59	<.001	+ve
DA	DA-CI / DA-HAcon		NHA-CIHA	NCI-CIHA	3.11	3.85	<.001	DA-CI

Note. *N* = 33. DA was quantified by the difference between NCI-CIHA and NHA-CIHA. BR = binaural redundancy; SQ = binaural squelch; HS = head-shadow effect; SRM = spatial release from masking; CIHA = bimodal fitting; CI = cochlear implant; DA = device advantage; +ve = positive value of binaural benefits or SRM; -ve = negative value of binaural benefits or SRM.

Figure 31 Group Average aSNR-50% Scores of the Participants in the CIHA Group

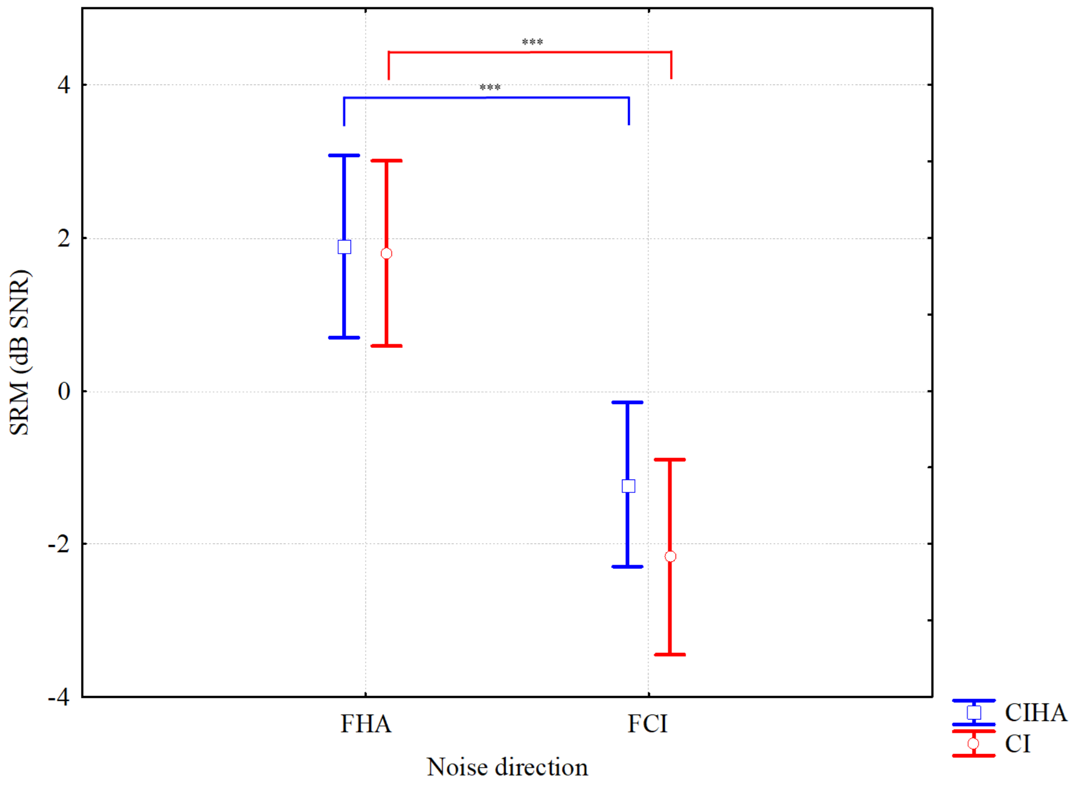


Note. The mean aSNR-50% scores of participants with CIHA (blue, squares) and CI (red, circles) are shown for NF (left), NHA (middle), and NCI (right). Statistical significance across conditions is indicated by brackets and asterisks above the symbols. Error bars represent *95% confidence interval*.

$^{**}p < .01$. $^{***}p < .001$.

For the four SRM results, the two-way repeated ANOVA showed that the main effect of the device fitting condition was not significant with $F(1, 32) = 1.73$, $p = .197$, $\eta_p^2 = .05$. The main effect of the noise direction was significant with $F(1, 32) = 28.09$, $p < .001$, $\eta_p^2 = .47$. However, the interaction effect was not significant with $F(1,32) = 1.30$, $p = .262$, $\eta_p^2 = .04$. When the noise moved from NF to NHA, the SRM with CIHA (FHA-CIHA) was not significantly different from that with monaural CI fitting (FHA-CI) ($p = .998$) (Figure 32). When the noise moved from NF to NCI, the SRM with CIHA (FCI-CIHA) was not significantly different from that with monaural CI fitting (FCI-CI) ($p = .299$). The results indicate that the binaural CIHA fitting cannot significantly improve the SRM when compared to the monaural CI fitting irrespective of the direction in which the source of noise moves. However, the results revealed that FHA-CIHA was significantly better than FCI-CIHA, and FHA-CI was significantly better than FCI-CI (Figure 32). The results also revealed that the noise at the HA side can significantly improve the SRM when compared to the case where the noise is at the CI side, regardless of CIHA or monaural CI fitting.

Figure 32 Group Average SRM Results of the Participants in the CIHA Group



Note. The mean SRM for participants with CIHA (blue, squares) and (red, circles) are shown for FHA (left) and FCI (right) noise directions. Statistical significance across conditions is indicated by brackets and asterisks above the symbols. Error bars represent *95% confidence interval*.

$^{**}p < .01$. $^{***}p < .001$.

4.2.2 Confidence Interval Analysis of Individual Results

The aSNR-50% scores of the individual participants in the pairwise comparisons discussed in Data Analysis (Table 8 and 9) revealed the performance of individual participants in different test conditions. For the same participant, if two *99% confidence intervals* of aSNR-50% scores of the pairwise comparison did not overlap, then the two means of aSNR-50% scores were considered statistically different, indicating that the participant showed significantly positive or negative binaural benefits, significantly positive or negative SRM, or significant DA. However, if two *99% confidence intervals* of aSNR-50% scores of the pairwise comparison were overlapping, then the results indicated that the participant showed non-significant binaural benefits, SRM, or DA.

In all of the figures in this section (i.e., Figure 33 through 53), the rhombuses (HAR in the HAHA group), squares (HAL in the HAHA group or CIHA in the CIHA group), and circles (HAHA in the HAHA group or CI in the CIHA group) denote aSNR-50% mean scores and the error bars denote *99% confidence interval* of aSNR-50% scores. The vertical axes represent the aSNR-50% scores (dB SNR). The upper horizontal axes represent the differences in mean aSNR-50% scores from the two test conditions, and the lower horizontal axes represent the participants, who are arranged according to the descending order of differences between two means of aSNR-50% scores. For binaural benefits and SRM, the condition pairs with significantly positive differences and those with non-significant differences are separated by the black dashed lines; the condition pairs with non-significant differences and those with significantly negative differences are separated by the black dotted lines, if there are any. For DA, the condition pairs with significant DA-HAL (NL-HAHA outperformed NR-HAHA) in the HAHA group or DA-CI (NCI-CIHA outperformed NHA-CIHA) in the CIHA group and those with non-significant differences are separated by the black dashed lines; the condition pairs with non-significant differences and those with significant DA-HAR (NR-HAHA outperformed NL-HAHA) in the HAHA group or DA-HAcon (NHA-CIHA outperformed NCI-CIHA) in the CIHA group are separated by the black dotted lines.

4.2.2.1 Individual aSNR-50% scores in the HAHA group

Figure 33 to 45 show the results of BR-HAR, BR-HAL, SQ-HAR, SQ-HAL, HS-HAR, HS-HAL, FL-HAHA, FR-HAHA, FL-HAL, FR-HAL, FL-HAR, FR-HAR, and DA of all 23 participants in the HAHA group, respectively. Table 18 and 19 list the number and proportion of participants in the HAHA group who obtained binaural benefits and SRM results, respectively, including significantly positive results (+ve), significantly negative results (-ve), and no difference. Table 20 lists the number and proportion of participants in the HAHA group who obtained the DAs of DA-HAL, DA-HAR, and no difference.

When compared to monaural HA fitting, most participants (20 of 23) with binaural HA fitting were able to achieve at least one significant binaural benefit. One participant (HAHA-F11) showed statistically equivalent SRiN performance with different device fitting conditions in all noise directions, indicating that this participant could not obtain either positive or negative binaural benefits with HAHA fitting when compared to monaural HA fitting. However, two participants (HAHA-F8 and HAHA-M8) with HAHA fitting could not achieve significant BR and HS advantages, and even showed a disadvantage of SQ.

While considering the SRM outcomes of participants in the HAHA group, Table 19 shows that five participants with HAHA fitting obtained either significantly positive FL-HAHA or FR-HAHA. However, three participants (HAHA-F9, HAHA-M1, and HAHA-M13) obtained either significantly negative FL-HAHA or FR-HAHA, and the other two participants (HAHA-M5 and HAHA-M6) obtained both significantly negative FL-HAHA and FR-HAHA. The remaining 13 participants with HAHA fitting obtained both non-significant FL-HAHA and FR-HAHA. For the participants with monaural HA fitting, when the noise moved from the front to the unaided ear, 10 participants obtained at least one significantly positive FR-HAL or FL-HAR; however, none of the participants had significantly negative FR-HAL and FL-HAR. In contrast, when the noise moved from the front to the aided ear, only HAHA-M11 obtained significantly positive FL-HAL and FR-HAR, and HAHA-M4 obtained significantly positive FL-HAL. However, the remaining 18 participants obtained at least one significantly negative FL-HAL or FR-HAR.

Figure 33 BR-HAL of the Participants with HAHA vs. HAR under the NF Condition

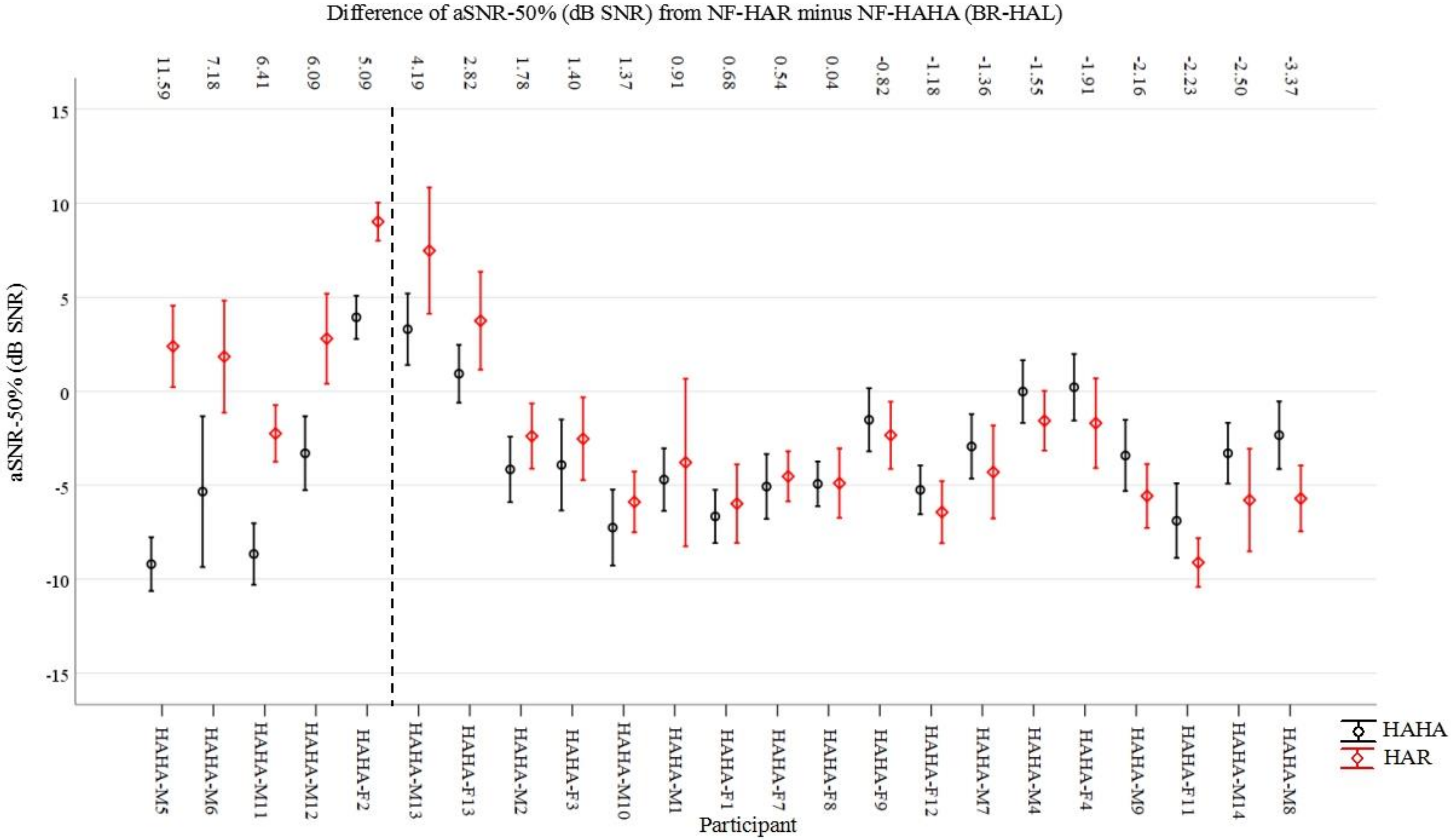


Figure 34 BR-HAR of the Participants with HAHA vs. HAL under the NF Condition

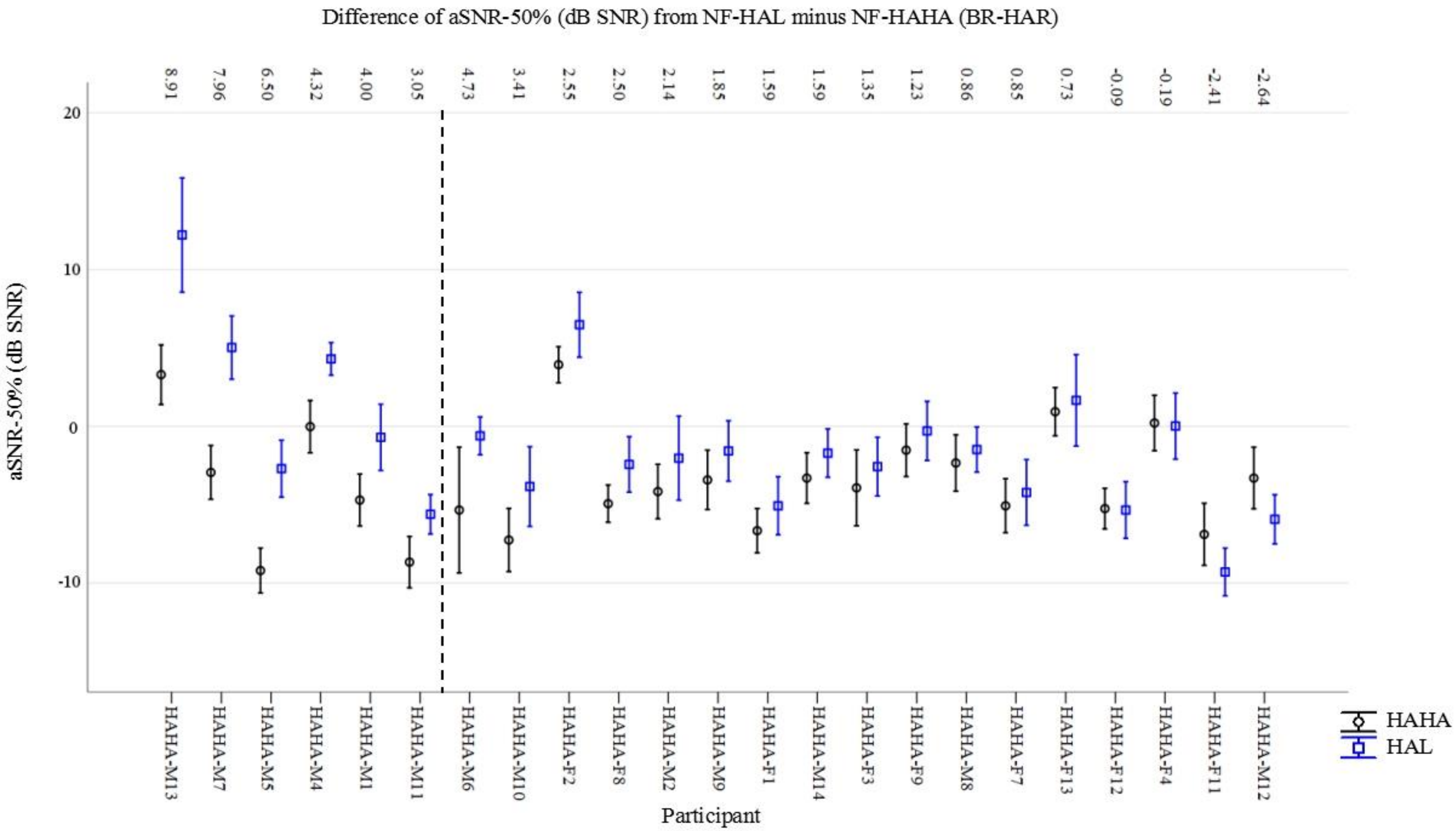


Figure 35 SQ-HAL of the Participants with HAHA vs. HAR under the NL Condition

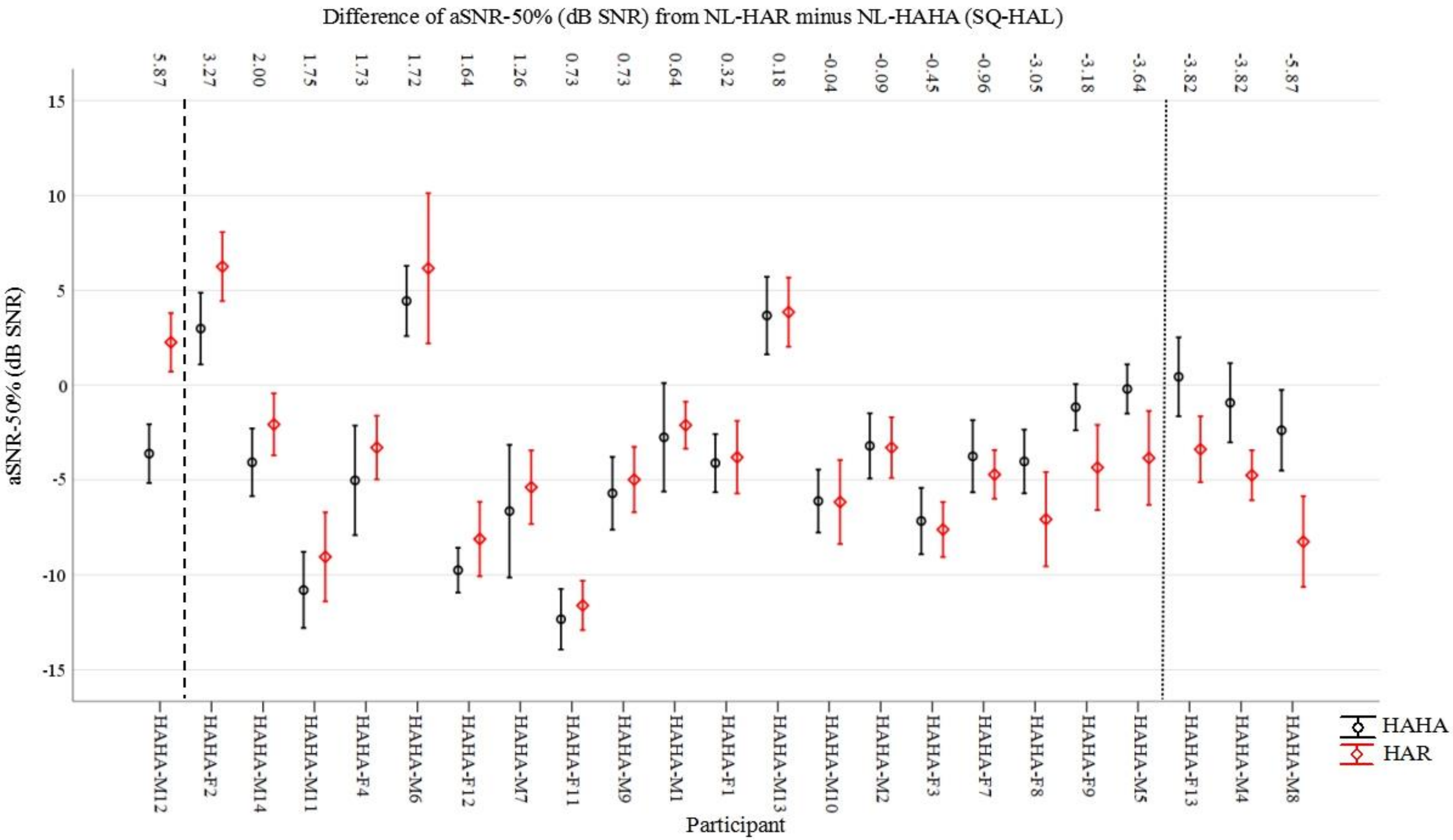


Figure 36 SQ-HAR of the Participants with HAHA vs. HAL under the NR Condition

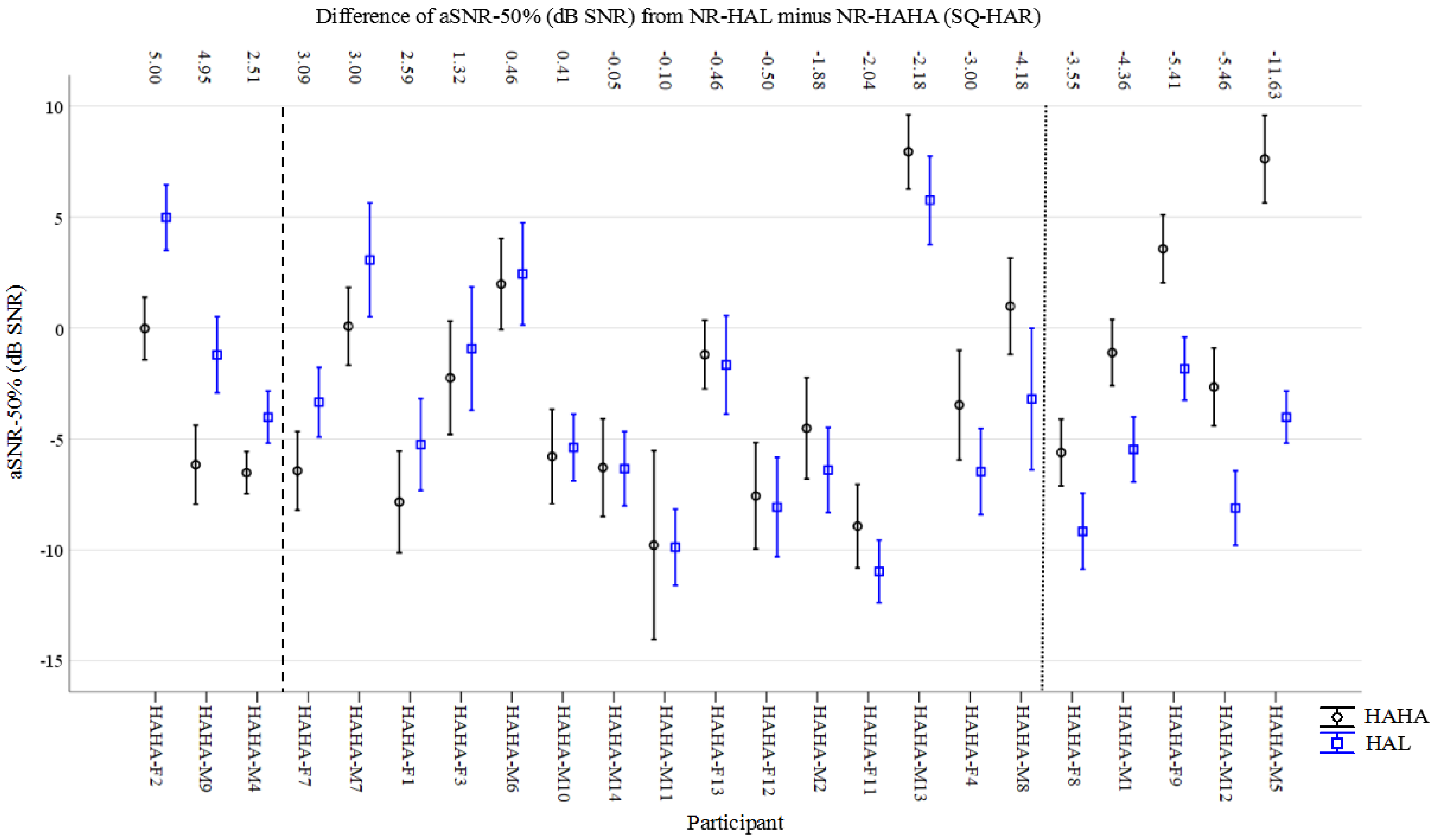


Figure 37 HS-HAL of the Participants with HAHA vs. HAR under the NR Condition

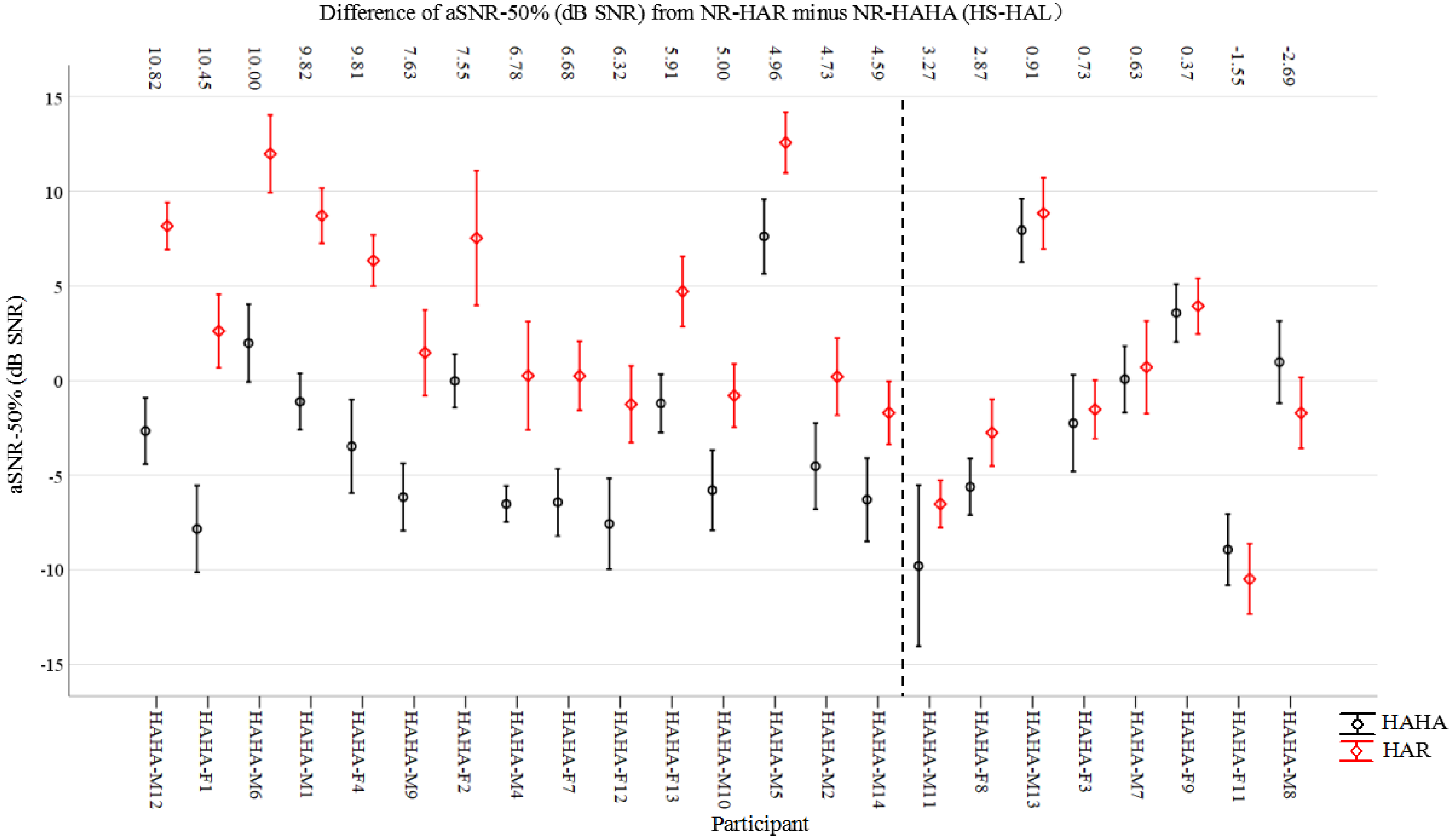


Figure 38 HS-HAR of the Participants with HAHA vs. HAL under the NL Condition

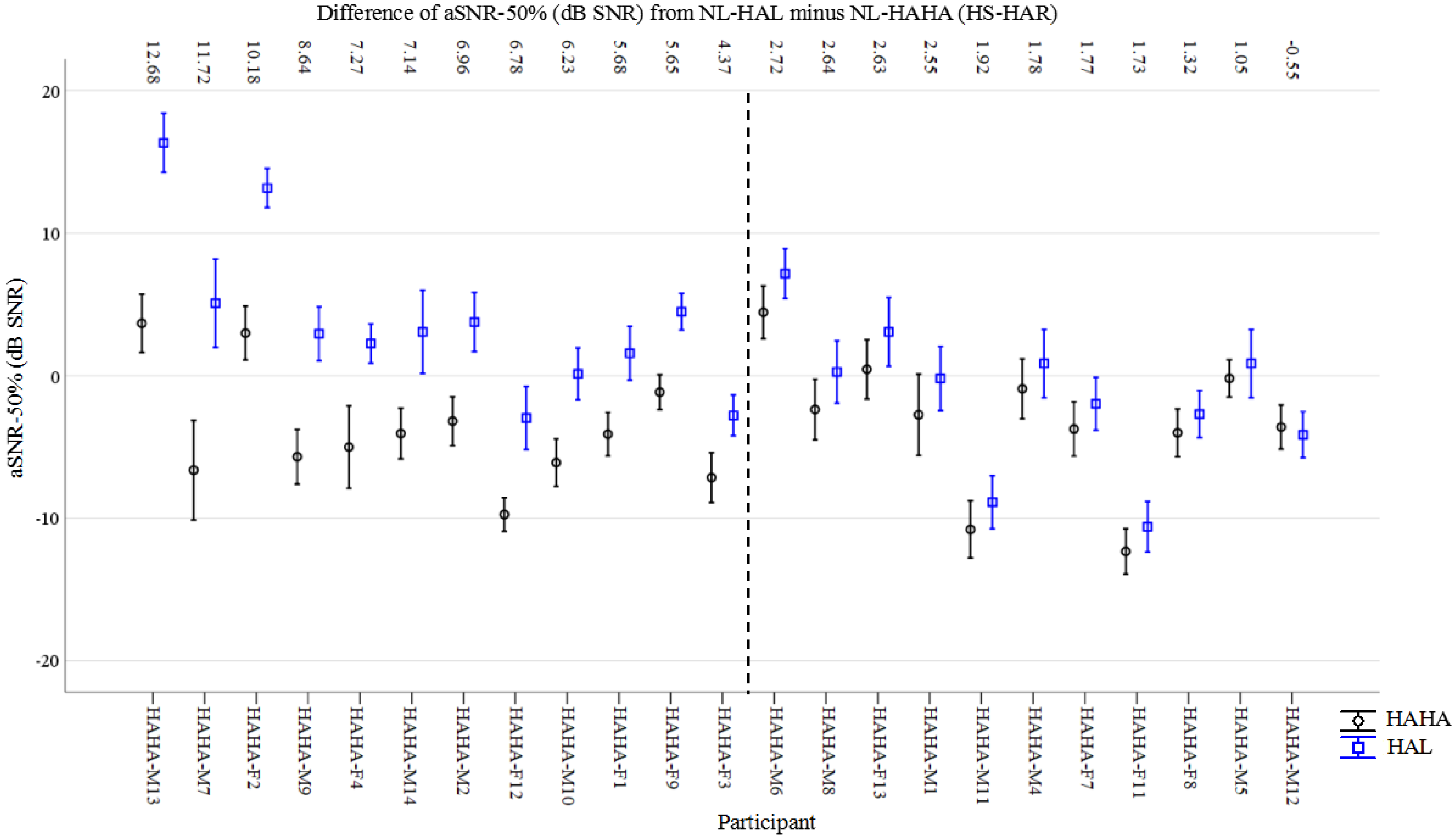


Figure 39 FL-HAHA of the Participants with HAHA under the NF vs. NL Condition

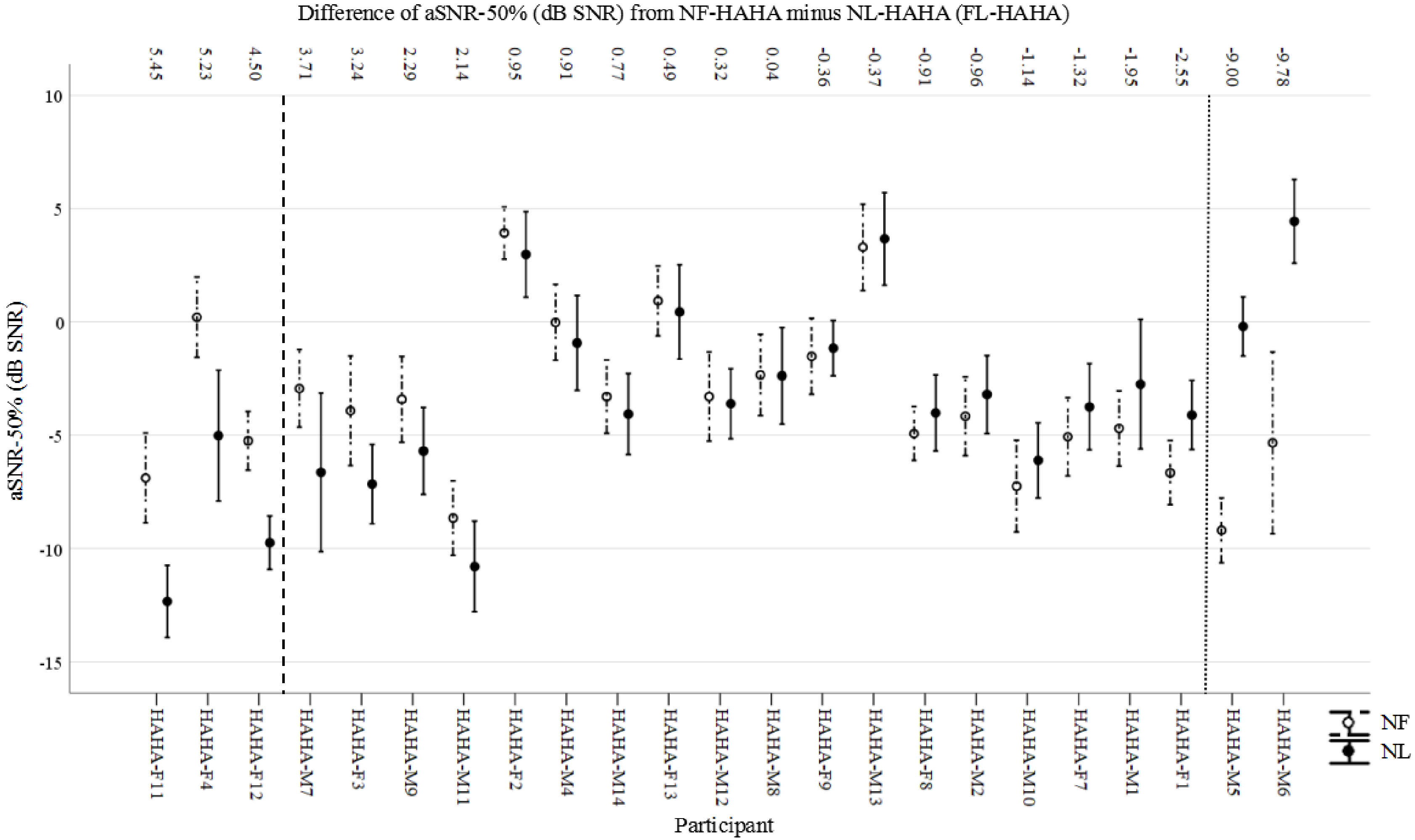


Figure 40 FR-HAHA of the Participants with HAHA under the NF vs. NR Condition

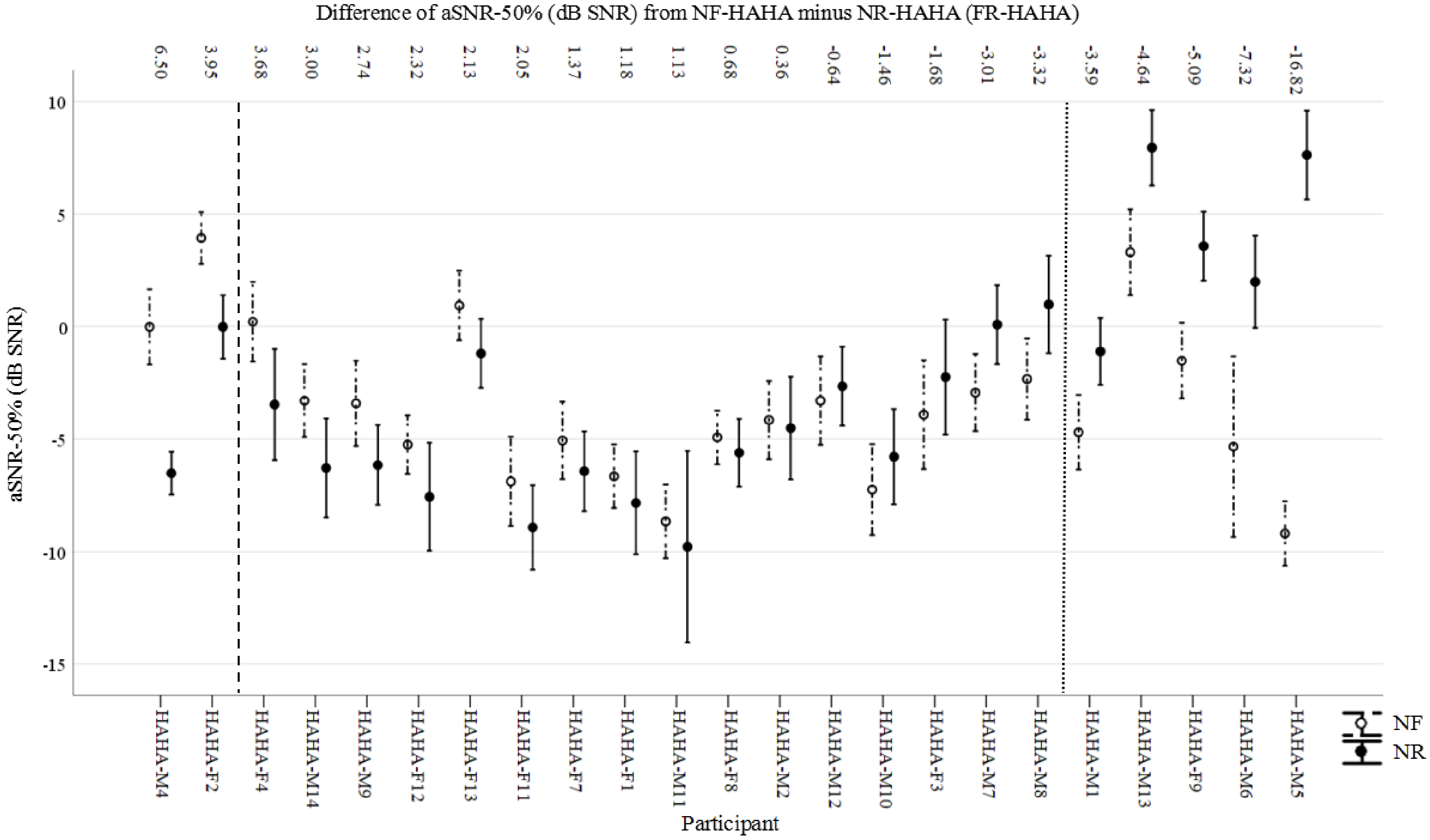


Figure 41 FL-HAL of the Participants with HAL under the NF vs. NL Condition

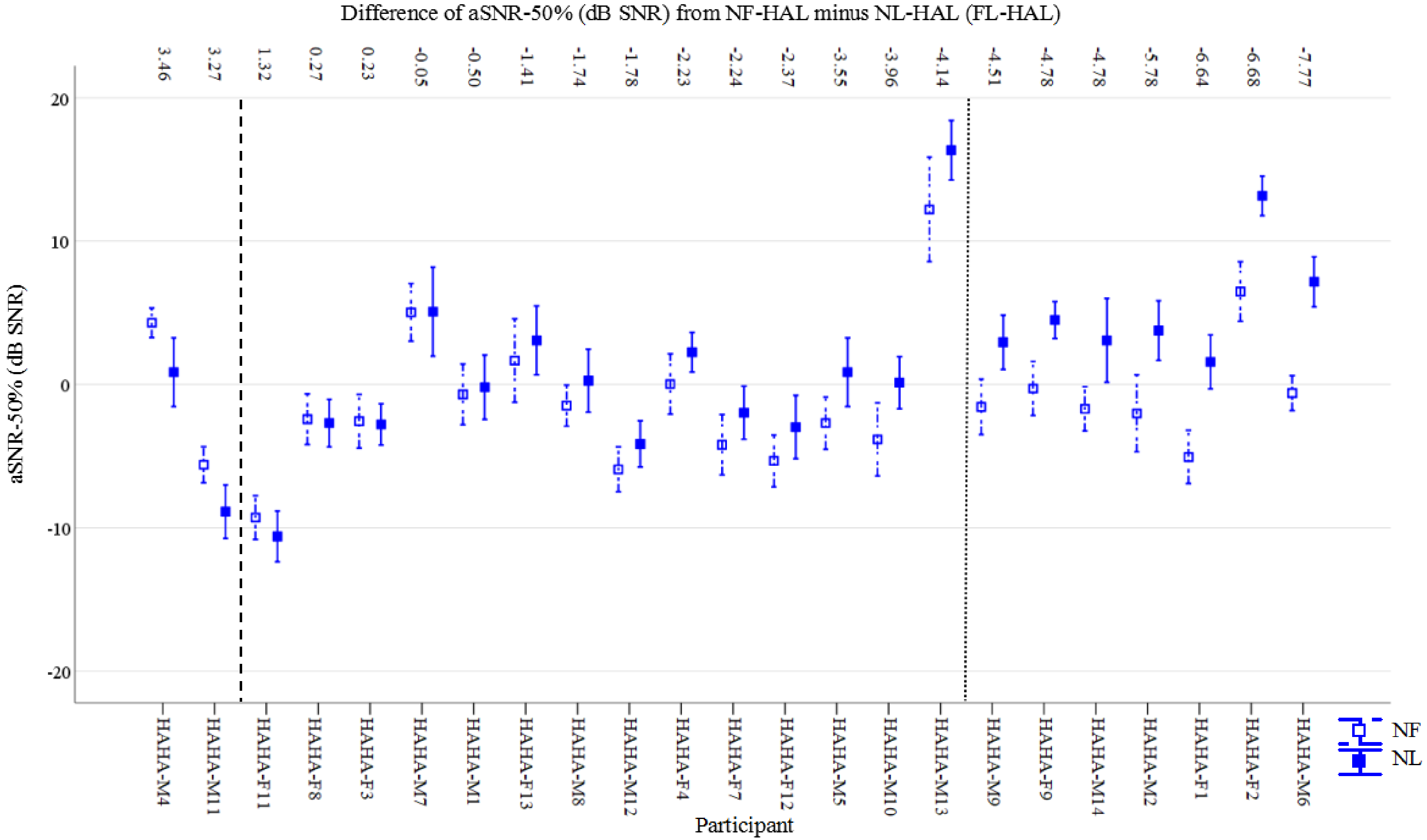


Figure 42 FR-HAL of the Participants with HAL under the NF vs. NR Condition

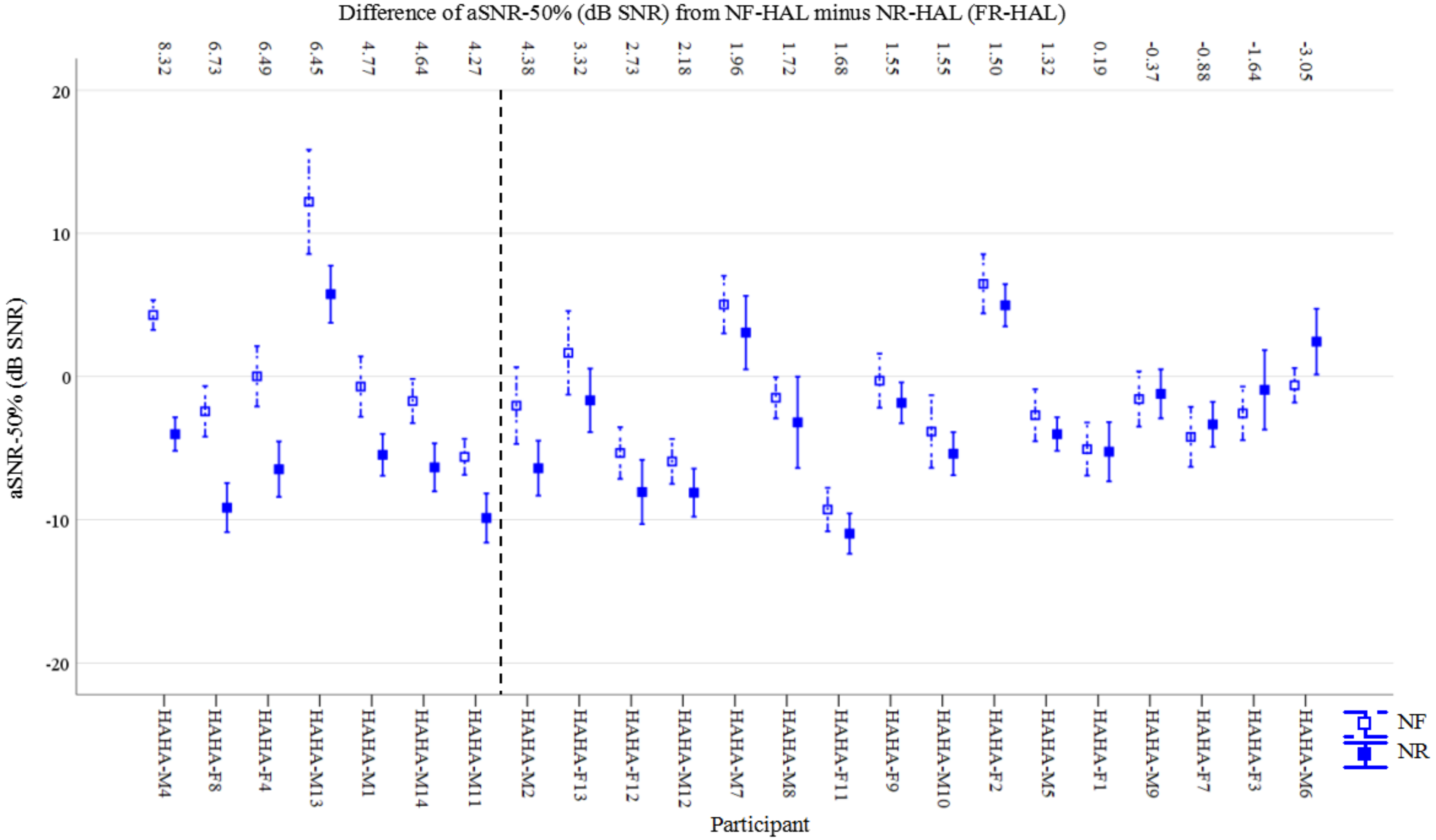


Figure 43 FL-HAR of the Participants with HAR under the NF vs. NL Condition

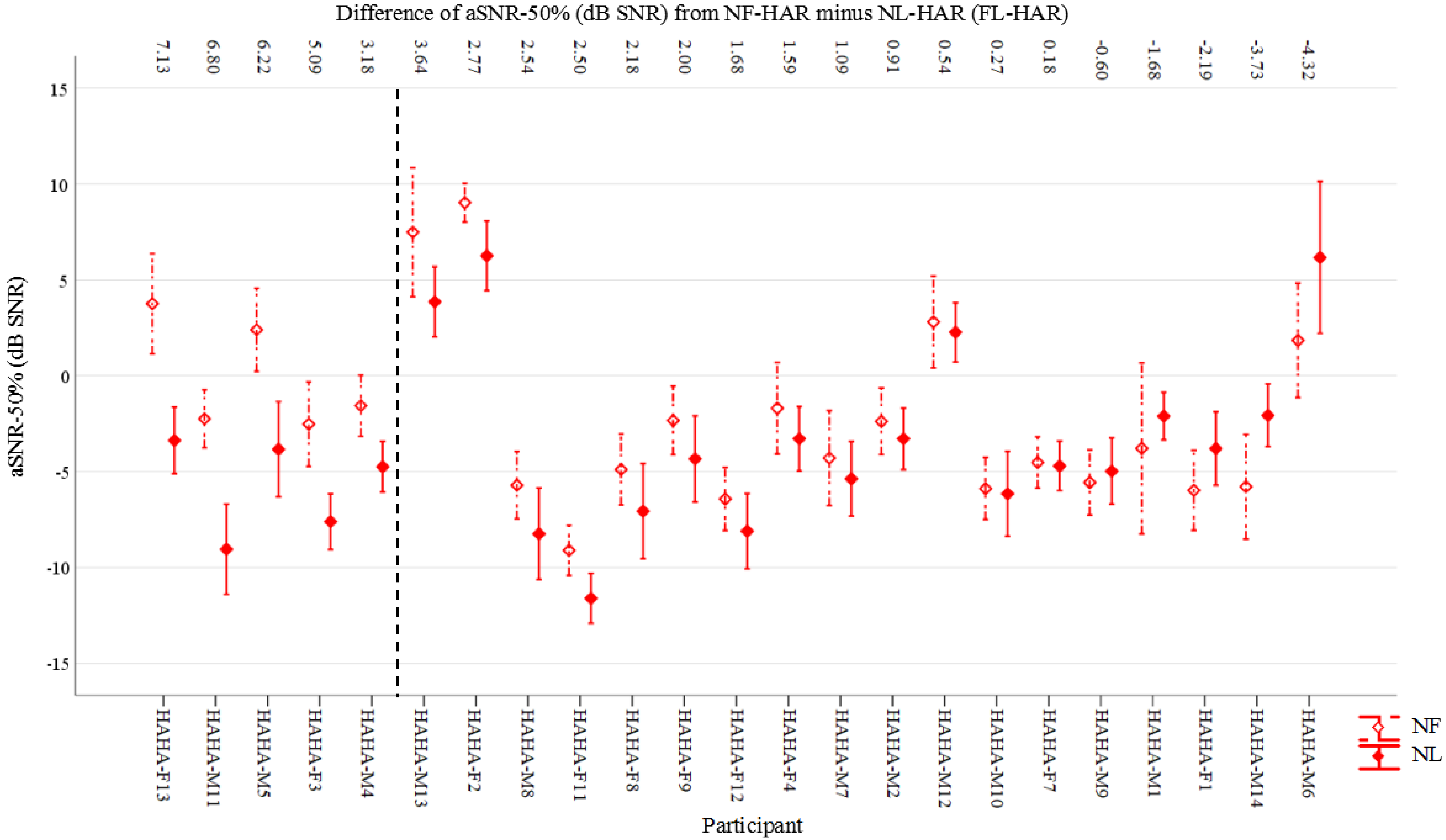


Figure 44 FR-HAR of the Participants with HAR under the NF vs. NR Condition

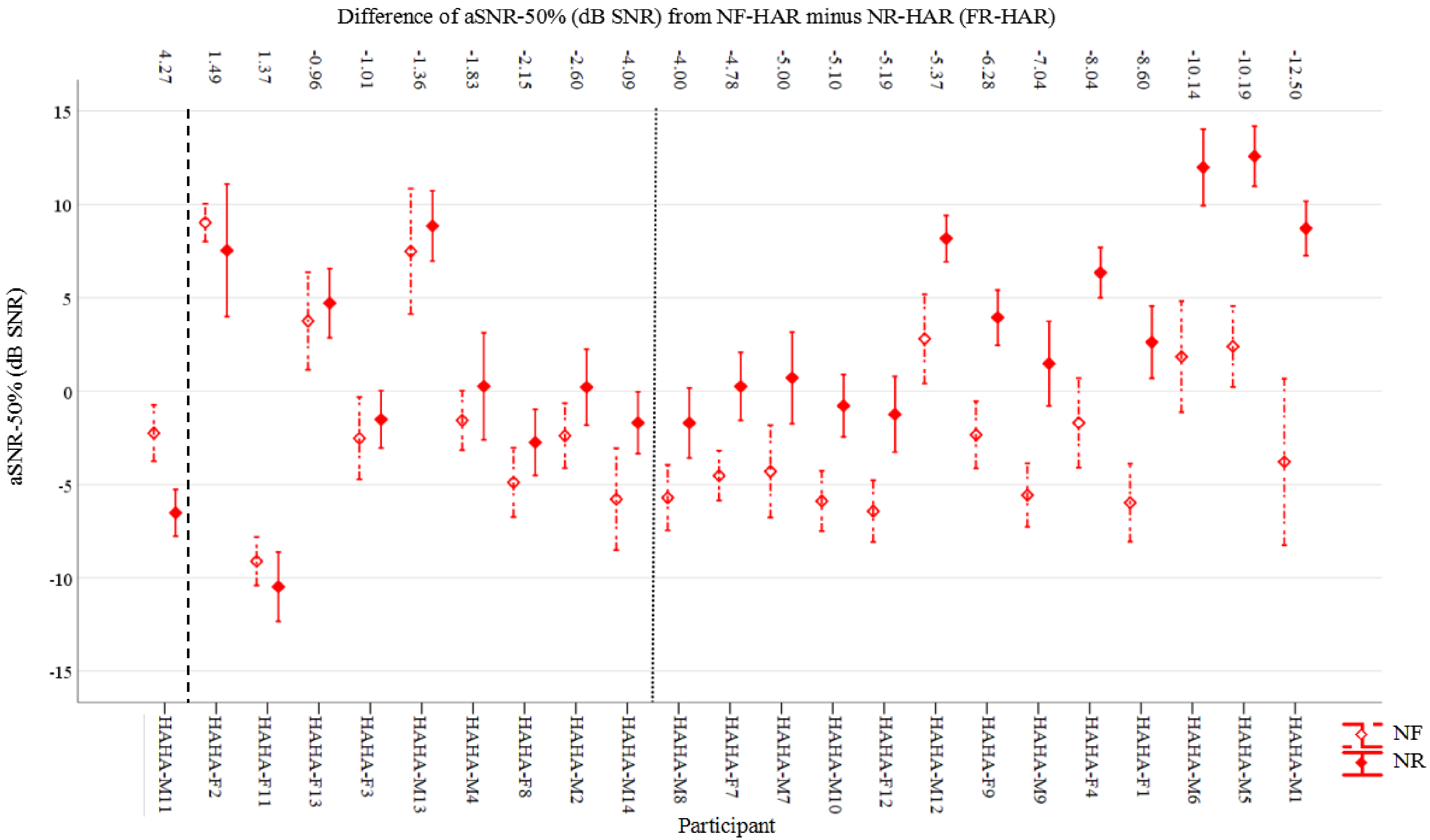


Figure 45 DA of the Participants with HAHA under the NL vs. NR Condition

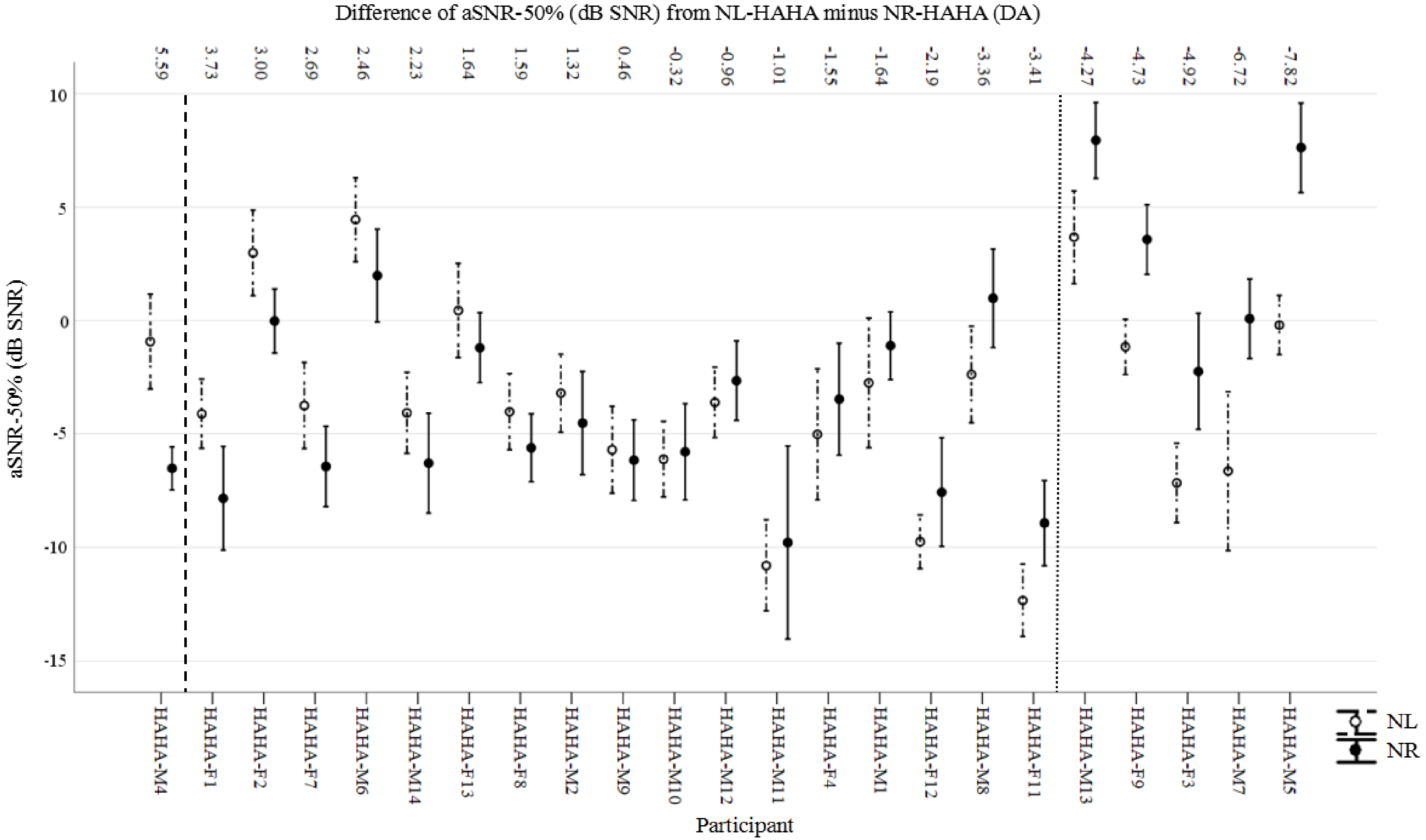


Table 18 ***Intra-participant Comparison Results of Binaural Benefits Obtained from the Participants in the HAHA Group***

Subject	Outcome (A - B)																		The number of binaural advantages	The number of binaural disadvantages	The number of non-significant binaural benefits
	NF-HAL minus NF-HAHA			NF-HAR minus NF-HAHA			NR-HAL minus NR-HAHA			NL-HAR minus NL-HAHA			NL-HAL minus NL-HAHA			NR-HAR minus NR-HAHA					
	+ve BR-HAR	-ve BR-HAR	No difference	+ve BR-HAL	-ve BR-HAL	No difference	+ve SQ-HAR	-ve SQ-HAR	No difference	+ve SQ-HAL	-ve SQ-HAL	No difference	+ve HS-HAR	-ve HS-HAR	No difference	+ve HS-HAL	-ve HS-HAL	No difference			
HAHA-F1			√			√			√			√	√			√			2	0	4
HAHA-F2			√	√			√					√	√			√			4	0	2
HAHA-F3			√			√			√			√	√					√	1	0	5
HAHA-F4			√			√			√			√	√			√			2	0	4
HAHA-F7			√			√			√			√			√	√			1	0	5
HAHA-F8			√			√		√				√			√			√	0	1	5
HAHA-F9			√			√		√				√	√					√	1	1	4
HAHA-F11			√			√			√			√			√			√	0	0	6
HAHA-F12			√			√			√			√	√			√			2	0	4
HAHA-F13			√			√			√		√				√	√			1	1	4
HAHA-M1	√					√		√				√			√	√			2	1	3
HAHA-M2			√			√			√			√	√			√			2	0	4
HAHA-M4	√					√	√				√				√	√			3	1	2
HAHA-M5	√			√				√				√			√	√			3	1	2
HAHA-M6			√	√					√			√			√	√			2	0	4
HAHA-M7	√					√			√			√	√					√	2	0	4
HAHA-M8			√			√			√		√				√			√	0	1	5
HAHA-M9			√			√	√					√	√			√			3	0	3
HAHA-M10			√			√			√			√	√			√			2	0	4
HAHA-M11	√			√					√			√			√			√	2	0	4
HAHA-M12			√	√				√		√					√	√			3	1	2
HAHA-M13	√					√			√			√	√					√	2	0	4
HAHA-M14			√			√			√			√	√			√			2	0	4
n	6	0	17	5	0	18	3	5	15	1	3	19	12	0	11	15	0	8	NA		
%	26	0	74	22	0	78	13	22	65	4	13	83	52	0	48	65	0	35			

Note. *N* = 23. +ve = positive value; -ve = negative value.

Table 19 ***Intra-participant Comparison Results of SRM Obtained from the Participants in the HAHA Group***

Subject	Outcome (A - B)																		The number of +ve. SRM	The number of -ve. SRM	The number of non-significant SRM
	NL-HAHA minus NF-HAHA			NR-HAHA minus NF-HAHA			NL-HAL minus NF-HAL			NR-HAL minus NF-HAL			NL-HAR minus NF-HAR			NR-HAR minus NF-HAR					
	+ve FL-HAHA	-ve FL-HAHA	No difference	+ve FR-HAHA	-ve FR-HAHA	No difference	+ve FL-HAL	-ve FL-HAL	No difference	+ve FR-HAL	-ve FR-HAL	No difference	+ve FL-HAR	-ve FL-HAR	No difference	+ve FR-HAR	-ve FR-HAR	No difference			
HAHA-F1			√			√		√				√			√		√		0	2	4
HAHA-F2			√	√				√				√			√			√	1	1	4
HAHA-F3			√			√			√			√	√					√	1	0	5
HAHA-F4	√					√			√	√					√		√		2	1	3
HAHA-F7			√			√			√			√			√		√		0	1	5
HAHA-F8			√			√			√	√					√			√	1	0	5
HAHA-F9			√		√			√				√			√		√		0	3	3
HAHA-F11	√					√			√			√			√			√	1	0	5
HAHA-F12	√					√			√			√			√		√		1	1	4
HAHA-F13			√			√			√			√	√					√	1	0	5
HAHA-M1			√		√				√	√					√		√		1	2	3
HAHA-M2			√			√		√				√			√			√	0	1	5
HAHA-M4			√	√			√			√			√					√	4	0	2
HAHA-M5		√			√				√			√	√				√		1	3	2
HAHA-M6		√			√			√				√			√		√		0	4	2
HAHA-M7			√			√			√			√			√		√		0	1	5
HAHA-M8			√			√			√			√			√		√		0	1	5
HAHA-M9			√			√		√				√			√		√		0	2	4
HAHA-M10			√			√			√			√			√		√		0	1	5
HAHA-M11			√			√	√			√			√			√			4	0	2
HAHA-M12			√			√			√			√			√		√		0	1	5
HAHA-M13			√		√				√	√					√			√	1	1	4
HAHA-M14			√			√		√		√					√			√	1	1	4
n	3	2	18	2	5	16	2	7	14	7	0	16	5	0	18	1	13	9	NA		
%	13	9	78	9	22	70	9	30	61	30	0	70	22	0	78	4	57	39			

Note. N = 23. +ve = positive value; -ve = negative value.

Table 20 ***Intra-participant Comparison Results of DA Obtained from the Participants in the HAHA Group***

Subject	Outcome (A - B)		
	NL-HAHA minus NR-HAHA		
	DA-HAL	DA-HAR	no difference
HAHA-F1			√
HAHA-F2			√
HAHA-F3		√	
HAHA-F4			√
HAHA-F7			√
HAHA-F8			√
HAHA-F9		√	
HAHA-F11			√
HAHA-F12			√
HAHA-F13			√
HAHA-M1			√
HAHA-M2			√
HAHA-M4	√		√
HAHA-M5		√	
HAHA-M6			√
HAHA-M7		√	
HAHA-M8			√
HAHA-M9			√
HAHA-M10			√
HAHA-M11			√
HAHA-M12			√
HAHA-M13		√	
HAHA-M14			√
n	1	5	17
percentage	4	22	74

Note. $N = 23$.

4.2.2.2 Individual aSNR-50% scores in the CIHA group

Figure 46 to 53 show the results of BR-HAcon, SQ-HAcon, HS-HA-con, FHA-CIHA, FCI-CIHA, FHA-CI, FCI-CI, and DA of all 33 participants in the CIHA group, respectively. Table 21 and 22 list the number and proportion of participants in the CIHA group who obtained binaural benefits and SRM results, respectively, including positive, negative, and no difference. Table 23 lists the number and proportion of participants in the CIHA group, who obtained the DA results of DA-CI, DA-HAcon, and no difference.

When compared to monaural CI fitting, Table 21 shows that most participants (24 of 33) with CIHA fitting can achieve at least one significant binaural benefit. Eight participants showed non-significant binaural benefits between the two device fitting conditions in all noise directions. One participant (CIHA-M5) with CIHA fitting could not achieve significant BR-HAcon and HS-HAcon, and even showed a significant disadvantage of SQ.

While considering the SRM outcomes of participants in the CIHA group, Table 22 shows that 13 participants with CIHA fitting achieved positive FHA-CIHA, and two participants achieved positive FCI-CIHA. However, three participants achieved negative FHA-CIHA and eight participants demonstrated negative FCI-CIHA. When the participants were fitted with monaural CI, nine participants achieved positive FHA-CI and two participants achieved positive FCI-CI. Conversely, three participants achieved negative FHA-CI and 12 participants demonstrated positive FCI-CI.

Figure 46 BR-HAcon of the Participants with CIHA vs. CI under the NF Condition

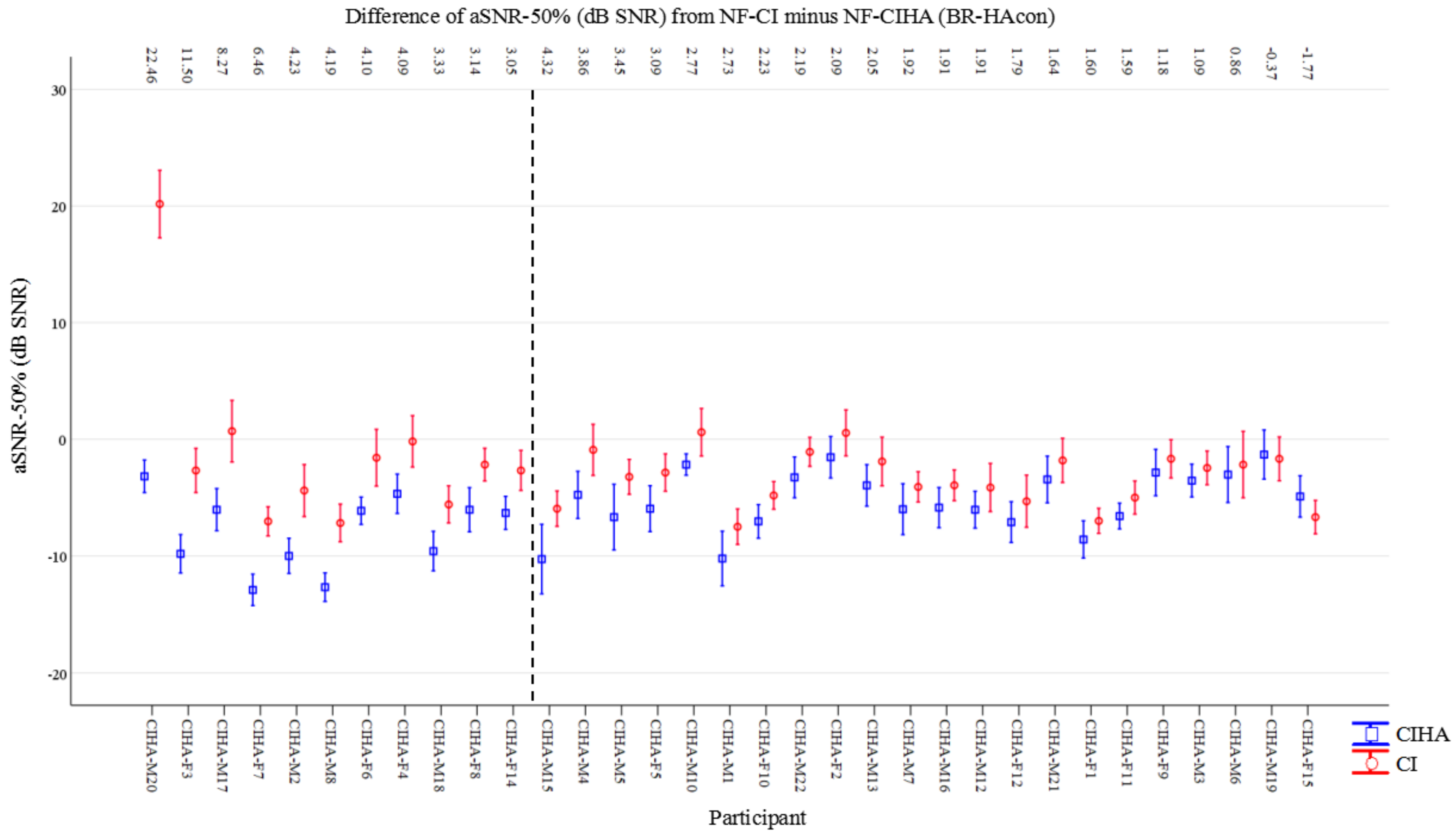


Figure 47 SQ-HAcon of the Participants with CIHA vs. CI under the NHA Condition

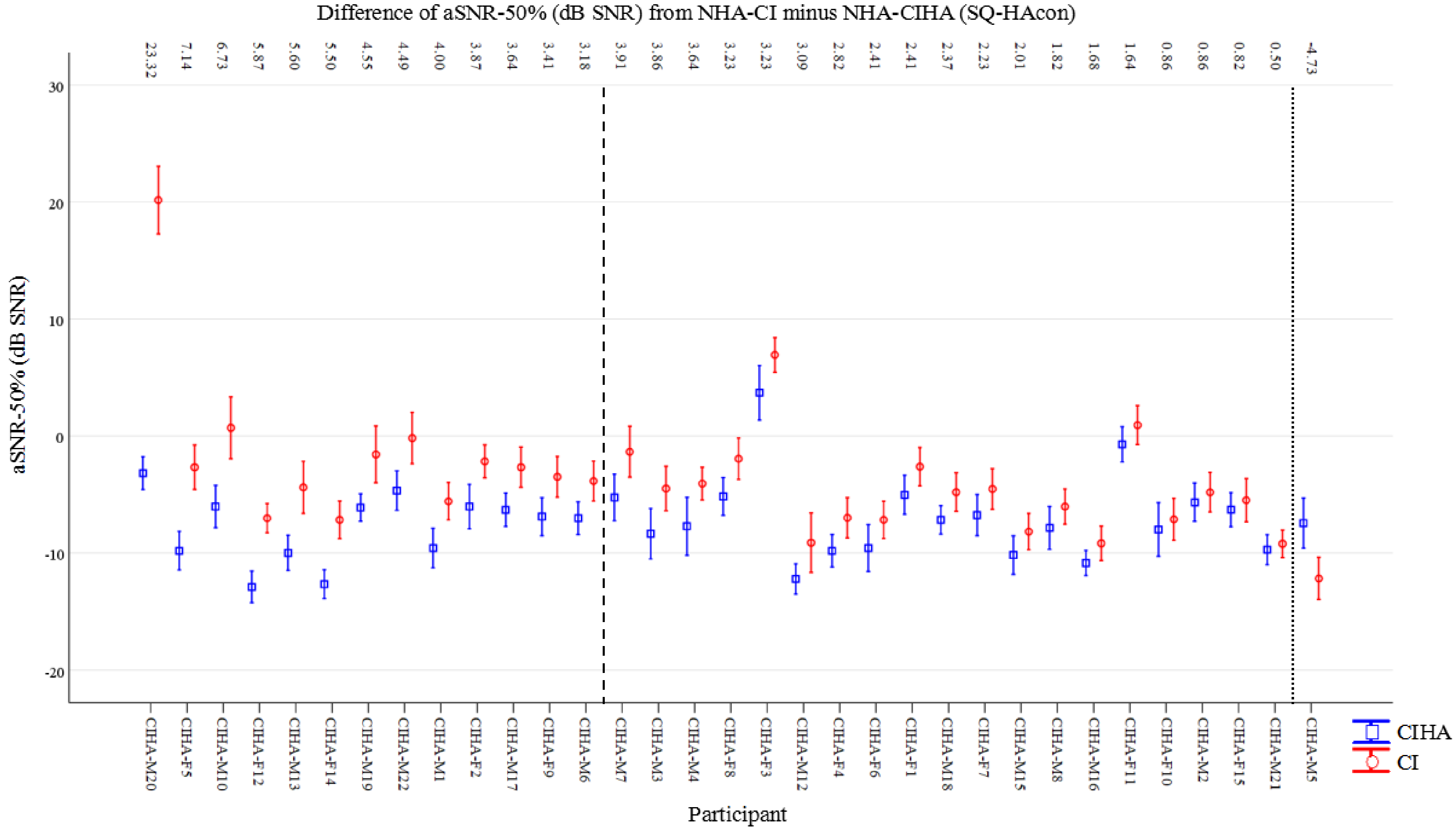


Figure 48 HS-HAcon of the Participants with CIHA vs. CI under the NCI Condition

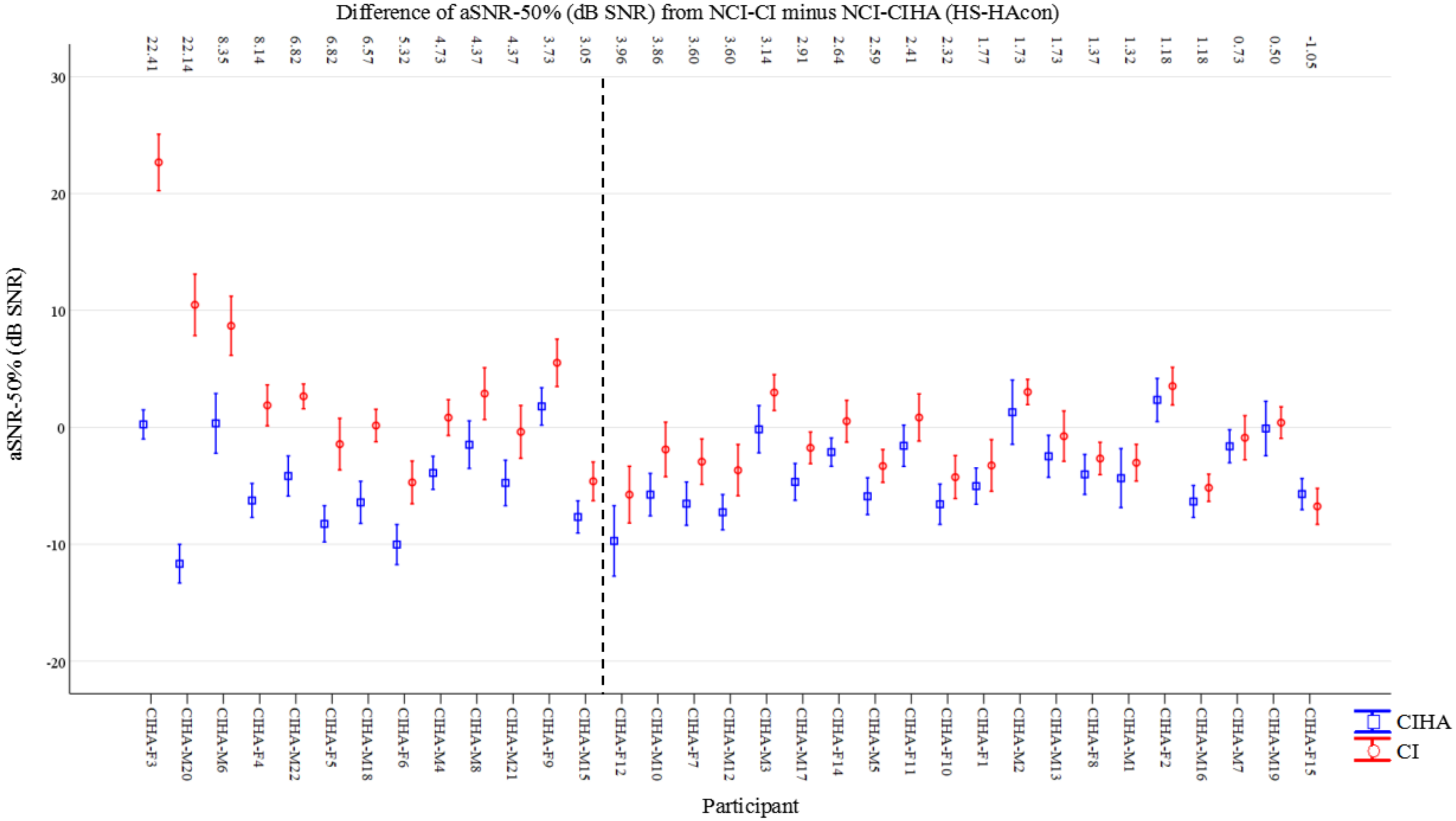


Figure 49 FHA-CIHA of the Participants with CIHA under the NF vs. NHA Condition

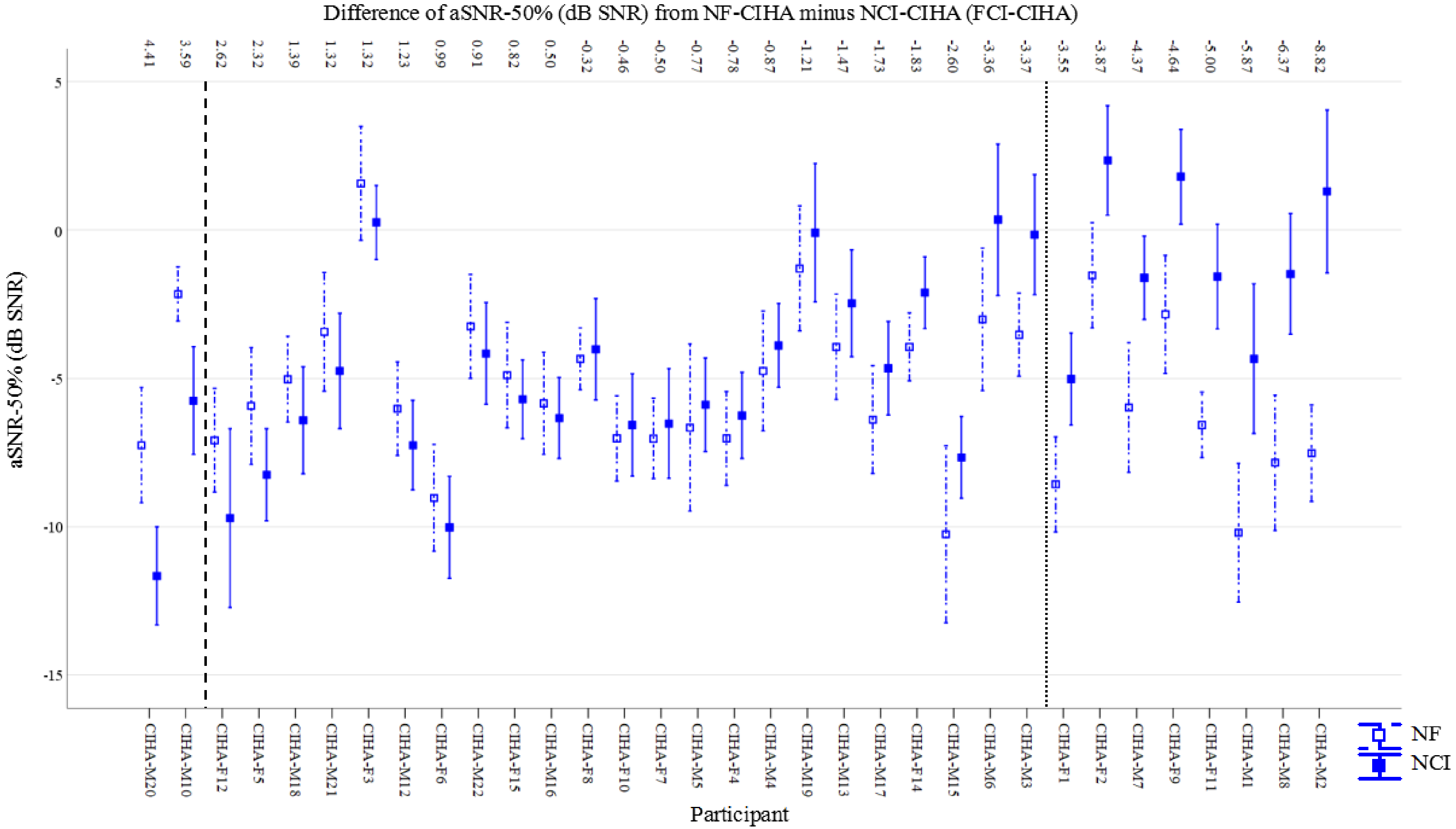


Figure 50 FCI-CIHA of the Participants with CIHA under the NF vs. NCI Condition

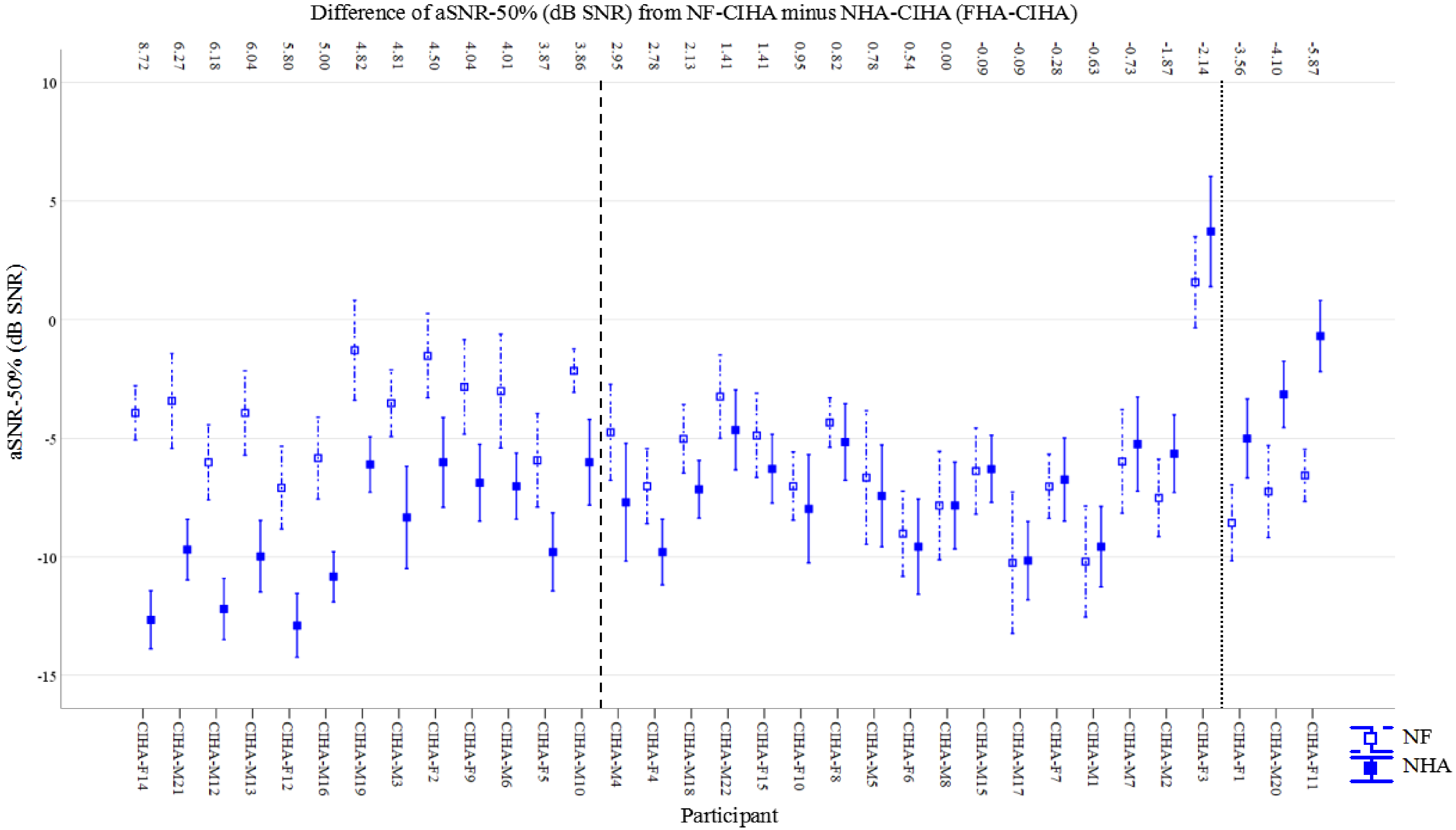


Figure 51 FHA-CI of the Participants with CI under the NF vs. NHA Condition

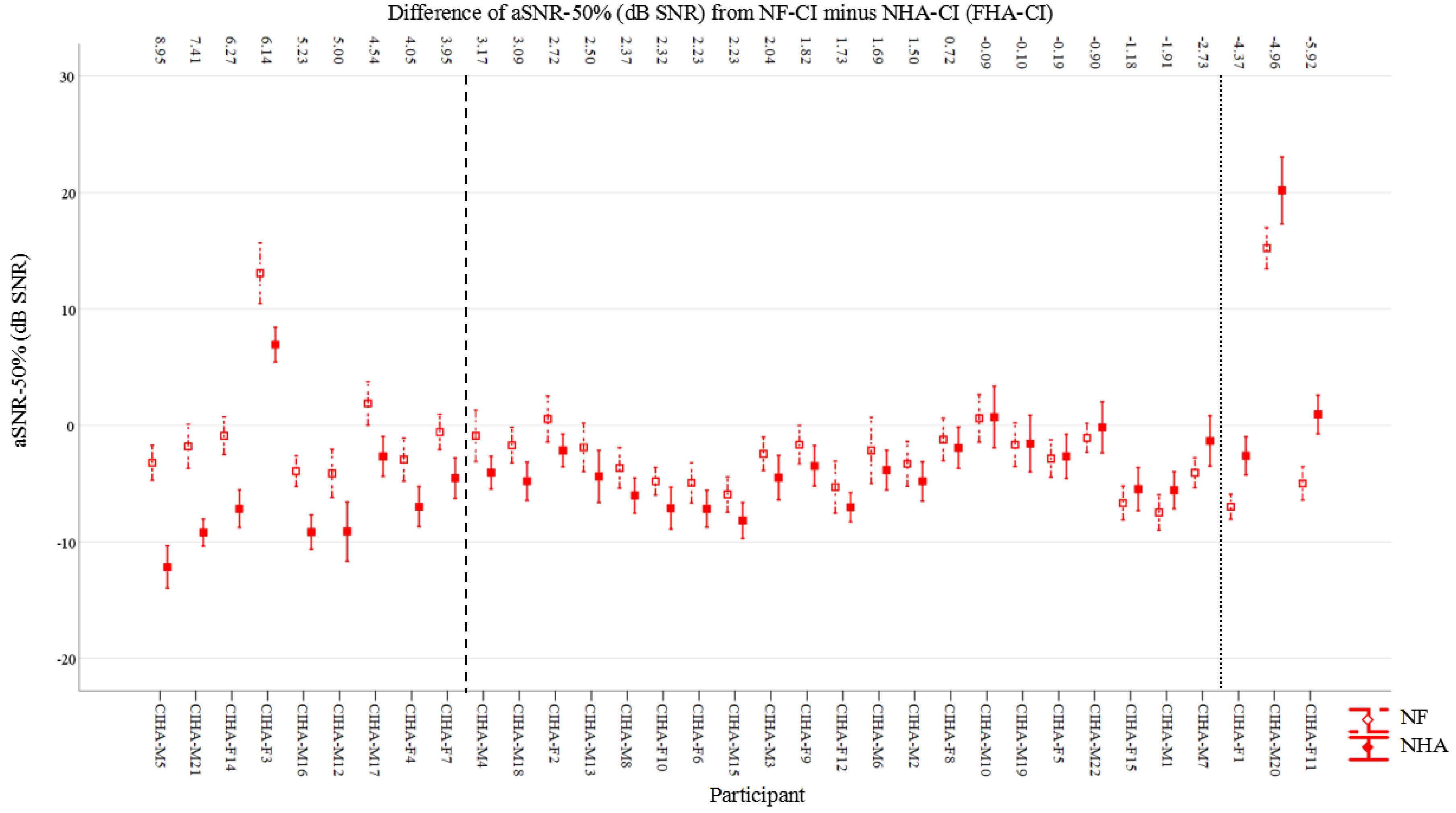


Figure 52 FCI-CI of the Participants with CI under the NF vs. NCI Condition

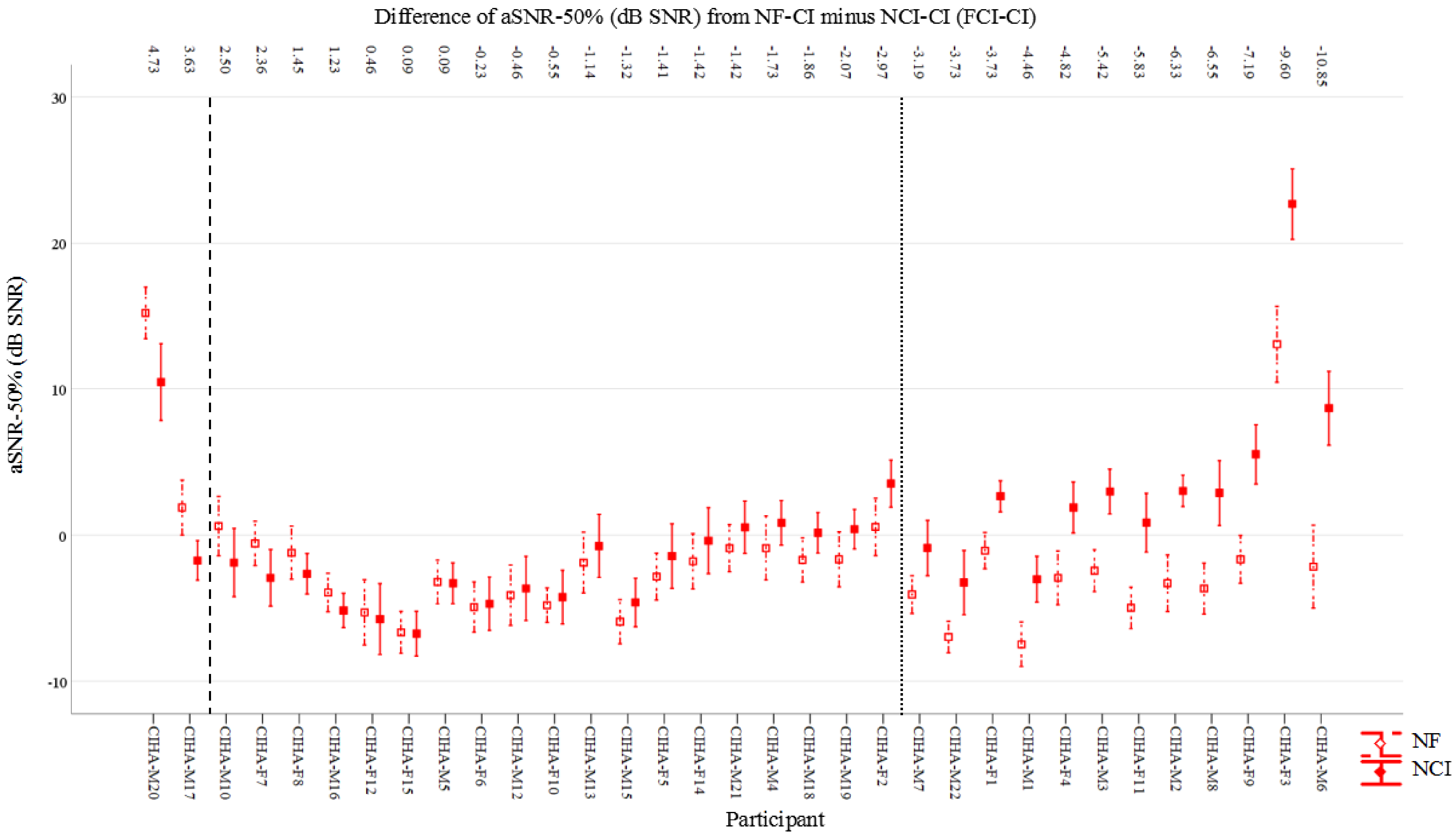


Figure 53 DA of the Participants with CIHA under the NCI vs. NHA Condition

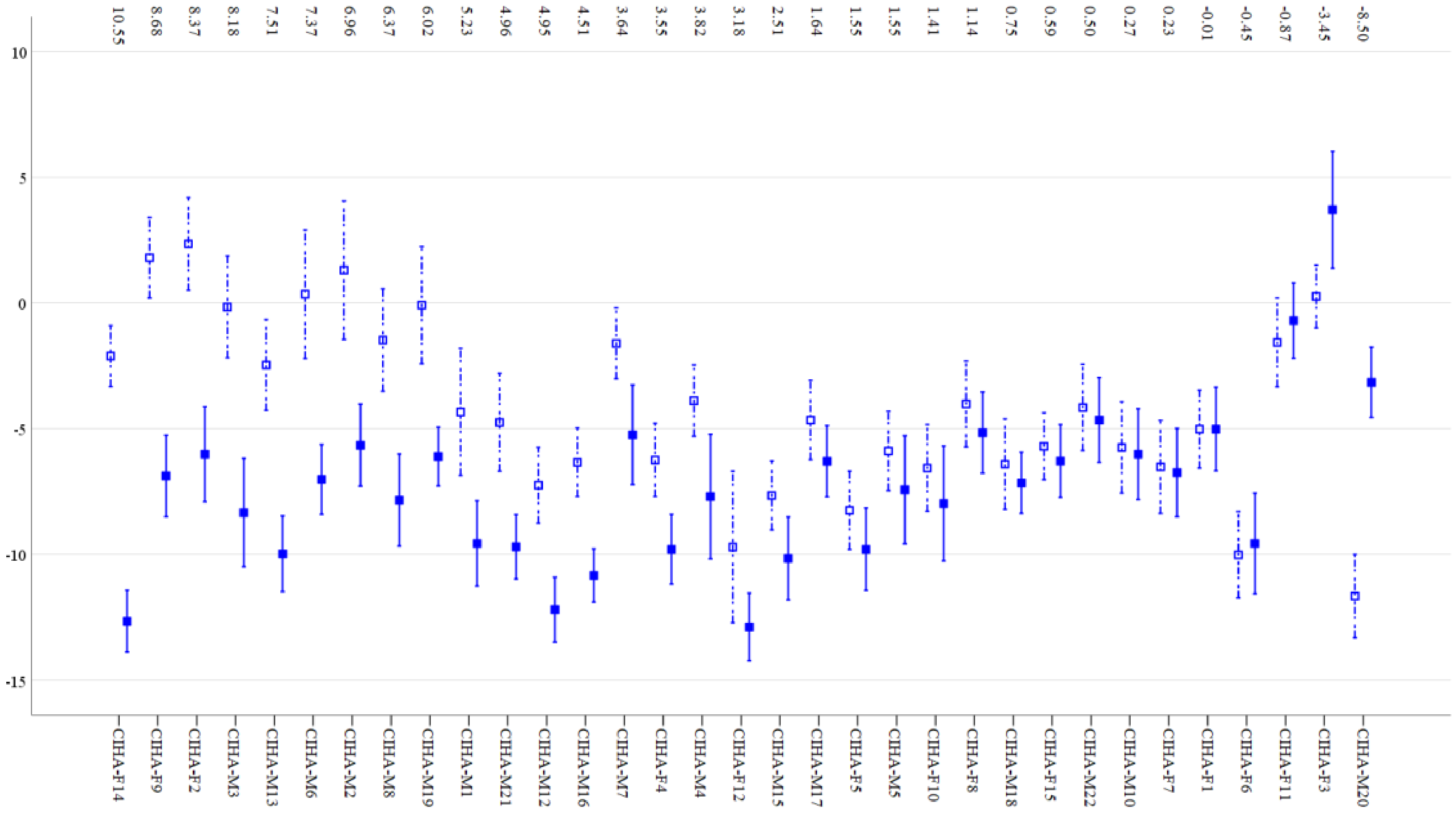


Table 21 ***Intra-participant Comparison Results of Binaural Benefits Obtained from the Participants in the CIHA Group***

Subject	Outcome (A - B): NF-CI minus NF-CIHA			Outcome (A - B): NHA-CI minus NHA-CIHA			Outcome (A - B): NCI-CI minus NCI-CIHA			The number of binaural advantages	The number of binaural disadvantages	The number of non-significant binaural benefits
	+ve BR-HAcon	-ve BR-HAcon	No difference	+ve SQ-HAcon	-ve SQ-HAcon	No difference	+ve HS-HAcon	-ve HS-HAcon	No difference			
CIHA-F1			√			√			√	0	0	3
CIHA-F2			√	√					√	1	0	2
CIHA-F3	√					√	√			2	0	1
CIHA-F4	√					√	√			2	0	1
CIHA-F5			√	√			√			2	0	1
CIHA-F6	√					√	√			2	0	1
CIHA-F7	√					√			√	1	0	2
CIHA-F8	√					√			√	1	0	2
CIHA-F9			√	√			√			2	0	1
CIHA-F10			√			√			√	0	0	3
CIHA-F11			√			√			√	0	0	3
CIHA-F12			√	√					√	1	0	2
CIHA-F14	√			√					√	2	0	1
CIHA-F15			√			√			√	0	0	3
CIHA-M1			√	√					√	1	0	2
CIHA-M2	√					√			√	1	0	2
CIHA-M3			√			√			√	0	0	3
CIHA-M4			√			√	√			1	0	2
CIHA-M5			√		√				√	0	1	2
CIHA-M6			√	√			√			2	0	1
CIHA-M7			√			√			√	0	0	3
CIHA-M8	√					√	√			2	0	1
CIHA-M10			√	√					√	1	0	2
CIHA-M12			√			√			√	0	0	3
CIHA-M13			√	√					√	1	0	2
CIHA-M15			√			√	√			1	0	2
CIHA-M16			√			√			√	0	0	3
CIHA-M17	√			√					√	2	0	1
CIHA-M18	√					√	√			2	0	1
CIHA-M19			√	√					√	1	0	2
CIHA-M20	√			√			√			3	0	0
CIHA-M21			√			√	√			1	0	2
CIHA-M22			√	√			√			2	0	1
n	11	0	22	13	1	19	13	0	20		NA	
%	33	0	67	39	3	58	39	0	61			

Note. N = 33. +ve = positive value; -ve = negative value.

Table 22 ***Intra-participant Comparison Results of SRM Obtained from the Participants in the CIHA Group***

Subject	Outcome (A - B)												The number of +ve. SRM	The number of -ve. SRM	The number of non-significant SRM
	NF-CIHA minus NHA-CIHA			NF-CIHA minus NCI-CIHA			NF-CI minus NHA-CI			NF-CI minus NCI-CI					
	+ve FHA-CIHA	-ve FHA-CIHA	No difference	+ve FCI-CIHA	-ve FCI-CIHA	No difference	+ve FHA-CI	-ve FHA-CI	No difference	+ve FCI-CI	-ve FCI-CI	No difference			
CIHA-F1		√			√			√			√		0	4	0
CIHA-F2	√				√				√			√	1	1	2
CIHA-F3			√			√	√				√		1	1	2
CIHA-F4			√			√	√				√		1	1	2
CIHA-F5	√					√			√			√	1	0	3
CIHA-F6			√			√			√			√	0	0	4
CIHA-F7			√			√	√					√	1	0	3
CIHA-F8			√			√			√			√	0	0	4
CIHA-F9	√				√				√		√		1	2	1
CIHA-F10			√			√			√			√	0	0	4
CIHA-F11		√			√			√			√		0	4	0
CIHA-F12	√					√			√			√	1	0	3
CIHA-F14	√					√	√					√	2	0	2
CIHA-F15			√			√			√			√	0	0	4
CIHA-M1			√		√				√		√		0	2	2
CIHA-M2			√		√				√		√		0	2	2
CIHA-M3	√					√			√		√		1	1	2
CIHA-M4			√			√			√			√	0	0	4
CIHA-M5			√			√	√					√	1	0	3
CIHA-M6	√					√			√		√		1	1	2
CIHA-M7			√		√				√		√		0	2	2
CIHA-M8			√		√				√		√		0	2	2
CIHA-M10	√			√					√			√	2	0	2
CIHA-M12	√					√	√					√	2	0	2
CIHA-M13	√					√			√			√	1	0	3
CIHA-M15			√			√			√			√	0	0	4
CIHA-M16	√					√	√					√	2	0	2
CIHA-M17			√			√	√			√			2	0	2
CIHA-M18			√			√			√			√	0	0	4
CIHA-M19	√					√			√			√	1	0	3
CIHA-M20		√		√				√		√			2	2	0
CIHA-M21	√					√	√					√	2	0	2
CIHA-M22			√			√			√		√		0	1	3
n	13	3	17	2	8	23	9	3	21	2	12	19		NA	
%	39	9	52	6	24	70	27	9	64	6	36	58			

Note N = 33. +ve = positive value; -ve = negative value.

Table 23 ***Intra-participant Comparison Results of DA Obtained from the Participants in the CIHA Group***

Subject	Outcome (A - B) NHA-CIHA minus NCI-CIHA		
	DA-HAcon	DA-CI	no difference
CIHA-F1			√
CIHA-F2	√		
CIHA-F3			√
CIHA-F4	√		
CIHA-F5			√
CIHA-F6			√
CIHA-F7			√
CIHA-F8			√
CIHA-F9	√		
CIHA-F10			√
CIHA-F11			√
CIHA-F12			√
CIHA-F14	√		
CIHA-F15			√
CIHA-M1	√		
CIHA-M2	√		
CIHA-M3	√		
CIHA-M4			√
CIHA-M5			√
CIHA-M6	√		
CIHA-M7	√		
CIHA-M8	√		
CIHA-M10			√
CIHA-M12	√		
CIHA-M13	√		
CIHA-M15			√
CIHA-M16	√		
CIHA-M17			√
CIHA-M18			√
CIHA-M19	√		
CIHA-M20		√	
CIHA-M21	√		
CIHA-M22			√
n	15	1	17
%	45	3	52

Note N = 33.

4.3 Regression Analysis Results of SII and aSNR-50%

4.3.1 Regression Results of the HAHA Group

Table 24 lists the correlation matrix results from the HAHA group. Figure 54 and 55 show the scatter plots between SII-HAL and SRiN performance in all noise directions with HAL and HAHA fitting, respectively. Figure 56 and 57 show the scatter plots between SII-HAR and SRiN performance in all noise directions with HAR and HAHA fitting, respectively.

The results of SII-HAL could explain 38.1% of the variance in NF-HAL with $F(1, 19) = 11.71$, $p = .003$, 47.9% of the variance in NL-HAL with $F(1, 19) = 17.50$, $p = .001$, 29.3% of the variance in NR-HAL with $F(1, 19) = 7.88$, $p = .011$, 20.4% of the variance in NF-HAHA with $F(1, 19) = 4.88$, $p = .040$, 40.3% of the variance in NL-HAHA with $F(1, 19) = 12.85$, $p = .002$, and 27.4% of the variance in NR-HAHA with $F(1, 19) = 7.17$, $p = .015$. Thus, SII-HAL could significantly predict NF-HAL ($\beta = -.62$, $t = -3.42$, $p = .003$), NL-HAL ($\beta = -.69$, $t = -4.18$, $p = .001$), NR-HAL ($\beta = -.54$, $t = -2.81$, $p = .011$), NF-HAHA ($\beta = -.45$, $t = -2.21$, $p = .040$), NL-HAHA ($\beta = -.64$, $t = -3.58$, $p = .002$), and NR-HAHA ($\beta = -.52$, $t = -2.68$, $p = .015$) (Table 25).

The results of SII-HAR could explain the 31.8% of the variance in NF-HAR with $F(1, 19) = 8.86$, $p = .008$, 47.9% of the variance in NL-HAR with $F(1, 19) = 17.43$, $p = .001$, 48.3% of the variance in NR-HAR with $F(1, 19) = 17.73$, $p < .001$, 38.3% of the variance in NL-HAHA with $F(1, 19) = 11.78$, $p = .003$, and 25.5% of the variance in NR-HAHA with $F(1, 19) = 6.49$, $p = .020$. However, SII-HAR could not explain the variance in NF-HAHA with $F(1, 19) = 0.88$, $p = .361$. Thus, SII-HAR could significantly predict NF-HAR (β = -.56, t = -2.98, p =.008), NL-HAR (β = -.69, t = -4.18, p =.001), NR-HAR (β = -.69, t = -4.21, p <.001), NL-HAHA (β = -.62, t = -3.43, p =.003), and NR-HAHA (β = -.51, t = -2.55, p =.020); however, it could not significantly predict NF-HAHA (β = -.21, t = -0.94, p =.361) (Table 25).

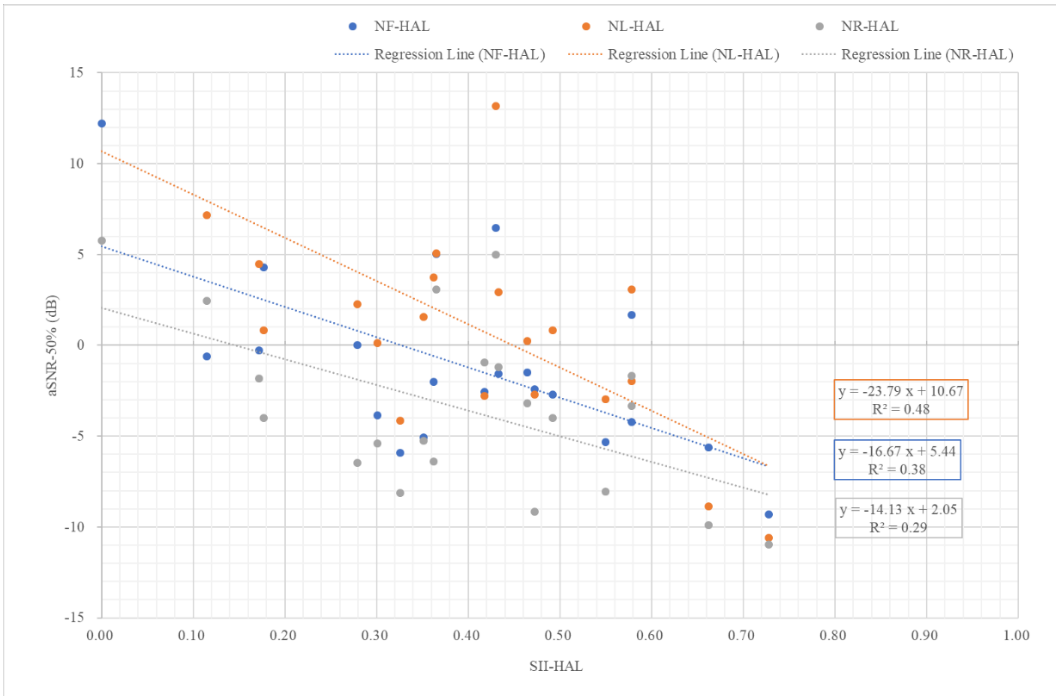
Table 24 ***Correlation Matrix Results from the HAHA Group***

Variable		SII-HAL	SII-HAR	NF-HAHA	NL-HAHA	NR-HAHA	NF-HAL	NL-HAL	NR-HAL	NF-HAR	NL-HAR	NR-HAR	BR-HAL	BR-HAR	SQ-HAL	SQ-HAR	HS-HAL	HS-HAR	FL-HAHA	FR-HAHA	FL-HAL	FR-HAL	FL-HAR	FR-HAR	DA
SII-HAL	*r*																								
	Sig. (2-tailed)																								
SII-HAR	*r*	.754**																							
	Sig. (2-tailed)	.000																							
NF-HAHA	*r*	-.452*	-.210																						
	Sig. (2-tailed)	.040	.361																						
NL-HAHA	*r*	-.635**	-.619**	.560**																					
	Sig. (2-tailed)	.002	.003	.008																					
NR-HAHA	*r*	-.523*	-.505*	.380	.721**																				
	Sig. (2-tailed)	.015	.020	.090	.000																				
NF-HAL	*r*	-.618**	-.320	.803**	.676**	.607**																			
	Sig. (2-tailed)	.003	.158	.000	.001	.004																			
NL-HAL	*r*	-.692**	-.467*	.698**	.808**	.674**	.870**																		
	Sig. (2-tailed)	.001	.033	.000	.000	.001	.000																		
NR-HAL	*r*	-.541*	-.317	.608**	.694**	.674**	.818**	.869**																	
	Sig. (2-tailed)	.011	.162	.003	.000	.001	.000	.000																	
NF-HAR	*r*	-.402	-.564**	.603**	.766**	.644**	.659**	.671**	.599**																
	Sig. (2-tailed)	.071	.008	.004	.000	.002	.001	.001	.004																
NL-HAR	*r*	-.621**	-.692**	.523*	.822**	.541*	.568**	.764**	.649**	.828**															
	Sig. (2-tailed)	.003	.001	.015	.000	.011	.007	.000	.001	.000															
NR-HAR	*r*	-.593**	-.695**	.347	.808**	.735**	.474*	.682**	.569**	.748**	.833**														
	Sig. (2-tailed)	.005	.000	.124	.000	.000	.030	.001	.007	.000	.000														
BR-HAL	*r*	-.073	-.497*	-.192	.420	.437*	.061	.174	.169	.667**	.529*	.596**													
	Sig. (2-tailed)	.753	.022	.404	.058	.047	.793	.451	.464	.001	.014	.004													
BR-HAR	*r*	-.477*	-.276	.115	.442*	.548*	.685**	.596**	.620**	.361	.307	.366	.337												
	Sig. (2-tailed)	.029	.226	.619	.045	.010	.001	.004	.003	.108	.176	.103	.136												
SQ-HAL	*r*	-.044	-.192	-.003	-.200	-.232	-.113	.010	-.005	.187	.394	.128	.234	-.184											
	Sig. (2-tailed)	.849	.406	.989	.385	.312	.626	.967	.984	.416	.077	.579	.308	.424											
SQ-HAR	*r*	.022	.265	.242	-.091	-.472*	.202	.177	.334	-.106	.084	-.260	-.356	.041	.290										
	Sig. (2-tailed)	.926	.245	.291	.695	.031	.379	.442	.139	.646	.719	.256	.113	.859	.202										
HS-HAL	*r*	-.192	-.362	.018	.251	-.208	-.087	.128	-.035	.261	.515*	.510*	.305	-.167	.480*	.224									
	Sig. (2-tailed)	.405	.107	.938	.272	.365	.708	.579	.881	.252	.017	.018	.180	.470	.028	.329									
HS-HAR	*r*	-.394	-.035	.494*	.146	.259	.642**	.701**	.619**	.199	.288	.166	-.216	.466*	.258	.408	-.089								
	Sig. (2-tailed)	.077	.879	.023	.527	.257	.002	.000	.003	.386	.206	.471	.347	.033	.258	.066	.702								
FL-HAHA	*r*	.317	.522*	.278	-.640**	-.484*	-.039	-.290	-.241	-.329	-.468*	-.616**	-.664**	-.405	.229	.329	-.274	.288							
	Sig. (2-tailed)	.161	.015	.222	.002	.026	.867	.203	.293	.145	.033	.003	.001	.068	.318	.145	.229	.205							
FR-HAHA	*r*	.206	.362	.336	-.329	-.744**	-.038	-.182	-.246	-.220	-.173	-.498*	-.584**	-.474*	.234	.655**	.225	.093	.693**						
	Sig. (2-tailed)	.370	.107	.136	.145	.000	.871	.430	.282	.338	.453	.022	.005	.030	.308	.001	.326	.687	.000						
FL-HAL	*r*	.414	.431	-.134	-.554**	-.393	-.168	-.633**	-.451*	-.306	-.634**	-.618**	-.252	-.117	-.197	-.037	-.392	-.392	.518*	.304					
	Sig. (2-tailed)	.062	.051	.564	.009	.078	.467	.002	.040	.177	.002	.003	.271	.615	.393	.873	.078	.079	.016	.181					
FR-HAL	*r*	-.158	-.023	.362	.007	-.075	.352	.050	-.250	.134	-.099	-.128	-.173	.144	-.183	-.203	-.089	.075	.327	.337	.453*				
	Sig. (2-tailed)	.493	.922	.107	.975	.748	.118	.831	.274	.562	.668	.582	.454	.535	.428	.377	.700	.748	.148	.135	.039				
FL-HAR	*r*	.383	.230	.124	-.111	.163	.142	-.172	-.097	.276	-.311	-.161	.223	.085	-.357	-.323	-.439*	-.155	.243	-.076	.567**	.397			
	Sig. (2-tailed)	.086	.316	.592	.633	.481	.538	.456	.677	.227	.169	.486	.331	.713	.112	.153	.046	.502	.288	.743	.007	.074			
FR-HAR	*r*	.392	.345	.223	-.266	-.308	.102	-.194	-.113	.113	-.227	-.576**	-.070	-.103	.039	.257	-.440*	-.003	.516*	.474*	.548*	.356	.580**		
	Sig. (2-tailed)	.079	.125	.330	.243	.175	.660	.400	.626	.627	.322	.006	.764	.656	.868	.260	.046	.988	.017	.030	.010	.113	.006		
DA	*r*	-.057	-.063	.164	.234	-.505*	-.010	.061	-.080	.051	.264	-.025	-.091	-.218	.076	.549*	.605**	-.181	-.119	.633**	-.138	.114	-.366	.100	
	Sig. (2-tailed)	.807	.788	.477	.307	.019	.965	.793	.729	.828	.248	.914	.694	.343	.742	.010	.004	.432	.608	.002	.552	.624	.103	.667	

Note. *N* = 21.

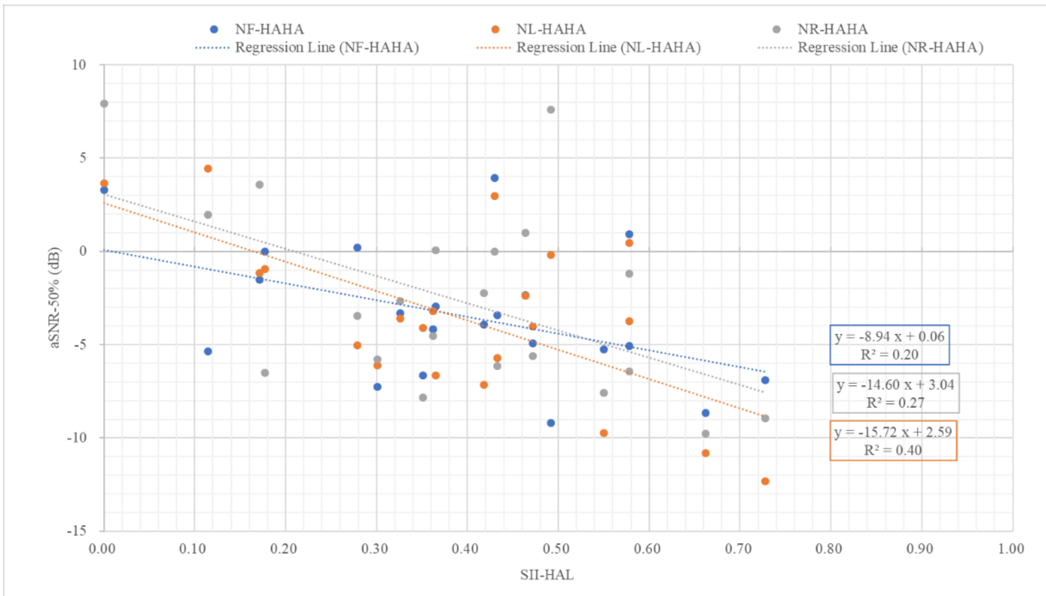
**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Figure 54 Scatter Plot between SII-HAL and SRiN performance of Participants with HAL Fitting



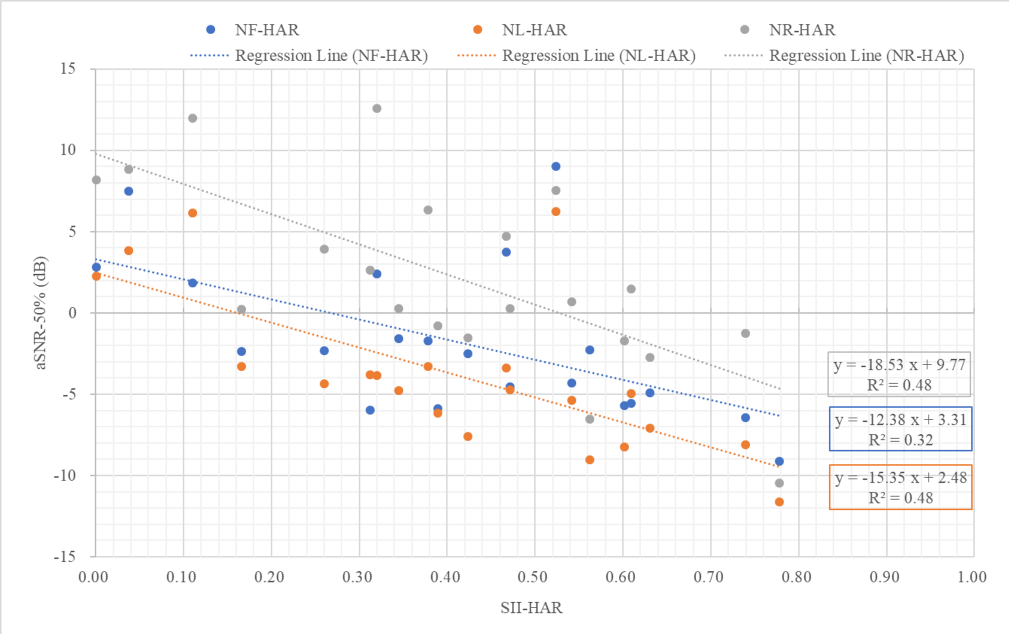
Note. *N* = 21.

Figure 55 Scatter Plot between SII-HAL and SRiN performance of Participants with HAHA Fitting



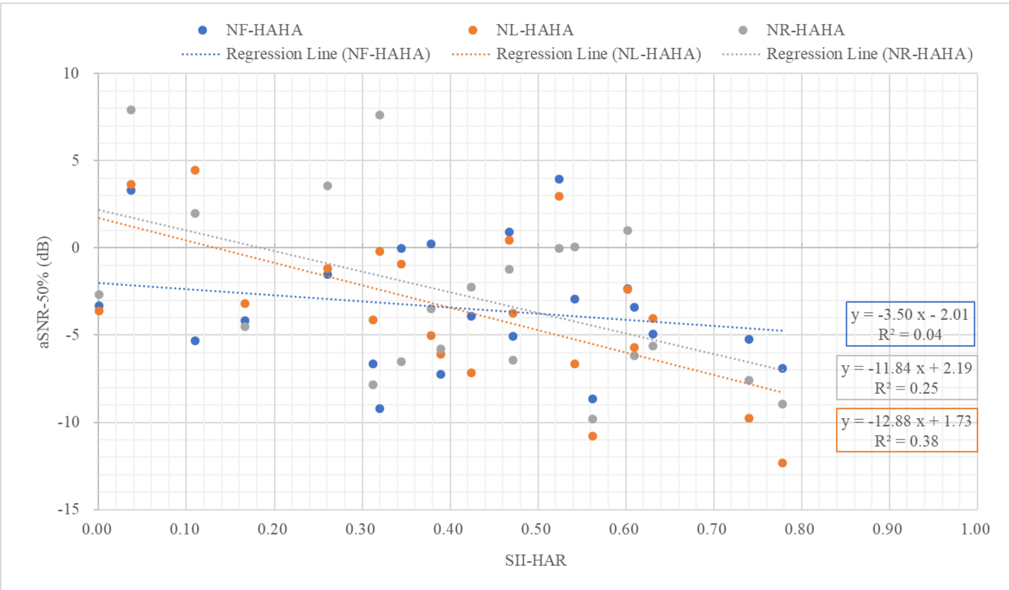
Note. *N* = 21.

Figure 56 Scatter Plot between SII-HAR and SRiN performance of Participants with HAR Fitting



Note. N = 21.

Figure 57 Scatter Plot between SII-HAR and SRiN performance of Participants with HAHA Fitting



Note. N = 21.

Table 25 ***Summary of Simple Regression Analysis between SII and aSNR-50% in the HAHA Group***

Variable	aSNR-50%	*B*	*SE*	*β*	R^2
SII-HAL	NF-HAL	-16.67^{**}	4.87	-.62	.38
	NL-HAL	-23.79^{**}	5.69	-.69	.48
	NR-HAL	-14.13^{*}	5.03	-.54	.29
	NF-HAHA	-8.95^{*}	4.05	-.45	.20
	NL-HAHA	-15.73^{**}	4.39	-.64	.40
	NR-HAHA	-14.60^{*}	5.45	-.52	.27
SII-HAR	NF-HAR	-12.38^{**}	4.16	-.56	.32
	NL-HAR	-15.36^{**}	3.68	-.69	.48
	NR-HAR	-18.54^{***}	4.40	-.69	.48
	NF-HAHA	-3.50	3.74	-.21	.04
	NL-HAHA	-12.89^{**}	3.76	-.62	.38
	NR-HAHA	-11.84^{*}	4.65	-.51	.26

Note. $N = 21$.

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

4.3.2 Regression Results of the CIHA Group

Table 26 lists the correlation matrix results from the CIHA group. Figure 58 and 59 show the scatter plots between the SII-CI and the SRiN performance in all noise directions with monaural CI and CIHA fitting, respectively. Figure 60 shows the scatter plots between SII-HAcon and SRiN performance in all noise directions with CIHA fitting.

The SII-CI could not significantly predict NF-CI with $F(1, 31) = 0.00$, p =.985, NHA-CI with $F(1, 31) = 2.46$, p =.127, NCI-CI with $F(1, 31) = 0.07$, p =.797, NF-CIHA with $F(1, 31) = 0.01$, p =.921, NHA-CIHA with $F(1, 31) = 1.22$, p =.277, and NCI-CIHA with $F(1, 31) = 0.00$, p =.950. Thus, the SII-CI was not a significant predictor of NF-CI (β = -.00, t = 0.02, p =.985), NHA-CI (β = -.27, t = -1.57, p =.127), NCI-CI (*β* = -.05, *t* = -0.26, *p* =.797), NF-CIHA (*β* = -.02, *t* = -0.10, *p* =.921), NHA-CIHA (*β* = -.20, *t* = -1.11, *p* =..277), and NCI-CIHA (*β* = -.01, *t* = -0.06, *p* =.950) (Table 27).

The SII-HAcon could not significantly predict NF-CIHA with *F*(1, 31) = 3.41, *p* =.075, NHA-CIHA with *F*(1, 31) = 1.23, *p* =.276, and NCI-CIHA with *F*(1, 31) = 2.28, *p* =.141. Thus, the SII-HAcon was not a significant predictor of NF-CIHA (*β* = -.32, *t* = -1.85, *p* =.075), NHA-CIHA (*β* = .20, *t* = 1.11, *p* =.276), and NCI-CIHA (*β* = -.26, *t* = -1.51, *p* =.141) (Table 27). However, the SII-HAcon could explain the 21.2% of the variance in BR-HAcon with *F*(1, 31) = 8.35, *p* =.007, and 12.8% of variance in SQ-HAcon with *F*(1, 31) = 4.56, *p* =.041. Thus, the SII-HAcon was a significant predictor of BR-HAcon (*β* = .46, *t* = 2.89, *p* =.007), and SQ-HAcon (*β* = .36, *t* = 2.14, *p* =.041). However, the SII-HAcon could not significantly predict HS-HAcon with *F*(1, 31) =1.68, *p* =.204; consequently, it was not a significant predictor of HS-HAcon (*β* = .23, *t* = 1.30, *p* =.204) (Table 28).

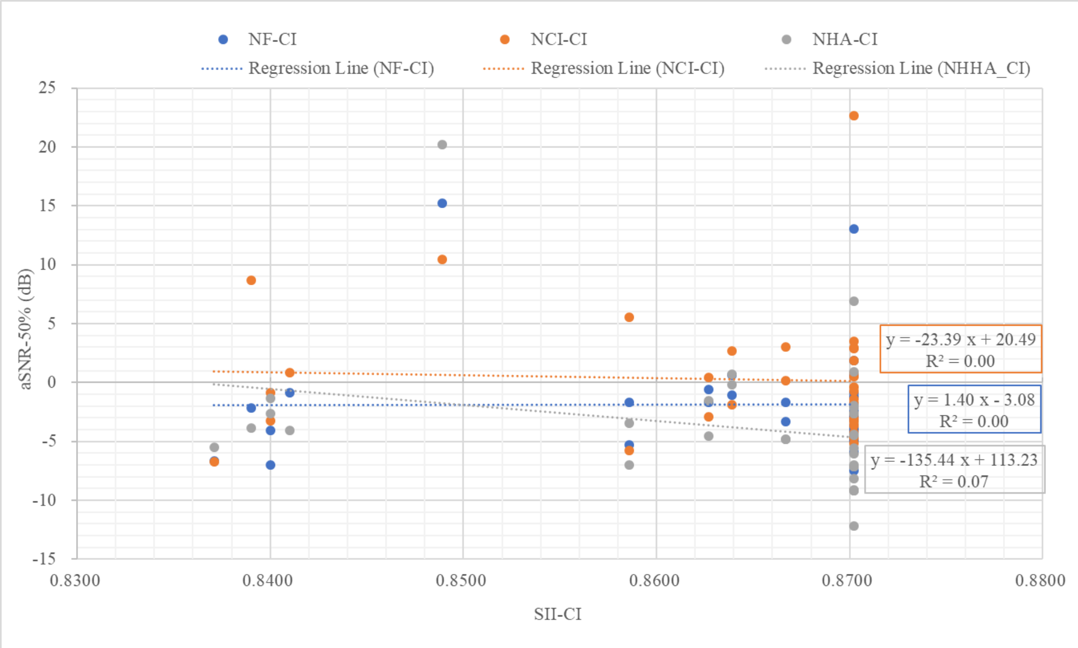
Table 26 ***Correlation Matrix Results from the CIHA Group***

Variable		SII-CI	SII-HAcon	NF-CIHA	NF-CI	NCI-CIHA	NCI-CI	NHA-CIHA	NHA-CI	BR-HAcon	SQ-HAcon	HS-HAcon	FHA-CIHA	FCI-CIHA	FHA-CI	FCI-CI	DA
SII-CI	*r*																
	Sig. (2-tailed)																
SII-HAcon	*r*	.126															
	Sig. (2-tailed)	.484															
NF-CIHA	*r*	-.018	-.315														
	Sig. (2-tailed)	.921	.075														
NF-CI	*r*	.003	.230	.479**													
	Sig. (2-tailed)	.985	.198	.005													
NCI-CIHA	*r*	-.011	-.262	.555**	.019												
	Sig. (2-tailed)	.950	.141	.001	.918												
NCI-CI	*r*	-.047	.040	.564**	.772**	.462**											
	Sig. (2-tailed)	.797	.824	.001	.000	.007											
NHA-CIHA	*r*	-.195	.195	.386*	.555**	.353*	.648**										
	Sig. (2-tailed)	.277	.276	.026	.001	.044	.000										
NHA-CI	*r*	-.271	.380*	.259	.796**	-.012	.629**	.681**									
	Sig. (2-tailed)	.127	.029	.146	.000	.949	.000	.000									
BR-HAcon	*r*	.015	.461**	-.092	.830**	-.331	.518**	.384*	.738**								
	Sig. (2-tailed)	.934	.007	.611	.000	.060	.002	.027	.000								
SQ-HAcon	*r*	-.211	.358*	.041	.633**	-.299	.332	.120	.808**	.692**							
	Sig. (2-tailed)	.239	.041	.821	.000	.090	.059	.508	.000	.000							
HS-HAcon	*r*	-.044	.227	.238	.842**	-.186	.786**	.471**	.705**	.804**	.576**						
	Sig. (2-tailed)	.809	.204	.182	.000	.299	.000	.006	.000	.000	.000						
FHA-CIHA	*r*	.180	-.441*	.400*	-.176	.084	-.202	-.691**	-.474**	-.454**	-.087	-.282					
	Sig. (2-tailed)	.317	.010	.021	.327	.643	.260	.000	.005	.008	.630	.112					
FCI-CIHA	*r*	-.002	.033	.219	.394*	-.690**	-.050	-.078	.239	.308	.387*	.426*	.249				
	Sig. (2-tailed)	.990	.855	.220	.023	.000	.780	.666	.181	.081	.026	.014	.162				
FHA-CI	*r*	.450**	-.309	.233	.067	.045	.028	-.358*	-.551**	-.072	-.460**	.000	.538**	.150			
	Sig. (2-tailed)	.009	.080	.193	.712	.804	.879	.041	.001	.691	.007	.998	.001	.406			
FCI-CI	*r*	.077	.237	-.259	.097	-.699**	-.558**	-.291	.054	.274	.307	-.130	.086	.594**	.044		
	Sig. (2-tailed)	.668	.184	.146	.591	.000	.001	.100	.766	.123	.082	.470	.633	.000	.807		
DA	*r*	-.156	.403*	-.174	.455**	-.605**	.134	.531**	.590**	.626**	.373*	.570**	-.664**	.559**	-.346*	.385*	
	Sig. (2-tailed)	.387	.020	.333	.008	.000	.459	.001	.000	.000	.033	.001	.000	.001	.049	.027	

Note. *N* = 33.

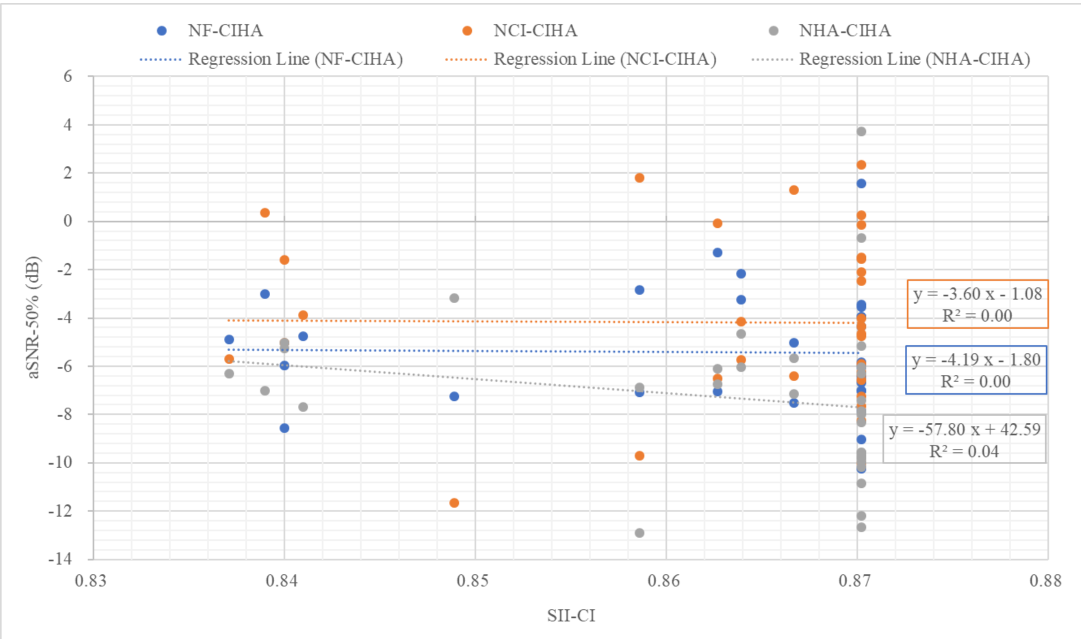
**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Figure 58 Scatter Plot between the SII-CI and SRiN performance of Participants with Monaural CI Fitting



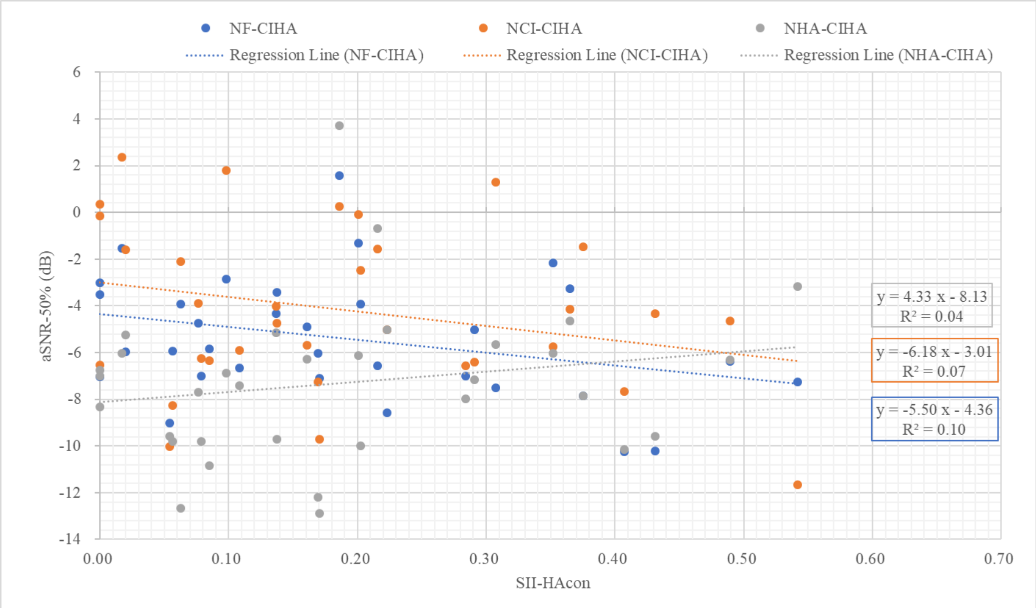
Note. N = 33.

Figure 59 Scatter Plot between the SII-CI and SRiN performance of Participants with CIHA Fitting



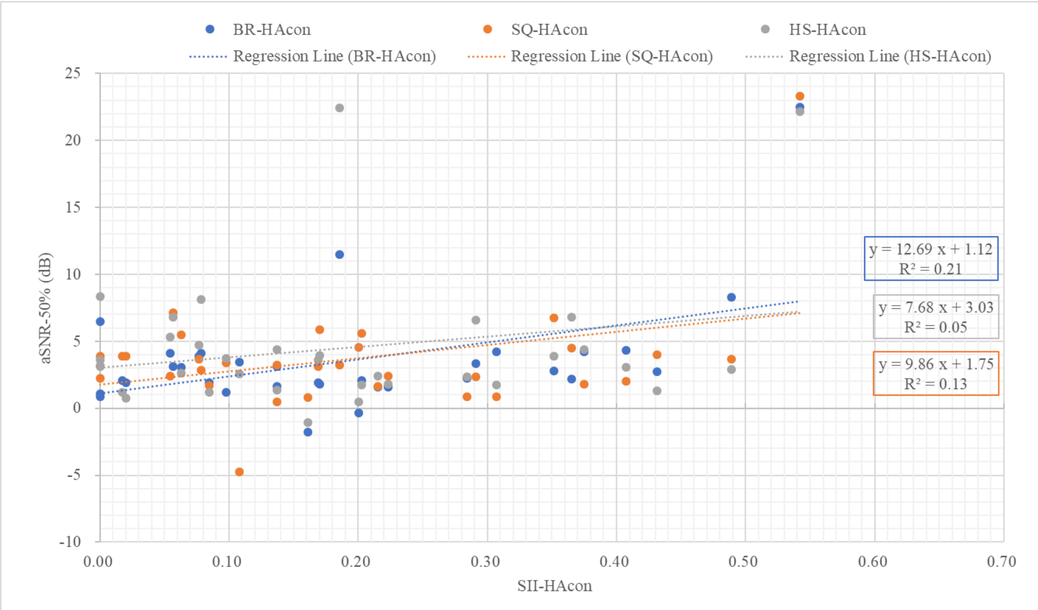
Note. *N* = 33.

Figure 60 Scatter Plot between the SII-HAcon and SRiN performance of Participants with CIHA Fitting



Note. *N* = 33.

Figure 61 Scatter Plot between SII-HAcon and the Binaural Benefits of Participants with CIHA Fitting



Note. *N* = 33.

Table 27 ***Summary of Simple Regression Analysis between SII and aSNR-50% of the CIHA Group***

Variable	aSNR-50%	*B*	*SE*	*β*	R^2
SII-CI	NF-CI	1.40	75.08	.00	.00
	NHA-CI	-135.44	86.44	-.27	.00
	NCI-CI	-23.39	89.92	-.05	.07
	NF-CIHA	-4.19	41.99	-.02	.00
	NHA-CIHA	-57.80	52.24	-.20	.04
	NCI-CIHA	-3.60	56.68	-.01	.00
SII-HAcon	NF-CIHA	-5.50	2.98	-.32	.10
	NHACIHA	4.33	3.90	.20	.04
	NCI-CIHA	-6.18	4.09	-.26	.07

Note. *N* = 33.

Table 28 ***Summary of Simple Regression Analysis between the SII and the Binaural Benefits of the CIHA Group***

Variable	Binaural benefit	*B*	*SE*	*β*	R^2
SII-HAcon	BR-HAcon	12.69**	4.39	.46	.21
	SQ-HAcon	9.86*	4.62	.36	.13
	HS-HAcon	7.68	5.92	.23	.05

Note. *N* = 33.

Chapter 5: Discussion

This research aimed to evaluate the SRiN performance in young Mandarin Chinese-speaking children with hearing loss. For clinicians, teachers, and families, the speech-in-noise test can help them understand the speech recognition abilities of children in daily life, especially in noisy environments, such as the classroom. As listening in noise is always a challenge for children with hearing loss, the clinicians, teachers, and families need to consider how to improve the SRiN performance of the children. With better SRiN performance, children with hearing loss can obtain better hearing, speech, and language development, and they may be easier to get into mainstream school and society. In this chapter, the SRiN performance of participants with different device fitting conditions in all noise directions are discussed based on the results obtained from the children with hearing loss using HAHA and CIHA fitting in Chapter 4. Section 5.1 first provides a general discussion for SRiN performance of children with hearing loss, then Section 5.2 and 5.3 discuss the binaural benefits and spatial advantages on the SRiN performance, respectively. Section 5.4 is a preliminary discussion of individual results from the intra-participant statistical evaluation, which can provide insights into the outcomes of interesting cases. The relationship between audibility and speech recognition performance is discussed in Section 5.5. Then, the implications, limitations, and conclusions of the present study are consecutively outlined.

5.1 SRiN Performance of Children with Hearing Loss

The participants with hearing loss had worse SRiN performance than their peers with NH, even though the participants listen in the binaural hearing condition. The participants with HAHA fitting achieved SNR levels of -3.50, -3.57, and -2.78 dB in the NF, NL, and NR conditions, respectively; the participants with CIHA fitting achieved SNR levels of -5.41, -7.30, and -4.19 dB in the NF, NHA, and NCI conditions, respectively. However, Yuen et al. (2019) investigated SRiN performance for children aged 4.83-5.25 years with NH using the same materials and adaptive procedure as the present study, and reported that the children obtained SNR levels of approximately -11 and -18 dB in the NF and NS conditions, respectively. The different SRiN performance between children with hearing loss and children with NH was more significant in the spatially separated condition than that in the co-located condition, suggesting that the spatial separation is very necessary for the children with hearing loss to recognise the speech.

In a relevant reference condition (i.e., listening with binaural hearing in the NF condition), the outcomes of participants in the present study were significantly different from the previous studies. Ching et al., (2011) investigated monosyllabic words perception of children (aged 3.2-11.9 years) with HAHA fitting in the eight-talker babble noise, and reported that the children performed SNR level of -0.02 dB in the NF. Compared to the present study, the worse SRiN performance of children in the previous study may be due to the test material and babble noise. The monosyllabic word has less redundant information than the disyllabic word in the present study. The babble noise not only introduces energetic masking but also informational masking, which is not involved in the SSN applied in the present study. Therefore, the speech-in-noise test in the previous study may be more difficult than the test in the present study. Additionally, the speech signal in the present study was Mandarin Chinese, which was different from English (non-tonal language) in Ching et al.'s (2011) study.

Lexical tones in Mandarin Chinese can convey meanings of syllables, and acoustic cues of lexical tones cannot be easily disturbed by noise when compared to the consonant and vowel portions (Fu et al., 1998; Kong & Zeng, 2006; Luo et al., 2009; Zhu et al., 2011). Thus, lexical tones in Mandarin Chinese may be another reason for the better SRiN performance of participants in the present study than that of children in the previous study that used English speech signals involving consonant and vowel information only. This language aspect of results is also observed in other previous research using non-tonal language. Some researchers used Dutch or German sentences with the SSN to investigate SRiN performance of adults with HAHA fitting (Festen & Plomp,1986; van Schoonhoven et al.,2016). Festen and Plomp (1986) found that the adults with PTA (unaided average hearing threshold for 500, 1000, and 2000 Hz)>50 dB HL performed SNR level of approximately -2 dB in the NF, and van Schoonhoven et al. (2016) found that the adults with PTA (unaided average hearing threshold for 500, 1000, 2000, and 4000 Hz)>40 dB HL performed SNR level of -1.2 dB in the NF. Lexical tones in Mandarin Chinese disyllabic words may be one reason for the better SRiN performance of participants with HAHA fitting in the present study compared to the outcomes in previous studies. In the NF, there are also some different outcomes individuals with CIHA fitting between the present study and previous studies. Litovsky et al., (2006) reported that children with CIHA fitting performed SNR levels of approximately -10 dB. The better outcomes in the previous study may result from the demographics. Children in the previous study (6-14 years) were older (i.e., had a longer duration of CI use and more hearing experience) than participants in the present study, so it is not surprising that these children could achieve better SRiN performance.

In each of three noise conditions, the CIHA group obtained better SRiN performance than the HAHA group. As far as these two groups can be compared in the present study, the results suggest that for children with severe loss replacing a HA with a CI can improve SRiN outcomes. Even though the across-group comparison is available here, the group data can hardly allow individual predictions, since replacing one HA by a CI can bring an individual with HAHA fitting advantages or disadvantages. However, from a funding perspective, outcomes from intra-participant comparison may provide an individual with a good argument about whether implanting one CI is worth the cost, which is discussed in Section 5.4. Moreover, since a variety of outcomes was observed across participants in both groups in the present study, contributions from the audibility or other factors to the variance in SRiN performance are discussed in Section 5.5.

5.2 Binaural Benefits of the SRiN Performance

This study evaluated the binaural benefits by measuring the SRiN performance of participants with binaural (HAHA or CIHA) versus those with monaural (monaural HA or monaural CI) hearing condition in different noise directions, and investigated whether binaural hearing can significantly improve the SRiN baseline performance with monoaural hearing. The binaural benefits of participants in the two groups are discussed in the following sections.

5.2.1 Binaural Benefits of the HAHA Group

In the speech and noise co-located condition (NF), the group comparison result suggested that the participants received a significant BR effect of 2.38 dB SNR on average from their second HA in the right ear (BR-HAR); however, the participants received a non-significant BR effect from the second HA in the left ear (BR-HAL, 1.43 dB average SNR). The group results of non-significant DA (-0.79 dB average SNR) indicate that the difference between BR-HAR and BR-HAL may be not caused by DA. However, the unaided threshold of left ear was worse than the right ear, and the SII-HAL was worse than the SII-HAR, so the lower BR-HAL compared to the BR-HAR may be resulted from the worse functional hearing ability of the left ear than the right ear. These results pertaining to the BR effect do not agree with the findings of Walden and Walden (2005), who determined that 23 of 28 participants performed worse with binaural HAHA fitting than with monaural HAR or HAL fitting in the NF condition. One possible reason for the binaural disadvantage is called binaural interference, which is caused by inappropriate fusion of signals received by two ears (Arkebauer Herbert et al., 1971; Chmiel et al., 1997; Jerger et al., 1993). Thus, the input from the ear with poorer speech recognition ability results in non-optimal processing of input from the ear with the better speech recognition ability. It should be noticed that Walden and Walden (2005) used a 4-talker babble noise as the noise signal, which is different from the SSN used in the present study. The babble noise involves competing speech and informational masking whereas the SSN only introduces energetic masking (Jerger, 2006). Hence, there is no surprise that the binaural interference was observed in their study but not in the present study. Although HL in terms of threshold sensitivity was symmetrical in both ears, significant differences in suprathreshold speech recognition ability between ears were observed in certain individuals (Walden & Walden, 2005). In these cases, the auditory input to the central processing system from the two ears can be different, leading to binaural interference. However, a later study (McArdle et al., 2012) replicated the research of Walden and Walden, and reported results that were clearly in contrast to those identified by Walden and Walden (2005), but match the findings of the present study. McArdle et al. (2012) determined that the SRiN performance with HAHA condition achieved a 2-4 dB better SNR performance on average than that with monaural HAL or HAR in the NF condition. However, the authors could not elaborate on the possible reasons for the inconsistent results in both studies and indicated a need for further examination. As participants with the same age and hearing threshold were considered in these two studies (refer to Table 1), the different findings may have resulted from the different suprathreshold processing abilities for binaural input of the participants between the two studies.

In the condition where the speech and noise were spatially separated (NL or NR) in the present study, the participants only received significant HS (HS-HAL of 5.02 dB SNR and HS-HAR of 4.90 dB SNR) by adding the second HA contralateral to the noise; however, a significant SQ advantage or disadvantage was not obtained by adding the second HA ipsilateral to the noise. These results in the spatially separated condition were consistent with previous studies (Festen & Plomp, 1986; Van Schoonhoven et al., 2016), where the addition of a second HA at the ear closer to the noise could not make participants achieve SQ, but its addition at the ear away from the noise could make participants achieve the HS. Even though both SQ and HS effect perform a role when the speech and noise are from different directions, the HS effect is more prominent than the SQ of the second HA, and the binaural benefits of HAHA fitting for SRiN performance improvement were primarily related to the advantage of the HS effect (Boymans, Monique & Dreschler, 2011; Markides, 1982).

In the present study, the binaural benefits for participants with binaural hearing were obtained using either HAL or HAR as the monaural hearing baseline. However, van Schoonhoven et al. (2016) selected the aided ear with a better pure-tone average (PTA) threshold as a monaural hearing reference condition, and only reported significant HS with HAHA fitting when compared to the monaural aided ear with better PTA. The approach in the study by van Schoonhoven et al., which compared the different outcomes with HAHA fitting and monaural HA on the ear with better aided PTA, can result in less room for improvement in the SRiN performance owing to the addition of the second HA. Therefore, this methodological approach may underestimate the binaural benefits. In the present study, the participants obtained average SNR values of 2.38 dB for BR-HAR, 5.02 dB for HS-HAL, and 4.90 dB for HS-HAR. However, van Schoonhoven et al. (2016) reported non-significant BR and lower magnitude of HS (4.1 dB of average SNR) for the participants. Overall, the group comparison results of the HAHA group in the present study showed binaural benefits of BR and HS and did not show any binaural disadvantages with any device fitting conditions in any noise directions. These findings support the use of binaural HAHA fitting for recognising speech in noisy environments for the majority of children with bilateral hearing loss using HA.

5.2.2 Binaural Benefits of the CIHA Group

When the participants were fitted with CIHA, the group comparison results of the SRiN performance were better than those obtained in monaural CI device fitting condition, regardless of the noise direction. Thus, the participants with CIHA fitting benefitted from adding the contralateral HA to the monaural CI fitting. The participants achieved significant BR-HAcon (3.54 dB of average SNR), SQ-HAcon (3.63 dB of average SNR), and HS-HAcon (4.49 dB of average SNR). These findings are in line with those of previous studies (Ching et al., 2005; Dincer D'Alessandro et al., 2015; Mok et al., 2010) that demonstrated statistically significant BR in the NF condition, SQ in the NHA condition, and HS in the NCI condition for children with CIHA fitting in comparison with monaural CI fitting. Ching et al. (2005), Dincer D'Alessandro et al. (2015), and Mok et al. (2010) used changes in the percentage of correct results as the outcome measure for speech perception in noise. However, the present study used changes in SRT as the outcome measure for the SRiN performance. Thus, it is difficult to directly compare the magnitudes of binaural benefits obtained by children with CIHA in the present study and those in previous studies.

Litovsky et al. (2006) measured SRT in noise for children with CIHA versus monaural CI fitting, and they determined that the binaural benefits of the children, on average, were negative or near zero in the NF, NHA, and NCI conditions. The authors explained that the non-significant binaural benefits of the group of participants could be due to the small sample size (N=10) and large individual variability of performance among the children. Mok et al. (2007) determined that children with CIHA fitting achieved statistically significant BR (1.3 dB of average SNR) and HS (2.2 dB of average SNR), but not SQ; however, all results were inferior to the binaural benefits obtained in the present study. This previous study used the stimulus /baba/ to measure sound detection threshold in noise, instead of using speech signal to measure the speech recognition threshold in noise. The binaural benefits of adding a contralateral HA to the monaural CI fitting in the speech detection task may be different from those obtained in the speech recognition task. The HA in CIHA fitting can provide low-frequency spectral information, which may better complement signals from the ear that is opposite to the CI for speech recognition (Mok et al., 2007). For example, these authors (Mok et al., 2006) investigated the consonant-vowel nucleus-consonant phoneme recognition performance of adults with CIHA and monaural CI fittings, and determined that the primary differences between the two device fitting conditions were the perception scores of the lower-frequency phoneme groups. The results indicated that the additional HA in the CIHA fitting can improve the recognition of the lower-frequency phones. Thus, the authors concluded that the binaural benefits of CIHA fitting in the speech recognition task could be due to the better recognition of the low-frequency components in speech signal. Moreover, the magnitude of binaural benefits in each of three noise conditions in Mok et al.'s (2006) study is lower than that in the present study. For example, in the NF, even though outcomes with monaural CI fitting in the present study (-1.87 dB SNR) was lower than the previous study (approximately -2.5 dB SNR), the outcomes with CIHA fitting in the present study (-5.41 dB SNR) was better than the previous study (approximately -4.0 dB SNR). Different languages of speech signal using in the studies may result in these different SRiN performances. Mandarin Chinese has four lexical tones with different F0 contours, which represent different meanings despite being an identical syllable (Luo et al., 2009). However, the modern CI system cannot encode and convey explicit pitch information within lexical tones (Chen, Yuan & Wong, 2017; Mao & Xu, 2017;

Moore, B. C. J., 2003). Thus, lexical tone recognition is a challenge for individuals with CI fitting, which can impact speech recognition. Additionally, the relative contribution of vowels is more than consonants in recognizing speech signals in Mandarin Chinese, and vowels contribute more in recognizing speech signals in Mandarin Chinese than English (Chen, F., Wong, Zhu, & Wong, 2015; Chen, F., Wong, & Wong, 2013; Cole, Yan, Mak, & Fanty, 1996), so the lower-frequency phonemes (e.g., vowels) recognition is important to the speech recognition in Mandarin Chinese. Compared to the non-tonal language in the previous study, for the speech recognition in Mandarin Chinese, adding the HA to the CI can improve not only the recognition of low-frequency components but also the recognition of lexical tones. In noisy environments, any acoustic cues or speech redundancies are necessary to recognise speech signals. In other words, the HA in the CIHA fitting is more useful in SRiN performance for the Mandarin Chinese-speaking population.

For the magnitudes of different binaural benefits of the CIHA group, Dieudonné and Francart (2020) observed that the binaural benefits of adults with NH using simulated bimodal hearing vocoder were related to the SNR level at the HA side. When the noise was near the CI side, the SNR level at the HA side was the best; when the noise was located at the HA side, the SNR level at the HA side was the worst; moreover, when the noise was from the front, the SNR level at the HA side was somewhere in between. Thus, the magnitude of benefit of adding a contralateral HA to the CI was the largest in the NCI condition (HS), smallest in the NHA condition (SQ), and somewhere in between in the NF condition (BR). This SNR dependency of binaural benefits is also observed in the present data of the children with real CIHA fitting: the amounts of BR was similar to the SQ and both benefits were lower than the HS benefit. Additionally, in the present study, the SRiN performance of participants with CIHA fitting was always compared with a fixed monaural CI fitting, which is also the better aided ear in all participants with CIHA, except for the participant, CIHA-M20. According to the potential underestimation of binaural benefits for the HAHA group mentioned in the last section, which compared the outcomes of participants with HAHA fitting to those with monaural HA fitting on the ear with better aided PTA, using monaural CI fitting as the only baseline could have underestimated the binaural benefits in the CIHA group. If the SRiN performance with the monaural HA fitting was measured as the baseline, it can be assumed that the binaural benefits would be larger than when using the monaural CI fitting as the baseline. Overall, the group comparison results of the CIHA group in the present study showed SRiN performance of the participants listening in binaural hearing condition was significantly better than those listening in monaural hearing condition, which could support the hypothesis that children with CIHA could obtain significant binaural benefits in each of three noise conditions.

5.3 SRM Obtained from Children with Hearing Loss

SRM is a measure of the outcome of the aSNR-50% improvement obtained in the NF condition when compared to the condition where speech and noise were spatially separated (NL or NR condition in the HAHA group; NHA or NCI condition in the CIHA group) for the participants in two groups with each device fitting condition. All SRM results are discussed in the following sections.

5.3.1 SRM for the HAHA Group

Six different SRM outcomes obtained from participants in the HAHA group are discussed in this section: FL-HAHA, FL-HAR, and FL-HAL when comparing the aSNR-50% results of participants with each device fitting condition in the NF versus NL condition; FR-HAHA, FR-HAL and FR-HAR when comparing the aSNR-50% results of participants with each device fitting condition in the NF versus NR condition.

According to the review of SRM (Section 2.3), the monaural part in SRM was the HS, which was related to the noise direction. The monaural part could contribute to the SRM, regardless of the device fitting conditions. The binaural part in the SRM was a combination of BR and SQ, which was related to binaural hearing. The binaural part can perform a role in the SRM only if the participants used binaural hearing. In the present study, the SRM for participants with monaural HA fitting could support the hypothesis that it can only be observed in children with monaural HA fitting that was contralateral to the direction of noise. When the noise moved from the front to the unaided side, only the monaural component (HS of the monaural HA-aided side) was retained and thus yielded an improvement in SRiN performance, which is represented by FR-HAL (2.60 dB of average SNR,) and FL-HAR (1.64 dB of average SNR). However, when the noise moved from the front to the monaural HA-aided side, neither the monaural component (HS) nor the binaural component (binaural benefits) affected the SRM; consequently, FL-HAL and FR-HAR were both negative (average SNR of -2.45 and -4.31 dB, respectively). For the SRM obtained from binaural hearing condition, the present study hypothesises that the participants with HAHA fitting can achieve significant SRM. However, the aSNR-50% results of participants with HAHA were not significantly different between the NF and NL conditions, and were not significantly different between the NF and NR conditions. Thus, the SRM for the participants with HAHA fitting (FL-HAHA and FR-HAHA) was not significant. Yuen et al. (2019) reported an average of 6.66 dB SNR of SRM for children with NH when the noise moved from the NF to NL condition and 6.77 dB SNR of SRM when then noise moved from the NF to NR condition. When compared to their peers with NH, the children with HAHA fitting in the present study demonstrated a deficit SRM for approximately 6 dB SNR.

When discussing the SRM for the participant with HAHA fitting, it is necessary to understand the component that yields an improvement in the SRiN performance. Dieudonné and Francart (2019) defined SRM as a combination of HS of monaural hearing, SQ of binaural hearing, and BR of binaural hearing; therefore, either of these three effects could affect SRM (refer to

Figure 1). The HS is a physical effect and is always beneficial to the SRM. However, when SQ is larger than BR (i.e. binaural contrast, which is defined as the difference between SQ and BR, is positive), the binaural hearing component could contribute to SRM. According to the framework illustrated in Figure 1, the present study disentangled the SRM for the participants with HAHA fitting (refer to Figure 2). Although the binaural contrast has never been explicitly evaluated for individuals with HAHA fitting in previous studies, to the best of my knowledge, the group average results (refer to Table 15) in the present study allowed the author to calculate the binaural contrast and SRM. In both panels A and B (refer to Appendix D1), the magnitudes of HS of the participants with monaural HA fitting were similar to those of the participants with HAHA fitting, and the values of SQ of the participants with HAHA fitting were negative. Thus, the SRM of FL-HAHA and FR-HAHA were both close to zero. The present data supported the conclusion of Dieudonné and Francart (2019) that the non-significant SRM for adults with NH could be caused by the offset between HS and BR. Moreover, current HAs in binaural hearing condition can independently process incoming signals of one another; consequently, different settings between two HAs in terms of compression, noise reduction, and adaptive algorithms may distort natural ITD and ILD cues, which could negatively impact the SRM for listeners with HAHA fitting (Marrone et al., 2008a; Marrone et al., 2008b; Marrone et al., 2008c; Neher et al., 2009). However, the present study focused on a sample of children wearing their personal HA; therefore, it did not investigate the effects of the processing parameters on the SRM.

The SRM between the participants with HAHA and monaural HA fittings were compared, and the results show that FL-HAHA is not significantly different from FL-

HAR; moreover, FR-HAHA is significantly worse than FR-HAL (Figure 30). These results can also be interpreted using the SRM framework of the participant with HAHA fitting (refer to Appendix D1). In both panels A and B, SQ was negative and BR was positive, resulting in a negative binaural contrast, which is equal to SQ minus BR. Thus, when the noise moved from the front to the monaural unaided side, adding the second HA near the source of noise could not improve the SRM; in fact, it could even decrease the SRM. However, when the noise moved from the front to the monaural aided side, FL-HAHA was significantly higher than FL-HAL, and FR-HAHA was significantly higher than FR-HAR. This improvement in SRM from monaural HA fitting to HAHA fitting may be primarily due to the complementary HS benefit of adding the second HA contralateral to the direction of noise. Different SRM results between the participants with monaural and binaural hearing condition suggest that the primary spatial cue contributing to SRM is the monaural component (HS), and not the binaural component (combination of SQ and BR). Certain previous studies (Dawes et al., 2013; Marrone et al., 2008b) used a different noise configuration to measure the SRM for monaural and binaural hearing condition. In their studies, the noise moved from the front to both sides (i.e. was simultaneously presented on the left and right sides). The long-term average SNR was equal at the two ears, thereby significantly reducing or eliminating the long-term effect of the HS effect of either ear. In this configuration, the authors determined that the SRM for adults with HAHA fitting was significantly better than that with monaural HA fitting, suggesting that listeners were able to utilise binaural BR and SQ cues to improve the SRM. It could be noticed that a speech-on-speech masking task was used in the previous studies (Dawes et al., 2013; Marrone et al., 2008b). The competing speech introduced informational masking as well as significantly different short-term SNR fluctuation between two ears, so it can provide a better ear (i.e., an ear with better SNR) that rapidly alternate between ears. The process that central auditory system uses the short-term ILD cues (HS effect) at the two ears to recognise speech signal is termed better-ear glimpsing (Best et al., 2015; Rana & Buchholz, 2016). However, neither informational masking nor better-ear glimpsing is relevant in the SSN applied in the present study, so it may be a reason why the SRM with HAHA fitting was not significantly different from that with unilateral HA fitting in the present study. Even though Ching et al. (2011) used 8-talker babble noise task and the same noise configuration as the studies of Dawes et al. (2013) and Marrone et al. (2008b), Ching et al. (2011) identified that children with HAHA fitting cannot obtain a significant SRM. In the present study, 19 of 23 children were diagnosed with hearing loss before three years of age, and 19 of 23 children have severe to profound sensorineural HL for both ears. When compared to the participants in the above studies (Dawes et al., 2013; Marrone et al., 2008b), who are post-lingually deafened adults with mild to moderate sensorineural HL, the pediatric participants in the present study and Ching's study (2011) had significantly limited listening experience. However, the ability to utilise and integrate binaural cues is acquired through listening experience (Litovsky, 2012). In other words, the post-lingually deafened adults were exposed to acoustic hearing for a long time before the onset of a HL. The HAHA fitting can re-activate the previously established spatial hearing ability (i.e., utilising better-ear glimpsing or binaural components of BR and SQ) to a certain extent in adults, whereas young children with congenital HL have limited access to acoustic sound prior to HA fitting. The limited listening experience of young children with HAHA fitting may be a possible reason for the non-significant SRM for the participants with HAHA fitting, resulting in different SRM results between adults and children. Additionally, the different test conditions were ordered from relatively easy (e.g., NL-HAHA or NR-HAHA) to difficult (e.g., NF-HAHA). If there was a potential learning effect, the first condition or the first two conditions (i.e., NL-HAHA or/and NR-HAHA) might have done the most of the learning. Since the learning effect usually follows an exponential performance improvement curve, not a linear one (i.e., a lot of learning in the beginning and then less and less), there may not have been any more learning effect left for the third condition (i.e., NF-HAHA). Therefore, the test sequence may result in the reduced/underestimated SRM for the participants.

5.3.2 SRM for the CIHA Group

Four different SRM outcomes that were obtained from participants in the CIHA group for four conditions are discussed in this section: FHA-CIHA and FHA-CI when comparing aSNR-50% results of participants with each device fitting condition in NF versus NHA condition; FCI-CIHA and FCI-CI when comparing aSNR-50% results of participants with each device fitting condition in the NF versus NCI condition.

For the participants with monaural CI fitting, when the noise moved from the front to the HA side, a better SNR situation occurred at the CI side due to the HS (monaural hearing component) than on the HA side, which resulted in a positive FHA-CI (1.80 dB of average SNR). However, when the noise moved from the front to the CI side, the SNR at the CI side decreased. The HS disadvantage of the CI side is represented by a negative FCI-CI (-2.17 dB of average SNR). For the SRM obtained from CIHA fitting, the participants achieved a positive FHA-CIHA (1.89 dB of average SNR) when compared to the NF versus NHA condition. Even though children in the CIHA group obtained a positive FHA-CIHA and FHA-CI, the SRM results of the participants (*M* = 4.6 years old, range: 3.1-6.6 years old) indicated a SNR that was approximately 5 dB worse than that of age-matched children with NH (*M* = 4.97 years old, range: 4.83-5.25 years old) (Yuen et al., 2019). Other previous studies also reported that the SRM for children with CIHA was poorer than that of their peers with NH (Litovsky et al., 2006; Mok et al., 2007; Nittrouer et al., 2013). In contrast, the aSNR-50% results of participants were not significantly different between the NF and NCI conditions, resulting in a deficit in FCI-CIHA. Thus, the SRM for participants in the CIHA group supports the hypothesis in the present study that positive SRM will only be obtained from NF to NHA conditions. In other words, regardless of the participants with CIHA or monaural CI fitting, the SRM results in FHA are better than those in the FCI condition. Different SNR situations at the CI side because of the HS (monaural component) is the most likely reason for the different SRM results between the FHA and FCI conditions. The findings related to SRM in the present study that FHA-CIHA was positive and FCI-CIHA was negative are consistent with previous studies. Litovsky et al. (2006) identified that the SRM for children with CIHA was significantly greater (approximately 2 dB, on average) when the noise was near the HA side than when it was near the CI side. Mok et al. (2007) also reported that when comparing NF with NHA conditions, the SRM for children with CIHA was an average SNR of 3.8 dB; however, when comparing NF and NCI conditions, the SRM was negative (-0.4 dB of average SNR). When the noise moved from the front to the CI side, Mok et al. (2007) believed that the negative SRM result could be owing to a better aided audibility in the CI ear than in the HA ear. Thus, in the NCI condition, the SNR improvement at the HA side may not be sufficient to compensate for the SNR decrease at the CI side. In general, the participants with CIHA or monaural CI fitting achieved significant SRM, at least in the FHA condition; therefore, the target speech signal and interfering sounds should be spatially separated in educational and home environments, if possible. For example, it may be better to install air conditioners in classrooms on the side or back walls instead of above the blackboards from where teachers often speak (Mok et al., 2007). If the noise sources are inevitably installed near the CI side, children can consider using other wearable assistive listening devices to improve the SNR, such as a remote microphone hearing assistance technology (HAT). Among the different HAT devices, a wireless frequency modulation (FM) system is an early development and is a widely used technology for individuals with hearing loss (Chen, J. et al., 2021). The FM system can prevent target signals from being affected by noise, distance, and reverberation, especially in educational environments; therefore, it can effectively improve the SNR (approximately 10 dB) of the amplified signals at the level of the ear canal of the listener (ASHA, 2002; Bertachini et al., 2015; Ross, 1992).

Similar to the discussion of SRM obtained from participants in the HAHA group, it is necessary to determine the components that contribute to the SRM for the participants with CIHA fitting. According to the framework illustrated in Figure 3, the present study disentangled the SRM for the participants with CIHA fitting (refer to Figure 4). The present data of the group results in Table 17 were used to calculate the SRM for the participants with CIHA fitting (refer to Appendix D2). In panel A, when the noise moved from the front to the HA side, the participants with monaural CI fitting could obtain an average SNR of 1.80 dB for FHA-CI, which was due to the HS of the monaural CI fitting (monaural component). When compared to the monaural CI fitting, the participants with CIHA fitting could obtain binaural benefits of adding a

HA, including an average SNR of 3.63 dB for SQ-HAcon and 3.54 dB for BR-HAcon (binaural component). The binaural contrast is a trade-off between supplying SQ and BR, which represents true binaural SQ and BC benefits of processing binaural cues on both sides (Dieudonné & Francart, 2020). However, the present data could not suggest the benefit of binaural cue processing for the participants, because the binaural contrast is near zero (i.e. BC = SQ-HAcon – BR-HAcon = 3.63 – 3.54 = 0.09 dB of SNR). Thus, the binaural contrast (binaural component) may not contribute to the observed SRM (FHA-CIHA) of participants with CIHA fitting in the present study. In panel B, when the noise moved from the front to the CI side, the participants with monaural CI fitting obtained an average SNR of -2.17 dB for FCI-CI. This resulted from the *reversal* HS of the monaural CI-aided side. When compared to the monaural CI fitting, the participants with CIHA fitting could obtain binaural benefits in terms of average SNR scores of 4.49 dB for HS-HAcon and 3.54 dB for BR-HAcon. Even though the SNR situation is better at the HA side in the NCI condition, according to the equation in panel B, the difference between HS-HAcon and BR-HAcon (4.49 - 3.54 = 0.95 dB SNR) could not sufficiently compensate for the negative FCI-CI. Thus, the SRM for the FCI-CIHA was absent in the participants. To the best of my knowledge, the present study is the first study to measure the different and isolated effects, including HS, BR, and SQ, to explicitly illustrate how they influence the SRM for children with CIHA fitting. The SRM results of CIHA fitting in the present study agree with the findings from the previous study of Dieudonné and Francart (2020). The authors measured the SRM for adults with NH using a simulated CIHA vocoder, which may not be involved in the binaural component. Thus, when the noise moves from the front to the HA side, the SRM is a trade-off between the SNR level change at the CI side, which is due to the HS of the monaural CI-aided side (i.e. SRM for FHA-

CI in the present study), and binaural contrast. When the noise moves from the front to the CI side, the SRM is mediated by the difference between the decrease in the SNR level at the CI side, which is due to the *reversal* HS of the monaural CI-aided side (i.e. SRM for FCI-CI in the present study), and an increase in the SNR level at the HA side.

When comparing the SRM between the participants with CIHA and monaural CI fittings, the results show that FHA-CIHA was not significantly different from FHA-CI, and FCI-CIHA was not significantly different from FCI-CI (Figure 32). Thus, regardless of the addition of an HA contralateral or ipsilateral to the noise, the CIHA fitting could not significantly improve the SRM through the monaural CI fitting. This result once again suggests that the SRM for participants with CIHA primarily arises from FHA-CI or FCI-CI, which is related to the HS or *reversal* HS of the monaural CI-aided side; however, it does not arise from the ability to process binaural cues in two ears (Dieudonné & Francart, 2020; Litovsky et al., 2004; Litovsky et al., 2006; Schleich et al., 2004). It is possible that listeners with pre-lingually profound HL using CIHA fitting have difficulties in utilising ITD cues (Ching et al., 2005; Ching et al., 2006b; Kan & Litovsky, 2015; Laback et al., 2015). The ear with CI has limited residual hearing at low frequencies, resulting in impacting temporal fine structure of ITD cues, because the auditory system is sensitive to the utilisation of ITD cues at frequencies lower than 1500 Hz. A compression within HA and CI speech processors could also reduce ILD cues, resulting in less different SNR levels between the two sides; consequently, it could be hard for the individuals to selectively attend to one ear with better SNR (Litovsky, 2012; Wiggins & Seeber, 2011; Williges et al., 2015).

5.4 Intra-Participant Comparison of aSNR-50% Results

Although certain previous studies of participants with HAHA (refer to Table 1) and CIHA fittings (refer to Table 2) reported error estimates (i.e. *M* and *SD*) of binaural benefits and the SRM obtained from group results, only a few studies have reported these outcomes from individual results, which may be limited by the speech-in-noise testing methods and procedures. To the best of my knowledge, the present study is the first to provide intra-participant error estimates of aSNR-50% from different test conditions for each participant with HAHA fitting (Figure 33 to 45) and CIHA fitting (Figure 46 to 53). Thus, not only the magnitude of binaural benefits and SRM, but the existence of binaural benefits and SRM can be statistically revealed within each young child with HAHA or CIHA fitting.

For the intra-participant comparison in the present study, individual aSNR-50% results across different test conditions were compared to detect subtle changes by adopting the rigorous criterion of the non-overlapping *99% confidence interval* of two aSNR-50% scores between the two test conditions. The group average results showed that participants listening in binaural hearing condition could obtain significant binaural and spatial advantages; however, the intra-participant comparison results reflected individual variability; certain participants obtained significantly positive binaural benefits and SRM, whereas others demonstrated non-significant binaural benefits and SRM, and some even showed negative binaural benefits and SRM. Therefore, the intra-participant comparison can reveal individual results which are different from and concealed in the group results. Based on the individual results from the individualised speech-in-noise tests, audiologists or clinicians can propose more specific and appropriate hearing prosthesis fitting suggestions for each individual with hearing loss.

5.4.1 Individual Results of the HAHA Group

In the NF condition, individual results indicated that 26 and 22% of participants with HAHA achieved statistically significant BR-HAR and BR-HAL, respectively, and no participants showed BR disadvantages. van Schoonhoven et al. (2016) also reported that even though some participants with HAHA fitting receive only little BR from the second HA in the NF, no disadvantage was observed. On the contrary, Walden and Walden (2005) reported that over 82% of participants performed worse with HAHA fitting than with monaural HA fitting. The difference in individual results among these studies may be due to the different noise type applied in the speech test. The babble noise used in the Walden and Walden's study involved informational masking and significant binaural interference, which were not introduced by the SSN used in the present study and van Schoonhoven et al.'s (2016) study. It should be noted that it is unclear what criterion was used in the previous study to classify the disadvantage of different device fitting conditions. For example, whether the authors used an unrealistic criterion set of 0 dB SNR; or they considered the test variability (i.e. all values within the *SD* or twice the *SD* were deemed equal), and the latter criteria can decrease the amount of participants performing binaural disadvantage.

In the condition where speech and noise were spatially separated, when a second HA was added closer to the noise, only a small proportion of participants in the HAHA group obtained binaural benefit, i.e. 13 and 4% of participants with HAHA achieved statistically significant SQ-HAR and SQ-HAL, respectively, which is in agreement with previous studies. Festen and Plomp (1986) reported that only 3 of 12 participants showed significant SQ; moreover, van Schoonhoven et al. (2016) identified that only 2 of 21 participants showed significant SQ.

In contrast, when a second HA was added contralateral to the direction of noise, all but four participants (HAHA-F8, HAHA-F11, HAHA-M8, and HAHA-M11) obtained the HS for at least one aided ear. Eight participants (35%) obtained the HS for both aided ears, and none of the participants obtained a HS disadvantage. When the aided ear is masked by noise, the SRiN performance is primarily determined by the contralateral ear that is at the shadow side with a higher SNR situation (Festen & Plomp, 1986). Thus, it is not surprising that the HS benefit was observed in several participants with the aided ear located contralateral to the noise.

For the SRM outcomes of participants in the HAHA group, most of the participants (13 of 23) with HAHA fitting achieved both non-significant FL-HAHA and FR-HAHA, which yielded non-significant group results for FL-HAHA and FR-HAHA. However, three participants (HAHA-F11, HAHA-F4, and HAHA-F12) still obtained significant results with SNR of 4.50-5.45 dB for FL-HAHA (Figure 39), and two participants (HAHA-M4 and HAHA-F2) obtained SNR of 3.95-6.50 dB for FR-HAHA (Figure 40). The magnitude of their SRM outcomes was close to the SRM values of their peers with NH, as obtained in a previous study (Yuen et al., 2019), thereby suggesting that these five participants (2.9-5.5 years old) with hearing loss can use spatial cues to develop SRM as young children with NH. From the individual results of BR (Figure 33 and Figure 34), SQ (Figure 35 and Figure 36), FR-HAL

(Figure 42), and FL-HAR (Figure 43), the participants (HAHA-F11, HAHA-F4, HAHA-F12, and HAHA-F2) obtained a positive HS for the monaural aided HA side, and better binaural contrast than most participants who obtained negative binaural contrast. These findings prove that these participants have better abilities than their peers in using binaural cues in the separated spatial condition to improve the SRM. Even though the individual results of HAHA-M4 showed a negative binaural contrast, HAHA-M4 achieved the best FR-HAL in the group. This result indicates that the better HS of the monaural HA side could compensate for the limited ability in processing binaural cues, which could also help in improving the SRM.

Individual results showed that 20 of the 23 participants with HAHA fitting in the present study could achieve at least one binaural benefit of BR, SQ, or HS related to the SRiN performance. However, one participant (HAHA-F11) could not achieve any significant binaural benefits. The individual results showed that HAHA-F11 had the best SRiN performance with monaural HA fitting in any noise direction; therefore, there could have been less room for improvement in the SRiN performance from binaural hearing condition, resulting in non-significant binaural benefits of BR, SQ, and HS. Two other participants (HAHA-F8 and HAHA-M8) achieved non-significant binaural benefits of BR and HS, and demonstrated a disadvantage of SQ when adding the second HA near the noise. The SRiN performance with monaural HA fitting (baseline result) of these two participants was not worse than that of other participants in the group. The possible reason for the non-significant BR and HS, and negative SQ benefits of these two participants may be the limited ability to combine and process binaural cues in the central auditory system, which needs to be further examined.

In the present study, the SRiN performance was measured in three fixed noise directions (NF, NL, and NR); however, in everyday listening environments, the sources of noise can be random and dynamic. The participants with HAHA fitting who could not obtain significant binaural benefits and SRM may encounter more difficulties in separating and understanding speech signal in noisy environments. For example, the individual results show that the participants (HAHA-F9 and HAHA-M6) with HAHA fitting could not obtain significant SRM with this fitting (Table 19). To achieve better SRiN performance for these children in educational environments (e.g. classrooms), children with HA fitting can consider using an FM or remote microphone system in combination with the HA. In certain previous studies, the researchers determined that the SNR level can be significantly improved by 10-20 dB when children with hearing loss used HA and FM systems together, which could help children to improve the SRiN performance (Boothroyd & Iglehart, 1998; Jacob et al., 2012; Lewis et al., 2004; Schafer & Thibodeau, 2006; Thibodeau & Schaper, 2014; Zanin & Rance, 2016). The FM system is useful when the teacher talks, but multiple microphones would be needed when a student asks (or answers) a question or the students are engaged in group work. However, it may not be the case in real educational environments due to the limitations of devices. Thus, replacing a HA with one CI may be another option for bilateral hearing aids users who have severe hearing loss and cannot obtain significant binaural and spatial benefits on SRiN performance. In addition to the improvement of SRiN performance, HAHA fitting is also beneficial for improving auditory localisation (Simon, 2005), sound quality, and spatial balance (Balfour & Hawkins, 1992; Cox, Robyn M. et al., 2011), and avoiding auditory deprivation (Gelfand & Silman, 1993; Hurley, 1999; Silman et al., 1984). Even though certain children with HAHA fitting were unable to obtain binaural or spatial advantages on SRiN performance, they may experience one or more of the other potential advantages. Thus, HAHA fitting is recommended as a default clinical practice.

5.4.2 Individual Results of the CIHA Group

The individual results showed that 33% of the participants with CIHA fitting achieved statistically significant BR-HAcon in the NF condition, suggesting that the binaural hearing condition of these participants can improve the representation of speech signal by combining redundancy information from both sides and/or using the complementary information from two different types of hearing prostheses. None of the participants showed negative BR-HAcon, revealing that none of the effects of adding the HA to the monaural CI fitting in the NF condition were harmful for all participants in the present study. These findings agree with those of previous studies that did not identify BR disadvantages in children with CIHA in comparison with those with monaural CI fitting in the NF condition (Ching et al., 2005; Holt et al., 2005; Mok et al., 2007; Mok et al., 2010). Other studies on adults (refer to Table 2) reported that a small portion of individuals with CIHA fitting showed negative BR when compared to the participants with monaural CI fitting (e.g. (Dunn et al., 2005; Illg et al., 2014; Morera et al., 2005; Morera et al., 2012). The children and adults in the previous studies had different demographic information, and these studies used different speech materials, noise types and procedures. Thus, it is difficult to compare the results of children with those of adults or to explain the different BR results between children and adults.

Modern CI technologies typically distort the fine timing and envelop information of the acoustic signals and only transform the envelope of the incoming acoustic sounds to electrical stimulation, resulting in a limited representation of phase information on the acoustic waveform. In contrast, HAs can preserve and transmit the fine timing information of acoustic signals, providing relatively intact temporal fine structure (Ching et al., 2005; Dincer D'Alessandro et al., 2015). Therefore, it is possible for individuals with CIHA fitting to extract temporal fine structure from the HA and timing envelop information from CI, and then combine the different timing cues in the respective devices for the SQ benefit in the speech recognition task. In the NHA condition, certain participants (13 of 33) obtained statistically significant SQ-HAcon, suggesting that these children did have the ability to integrate the good timing information provided by the HA and the poor timing information provided by the CI to improve the SRiN performance. For most of the participants (19 of 33) with absent SQ-HAcon, it is possible that different mechanical, electrical, and electronic parts in the HA and CI created a significant time delay and mismatch, which could preclude individuals with CIHA fitting from utilising the ITD cues to improve the SRiN performance (Ching et al., 2001; Ching et al., 2006b; Zirn et al., 2015; Zirn et al., 2018). One participant (CIHA-M5) showed a significant SQ-HAcon disadvantage. This result agrees with previous studies (Litovsky et al., 2006; Mok et al., 2007) (refer to Table 2), which also reported the disadvantage of adding a HA near the source of noise among children with CIHA fitting. Mok et al. (2006) stated that the mid-to-high-frequency information provided by the HA could conflict or interfere with the information provided by the HA, resulting in an adverse effect on the SRiN performance with CIHA fitting. In the present study, the aided threshold of the HA of CIHA-M5 was 30-35 at 1000-4000 Hz, which is significantly better (10-20 dB HL) than the average group results. Thus, the aided thresholds in the non-implanted ear may account for the non-significant BR and HS and negative SQ results of this participant. Additionally, in the NHA condition, CIHA-M5 with monaural CI fitting could focus on the input in the CI with a better SNR level, which was due to the HS of the monaural CI side. However, when adding the HA in the worse SNR level situation, the different SNR levels between the HA and CI sides were reduced. Thus, this can affect the selective attention to the CI side, resulting in worse SRiN performance of CIHA fitting than monaural CI fitting. Moreover, nearly half of the participants (13 of 33) with CIHA fitting also obtained significant HS-HAcon in the NCI condition, and no participants achieved a disadvantage of HS-HAcon. Adding a HA in the direction contralateral to the noise probably provided more audibility in this non-implanted ear than that with monaural CI fitting, which could combat noise and receive ILD cues to improve the SRiN performance.

Participant CIHA-M20 warrants a special discussion because his performance was significant. This participant achieved significant binaural benefits of BR-HAcon, SQ-HAcon, and HS-HAcon by adding the HA. One possibility is the difference in hearing thresholds (Appendix B) between HA and CI. The aided threshold of the HA is 5-15 dB HL better than that of the CI in the range of 250-4000 Hz, and the unaided threshold of the non-implanted ear has an upward-sloping trend that is better than 70 dB HL for over 2000 Hz. In addition, the participant with unaided fitting achieved four out of five correct perceptions of /s/ and /sh/, but only two out of five correct perceptions of /m/ and /u/ in the Ling Six Sound Check at a normal speaking level. These results indicate that the ear with the HA could provide more functional auditory stimuli than the ear with the CI. Moreover, the individual results of DA (Figure 53) showed that most of the participants had more DAs related to CI than HA for the SRiN performance; however, the data from CIHA-M20 showed that the HA is the dominant device in the CIHA fitting. This is a possible reason for the significantly positive SRM for FCI-CIHA and FCI-CI, but significantly negative FHA-CIHA and FHA-CI for this participant. The present study could not collect information on CI mapping details; therefore, it was also recommended that the parameters and settings of the CI, such as the setting of the T-levels in the CI map, could be examined for this participant.

The individual results also showed that 8 out of the 33 participants with CIHA could not obtain any significant binaural benefits in any noise direction. Amongst these eight participants, the aSNR-50% results of six participants (CIHA-F1, CIHA-F10, CIHA-F15, CIHA-M3, CIHA-M12, and CIHA-M16) with monaural CI fitting in all noise directions (refer to Figure 46 to Figure 48) were significantly better (approximately 4 dB SNR) than the average results of the remaining participants. Thus, these participants with CIHA fitting may have limited room to improve the SRiN performance by using the monaural CI fitting, resulting in non-significant binaural benefits of BR, SQ, and HS. Other participants (CIHA-F11 and CIHA-M7) may not have been able to integrate the acoustic and electric input from respective devices in the central processing system, resulting in non-significant binaural benefits. The limited processing of binaural information can also restrict the participants in utilising ITD and ILD cues in the separated spatial conditions. For example, when the noise moved from the front to the side with the HA, CIHA-F1 also performed significantly negative SRM.

As in the previous discussion, when the primary goals are to improve the SNR level and SRiN performance of children in educational environments, an FM system or a remote microphone in addition to the CI and HA should be recommended prior to replacing the HA with the second CI for the participants with CIHA fitting who cannot achieve significant binaural and spatial benefits. In a meta-analysis comparing binaural benefits for the SRiN performance of the children and adults with CICI or CIHA fitting (Schafer et al., 2011), the researchers identified that the individuals with CICI fitting achieved all binaural benefits including BR, SQ and HS; however, the individuals with only CIHA fitting achieved BR and HS; the obtained size of SQ and HS with CICI fitting (0.37 and 1.26, the number of studies is 23 and 20, respectively) was higher than with CIHA fitting (0.16 and 0.69, the number of studies is 8 and 10, respectively). However, considering the marginal advantage in the SRiN performance with CICI fitting over that with the CIHA fitting, the CIHA fitting may be a first-order appropriate arrangement for the non-implanted ear of children with bilateral hearing loss using a single CI. If the individual prefers to implant the second CI on the non-implanted ear, the SRiN performance with CIHA fitting can also offer a baseline for future evaluation.

5.5 Audibility and SRiN Performance

According to the definition by Erber (1982) of the hierarchy of listening skills, if speech signal cannot be detected, they cannot be recognized. SII provides a method to quantify the audibility of speech signal (ANSI, 1997). Compared to the common clinical measure of four-frequency average pure-tone threshold, SII calculation involves FIF of the specified speech signal in individual frequency regions. Even though the threshold can describe the hearing sensitivity of pure-tone signals, individuals with the same threshold may have different SII, resulting in receiving varying amounts of useful speech information. Therefore, the present study applied the SII of the monaural aided ear to represent aided audibility. This section discusses the comparison between the SII and SRiN performance of participants.

5.5.1 SII and SRiN Performance of the HAHA Group

The results revealed a monotonic improvement in the SRiN performance of the participants with HAL and HAHA fitting in all noise directions (NF-HAL, NL-HAL, NR-HAL NF-HAHA, NL-HAHA, and NR-HAHA), with increasing aided audibility of HAL (SII-HAL). Similarly, the SRiN performance of participants with HAR in all noise directions (NF-HAR, NL-HAR, NR-HAR) and with HAHA fitting in the NL and NR directions (NL-HAHA, and NR-HAHA) were better with increasing aided audibility of HAR (SII-HAR) (refer to Table 25). The data in the present study suggest that the SII of HA (audibility of individual aided ear) performs a significant role in the SRiN performance, which supports the hypothesis that the aided SII obtained from the monaural HA fitting can predict the SRiN performance of the participants. These results are also in agreement with those of previous studies (McCreery et al., 2015; McCreery et al., 2019). These previous researchers investigated the effect of aided audibility on speech recognition in degraded environments, such as in steady-state speech-shaped noise and in noise with a simulation of 600 ms of reverberation time. They identified that children with better aided SII of HA demonstrated better speech recognition. In real life, consideration of problems with loudness discomfort, most HA fitting rationales only compensate a portion (about half) of the audiogram. Hence, the reduced audibility for individuals with hearing loss is only partially compensated for by amplifying sounds from the HA. Since the speech has a lot of redundant information, it is enough for the participants with HA fitting to understand it, even though they can only hear parts of speech signal instead of all components/details of speech signal. However, when a noise signal is added, speech redundancies become important for understanding speech in the noise. Therefore, the participants with better SII can hear more useful speech information that are above their aided hearing threshold. However, it is noticed that the SII of monaural HA fitting can explain the 20-48% difference in the SRiN performance of the participants in the different noise conditions (refer to Table 25), suggesting that other factors may also contribute to the SRiN performance. Bost et al. (2019) determined that when signals are audible to the listener, as in the case of individuals with NH or HA fitting, suprathreshold factors, including cognitive and linguistic abilities, also perform an important role in the processing that transforms the available signals into a meaningful message in a challenging listening environment, such as speech in noise. In addition, the separation of speech signal from the noise requires cognitive skills such as attention to direct focus and suppression of noise (Carlile & Corkhill, 2015; Jones, P. R. et al., 2015), and the ability to hold information in short-term memory for lexical recognition (Francis, 2010; Rönnberg et al., 2010). Moreover, linguistic factors, including lexical, semantic, and syntactic contexts, facilitate word and phoneme recognition, and the SRiN performance of children can be affected by the development of linguistic abilities, including vocabulary knowledge, phonemic categorisation, and language competency (Boothroyd, 1970; Eisenberg et al., 2002; Nittrouer & Boothroyd, 1990). Ching et al. (2018) also reported that both cognitive and language abilities are significant predictors of the SRiN performance of children with HA fitting, but the aided audibility was not a significant predictor after considering demographic and language factors. Certain reviews (Akeroyd, 2008; Ching & Harvey, 2013; Loughrey et al., 2018) identified a significant relationship between cognitive function and speech recognition performance, especially in the elderly population; however, the effect of cognitive ability was weaker than that of audibility. For relationships between these factors and the SRiN performance, certain researchers have demonstrated that audibility can directly affect SRiN and reverberation, because audibility has direct effects on the access of an individual to acoustic signals; moreover, audibility also had cumulative effects on the long-term language development of an individual that is related to SRiN and reverberation (McCreery et al., 2015, 2017, 2019; Tomblin et al., 2014, 2015; Walker et al., 2019). Thus, the effect of audibility on SRiN and reverberation was direct and mediated by the relationship between audibility and language ability. In the present study, the closed-set material was used to measure the SRiN performance, which can minimise the effects of vocabulary knowledge and language ability on the speech recognition performance. Thus, the measurement can disambiguate the complex relationships between the factors of audibility and language ability, and the findings support the fact that a better aided SII of the HA can immediately promote the SRiN performance. further examinations are required to investigate whether the mediating effects of linguistic and cognitive factors can contribute to explaining the additional variance in SRiN performance.

5.5.2 SII and SRiN Performance of the CIHA Group

Data in the present study show that SII of only CI (SII-CI) cannot predict the SRiN performance (NF-CIHA, NHA-CIHA, NCI-CIHA, NF-CI, NHA-CI, and NCI-CI) of participants in the CIHA group, irrespective of the direction of the noise source. This finding supports the results of a recent study (Lee et al., 2019). The researchers calculated the SII to investigate whether it can be applied for predicting the SRiN performance of post-lingually deafened adults with CI fitting. They determined that the perception scores in a noisy environment for participants with CI fitting were considerably below the TF curve developed for the individuals with NH (RMSE denotes the root-mean-square error between the data points and TF curve is 0.341); therefore, the SII of CI alone cannot predict the SRiN performance. Then, these researchers developed a new SII model for the participants with CI fitting, thereby incorporating demographic variables and measurable capabilities as predictive factors (i.e. cognitive skill, temporal resolution, duration of hearing loss, and aided audibility), which improved the accuracy of SII prediction in individuals with CI fitting (RMSE = 0.058). In the present study, the SII-CI values were consistently high across all participants with CIHA fitting (M=0.86, SD=0.01); however, the SRiN performance showed large individual variability among the participants. The results suggest that auditory factors other than audibility and non-auditory factors may contribute to the variance. Many previous studies of CI recipients reported that spectral and temporal aspects of auditory processing ability were related to speech recognition performance (Gifford et al., 2018; Gnansia et al., 2014; Jones, G. L. et al., 2013; Nie et al., 2006; Xu & Zheng, 2007). In addition to auditory processing factors, other demographic and non-auditory factors, including age at CI implantation, duration of hearing loss, communication mode, language ability, and cognitive function, could contribute to the obvious variances in speech recognition performance among children (Ching et al., 2018; MacCutcheon et al., 2019; Pisoni et al., 1999; Schafer & Utrup, 2016) and adults (Blamey et al., 2013; Holden et al., 2013; Lazard et al., 2012) with CI fitting.

The SII of the ear with HA fixed in a direction contralateral to the CI side (SII-HAcon) could not predict the SRiN performance of participants with CIHA fitting (NF-CIHA, NHA-CIHA, and NCI-CIHA). When compared to the audibility of the CI side, SII-HAcon was quite low (*M*=0.19, *SD*=0.15), and provided inadequate functional hearing and speech recognition performance for the participants. One possible reason is that the cochlear implantation criteria in mainland China are stringent, which requires individuals to have severe to profound hearing loss in both ears (Editorial Board of Chinese Journal of Otorhinolaryngology Head and Neck Surgery et al., 2014). Additionally, the Chinese government provides financial support for a single CI for each child (CRRCHSI, 2012). These policies result in most Mandarin Chinese-speaking children obtaining a monaural CI fitting with limited residual hearing in the non-implanted ear. Therefore, the contribution of the aided HA to the SRiN performance could be limited by the poorly aided SII of the HA. Moreover, the results of the present study showed that SII-HAcon significantly contributed to the binaural benefits of BR-HAcon and SQ-HAcon. These findings are in line with those previously reported (Tao et al., 2018) that the residual hearing at low frequencies (i.e. 125 and 250 Hz) of the non-implanted ear could contribute to the binaural benefits for the speech recognition task, suggesting that individuals with CIHA fitting primarily used the F0-related low-frequency acoustic information to improve the SRiN performance. Another previous study (Dorman et al., 2014) used an external signal processor to determine the level of acoustic and electrical signals and directly delivered stimulation to the participant to investigate the function of binaural benefit and the level of acoustic signals in the non-implanted ear. They determined that even though the level of acoustic signals was significantly softer than that at the CI side, it could contribute to binaural benefits. When the level of acoustic signals was balanced to that at the CI side, it provided the most binaural benefits for the SRiN performance. Furthermore, the present study identified that SII-HAcon was not a significant predictor of HS-HAcon. This could be caused by the limited aided audibility of the HA at high frequencies. The current HA cannot provide sufficient gain (aided audibility) at high frequencies (Dillon, 2001; Moore, et al., 2001; Wolfe et al., 2011), and SII-HAcon in the present study primarily depended on the aided audibility at low frequencies. However, the head primarily blocks and attenuates high-frequency sounds with short wavelengths; consequently, the ILD cues and HS are significant at high frequencies (Litovsky, 2012; Van Hoesel, 2012). Thus, it is difficult to predict the HS-HAcon that is relative to the high-frequency sounds using the SII-HAcon, which is primarily caused by the low-frequency amplification. In general, if individuals with severe to profound bilateral hearing loss only receive HAs, the SII for those HA-aided ears could be limited in terms of their SRiN performance. However, if these individuals receive monaural CI fitting, the aided audibility of HA on the non-implanted ear could provide complementary acoustic information for the CI side and perform an important role in the binaural benefits of the SRiN performance.

5.6 Implications

The findings in the present study related to young children with HA or CI fittings have multiple implications for experimental and clinical audiology. This study overcomes the substantial limitations of previous studies. First, from the summary of previous studies that investigated the SRiN performance of individuals with HAHA and CIHA fittings (refer to Tables 1, 2, and 3), it can be noted that most participants were adults and school-age children, probably because of the limitations of reliably available speech-in-noise testing materials and procedures for young children. This study used a Mandarin Spoken Word-Picture Identification Test (Adaptive version) (MAPID-A) to measure the SRiN performance of Mandarin Chinese-speaking children at a much younger age with HAHA fitting (*M* = 4.4 years old, range: 2.9-7.5 years old) and CIHA fitting (*M* = 4.6 years old, range: 3.1-6.6 years old). The MAPID-A can provide a standardised, reliable, and valid speech-in-noise test with an adaptive procedure for native Mandarin Chinese-speaking children who are over three years old, which is a better tool for examining individual differences in the SRiN performance when compared to other materials that yield near basal or ceiling levels in terms of the SRiN performance. Second, certain studies did not measure the SRiN performance of individuals with binaural and monaural hearing condition in conditions with multiple sources of noise from different directions (i.e. only measured in the NF condition). This study may be the first study to measure the SRiN performance of young children with hearing loss in many different fitting and noise conditions in such an exhaustive way. Third, most studies reported group results of binaural benefits and SRM with error estimates; however, only a few studies reported individual results with error estimates. The present study on children with HAHA and CIHA fittings may be the first study that not only reported group results, but also individual results with error estimates based on intra-participant comparison. The intra-participant statistical evaluation of the binaural benefits and SRM for individuals with hearing loss can provide personalised counselling for future hearing protheses or aided listening device fitting recommendations. For example, if the HAHA fitting cannot offer binaural benefits or SRM, the monaural HA fitting can offer better SRiN performance in at least certain conditions (e.g. noise and speech are separated and the noise is near the unaided side). If individuals listening in binaural hearing condition cannot obtain significant binaural benefits or SRM, they can consider changing the noise reduction technologies in devices (e.g. directional microphone), combine the FM system or remote microphone with the devices, or replace a HA with one CI. In addition, by considering the variable SRiN performance in children with hearing loss, it is not possible to estimate the SRiN performance of individuals with reference data from a control group. The intra-participant comparison can use the performance of an individual as the baseline to sensitively investigate any subtle SRiN changes in each individual when using new processing settings or hearing prosthesis. Therefore, the individual results from the intra-participant statistical evaluation can help clinicians and audiologists to feasibly and effectively identify preschool children who may be at risk of difficulty listening to speech in advertise situations, such as future noisy environments in the school, and then help them through counselling and providing appropriate hearing rehabilitation approaches for each child. Fourth, excluding very few participants who could not obtain binaural benefits listening in binaural hearing condition, the results of the present study suggest that binaural hearing condition is beneficial for most participants to improve the SRiN performance. Thus, binaural hearing condition is important to provide potential binaural and spatial advantages for SRiN performance and should be recommended as a default for children with bilateral hearing loss in clinical practice. Moreover, aided audibility through the HA affects the SRiN performance of children with HAHA fitting and in the binaural benefits of the children with CIHA fitting, even though residual hearing is limited. Thus, the aided SII measurement of the HA can be an important part of clinical verification. In general, the main contribution of the thesis is the completeness of the provided data set that has not been provided before, the validation of a novel speech test in Mandarin Chinese that can be used with young children in clinical applications, and the provided evidence that this speech test is sensitive to reveal even small individual effects/benefits of hearing devices, SRM, and binaural hearing. For the Mandarin Chinese-speaking population, there exist very few other tests that allow reliable assessment of young preschool-age children, even though it is probably one of the most important ages for impactful hearing assessments. Hence, the present study is important and it makes an original contribution to the knowledge of the subject with which it deals.

5.7 Limitations and Directions for Future Study

The present study has several limitations with regard to the research scope and methodology. It should be acknowledged that some children were excluded from the present study in the Section 3.1. It is possibility that these children who refused to finish the test for other reasons (e.g., a dislike of the speech recognition when listening in noise) may also have led to decreased binaural benefits if it had been possible to complete the speech-in-noise test of these children. Moreover, the present study focused on evaluating the SRiN performance of children with HAHA and CIHA fittings, but it was not designed to evaluate the effects of the parameters in HA and CI other than audibility on the SRiN performance. Thus, the speech-in-noise test was conducted with children using their HA and CI at their daily usage settings and were not manipulated during the testing procedure, which was already clarified in the Section 3.1. However, individually different parameters in HA (e.g. compression mode and noise reduction) or CI (e.g. coding strategies) among the participants may contribute to differences in the SRiN performance. In particular any directional microphone processing (fixed and/or adaptive) can effect on the SRiN performance in the spatially separated test condition, and thus the SRM, so future studies should manipulate these parameters to address this question. Moreover, the present study used the SSN task, and it is unclear how the present laboratory measures reflect real-world experience and benefits of individuals with hearing devices. Thus, future studies can address this issue by applying more realistic measurements (or an ecologically valid assessment) in the laboratory, such as a speech test in a multiple-talker babble noise. In addition, the present study investigated the relationship between aided audibility and the SRiN performance in children with hearing loss. The results show that the aided SII cannot fully explain the variances in SRiN performance. Thus, future studies should measure suprathreshold auditory processing and non-auditory factors, such as spectral and temporal processing abilities, linguistic development, and cognitive function, to examine whether these factors contribute to the remaining variability in the SRiN performance of children with hearing loss.

5.8 Conclusions

The present study primarily aimed to evaluate the SRiN performance of preschool children with monaural and binaural hearing condition. Children with HAHA fitting demonstrated significant binaural benefits of BR-HAR, HS-HAR, and HS-HAL related to the SRiN performance. However, they could not achieve significant SRM with HAHA fitting in spatially separated speech and noise conditions. Children with CIHA fitting demonstrated significant binaural benefits of BR-HAcon, SQ-HAcon, and HS-HAcon. Furthermore, they achieved significant SRM only when the noise moved from the front to the HA side, even though the magnitude of the SRM was lower than that of their peers with NH. Intra-participant comparison explicitly showed significant individual variability in the SRiN performance across children in the present study. Most participants in the HAHA and CIHA groups achieved at least one significant binaural benefit, whereas some demonstrated non-significant binaural benefits, and one participant even obtained significantly negative binaural benefits. The findings suggest that children with bilateral hearing loss should receive binaural hearing condition to obtain potential binaural and spatial advantages on SRiN performance. Even though certain unknown factors may account for variances in the SRiN performance of children with hearing loss, aided audibility of monaural HA fitting (SII-HAL and SII-HAR) in the HAHA group can significantly contribute to explaining the 20-48% of the variances in the SRiN performance under different noise conditions. Neither the aided audibility of monaural CI (SII-CI) or HA (SII-HAcon) could contribute to the SRiN performance in any noise direction of participants in the CIHA group. However, SII-HAcon performed an important role in the binaural benefits of BR-HAcon and SQ-HAcon. The empirical evidence in the present study encourages clinicians and audiologists to evaluate the SRiN performance of individual clients using the validated objective SRiN measure, i.e. MAPID-A. The speech-in-noise test can help teachers and parents understand the SRiN performance of young children with hearing loss in educational environments, and it can provide empirical evidence for clinicians and audiologists for future clinical services and counselling.

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Appendix A

Demography Data Collection

Table A1 ***Demographic Information of Participants in the HAHA group***.

Participant	Gender	Age (y; m)	Newborn hearing screening	Age at diagnosis of deafness (y; m)	Etiology	Age at HA fitting (y; m)		HA type		Duration of HAHA use (y; m)
						L	R	L	R	
HAHA-F1	F	4; 3	Failed	0; 6	Unknown	2; 6	2; 6	Unitron Quantum 2 HP	Unitron Quantum 2 HP	1; 6
HAHA-F2	F	2; 9	Unknown	0; 8	Otitis media	0; 11	0; 11	Phonak Bolero Q70-M13	Phonak Bolero Q70-M13	1; 10
HAHA-F3	F	4; 1	Failed	1; 6	Unknown	2; 1	2; 1	Phonak Naida S V SP	Phonak Naida S V SP	2; 0
HAHA-F4	F	5; 5	Failed	0; 1.5	GJ B2 mutation	3; 11	3; 11	Unitron Max 20 SPm	Unitron Max 20 SPm	1; 6
HAHA-F7	F	4; 9	Failed	0; 1.5	GJ B2 mutation	4; 3	4; 3	Oticon Safari 300 SP	Oticon Safari 300 SP	0; 7
HAHA-F8	F	3; 6	Failed	2; 0	Hereditary	2; 1	2; 1	Phonak sky Q90 SP	Phonak sky Q90 SP	1; 4
HAHA-F9	F	4; 0	Failed	0; 2	Unknown	1; 3	1; 3	Starkey Muse i2400 BTE 13	Starkey Muse i2400 BTE 13	2; 8
HAHA-F11	F	4; 10	Pass	2; 6	Otitis media	2; 6	2; 6	Oticon Safari 300P	Oticon Safari 300P	2; 4
HAHA-F12	F	3; 7	Failed	2; 0	Unknown	2; 1	2; 1	Phonak Bolero Q70 P	Phonak Bolero Q70 P	1; 6
HAHA-F13	F	3; 10	Failed	2; 11	Unknown	2; 11	2; 11	Widex D-FA 330	Widex D-FA 330	0; 11
HAHA-M1	M	4; 9	Failed	0; 4	LVAS	2; 6	2; 6	Oticon Safari 600 SP	Oticon Safari 600 SP	2; 3
HAHA-M2	M	4; 0	Failed	2; 7	Unknown	2; 8	2; 8	ReSound LiNX DW-777	ReSound LiNX DW-777	1; 4
HAHA-M4	M	3; 6	Failed	2; 7	Unknown	2; 7	2; 7	Widex D-FA 220	Widex D-FA P 220	0; 11
HAHA-M5	M	3; 5	Unknown	2; 8	Unknown	2; 8	2; 8	Oticon Safari 300 SP	Oticon Safari 300 SP	0; 9
HAHA-M6	M	4; 9	Failed	2; 6	Unknown	3; 0	3; 0	Starkey Muse i2400 mini BTE 312	Starkey Muse i2400 mini BTE 313	1; 9
HAHA-M7	M	3; 8	Pass	2; 8	Mondini deformity	2; 8	2; 8	Oticon Safari 300 SP	Oticon Safari 300 SP	1; 0
HAHA-M8	M	5; 10	Unknown	1; 10	Otitis media	3; 10	3; 10	Oticon Safari 300 SP	Oticon Safari 300 SP	2; 0
HAHA-M9	M	3; 3	Failed	0; 8	GJ B2 mutation	2; 9	2; 9	Resound Enya EY288-DW	Resound Enya EY288-DW	0; 7

HAHA-M10	M	5; 1	Pass	4; 6	LVAS	4; 7	4; 7	Resound Verso VO988-DW HP	Resound Verso VO988-DW HP	0; 7
HAHA-M11	M	4; 7	Unknown	2; 5	Otitis media	3; 4	3; 7	Widex D-FA 330	Widex D-FA 330	1; 0
HAHA-M12	M	6; 4	Pass	5; 4	Unknown	5; 4	5; 4	Widex D-FA P 330	Widex D-FA P 330	1; 0
HAHA-M13	M	7; 5	Unknown	6; 0	Unknown	6; 9	6; 9	Phonak Naida S IX SP	Phonak Naida S IX SP	0; 8
HAHA-M14	M	5; 1	Failed	3; 6	Unknown	3; 6	3; 6	Widex D-FS 330	Widex D-FS 330	1; 6

Note. F= Female; L = left ear; LVAS = large vestibular aqueduct syndrome; M = Male; R = right ear; Y = yes; y; m = year and month;

Table A2 ***Demographic Information of Participants in the CIHA group.***

Participant	Gender	Age (y; m)	Newborn hearing screening	Age at diagnosis of deafness (y; m)	Etiology	Pre-operation HA fitting: side	Pre-operation HA fitting: duration ≥ 0; 6	Duration of CI use (y; m)	Post-operation CIHA fitting: Onset of contralateral HA fitting (y; m)	HA side	HA type	CI side	CI processor	Duration of CIHA use (y; m)
CIHA-F1	F	5; 0	Unknown	2; 6	LVAS	L	Y	1; 10	0; 3 post-operation	L	Resound MA1T70-V	R	N5	1; 7
CIHA-F2	F	4; 2	Unknown	1; 10	Unknown	BI	Y	1; 6	0; 6 post-operation	L	Resound Alera-477	R	N6	1; 0
CIHA-F3	F	4; 6	Unknown	2; 4	Unknown	BI	Y	1; 6	0; 3 post-operation	L	Unitron Max 20 SP	R	N6	1; 3
CIHA-F4	F	4; 10	Failed	0; 1.5	Unknown	BI	Y	0; 9	0; 3 post-operation	L	Unitron Max E SP	R	Opus 2	0; 6
CIHA-F5	F	3; 10	Unknown	1; 10	Unknown	R	Y	1; 3	0; 3 post-operation	R	Phonak Naida S V SP	L	N6	1; 0
CIHA-F6	F	3; 6	Failed	0; 6	Hereditary	BI	Y	1; 8	0; 6 post-operation	L	Unitron Max 6 SP	R	N6	1; 2
CIHA-F7	F	6; 2	Unknown	2; 10	Unknown	BI	Y	0; 8	0; 2 post-operation	L	Starkey EXP16 PP	R	N5	0; 6
CIHA-F8	F	3; 11	Failed	0; 10	LVAS	BI	Y	0; 6	Simultaneously	R	SIEMENS pure carat 701	L	N6	0; 6
CIHA-F9	F	6; 6	Unknown	2; 6	Unknown	L	Y	3; 0	2; 0 post-operation	L	Widex Camisha	R	N5	1; 0
CIHA-F10	F	4; 8	Unknown	2; 0	Unknown	BI	Y	1; 4	0; 8 post-operation	L	Rexton Accord HP	R	N6	0; 8
CIHA-F11	F	3; 6	Failed	0; 1.5	Unknown	BI	Y	2; 1	0; 3 post-operation	L	Phonak sky Q70 SP	R	Neptune	1; 10
CIHA-F12	F	5; 1	Unknown	3; 0	Unknown	NA	NA	2; 0	1; 6 post-operation	L	Widex D-FA 330	R	Freedom	0; 6
CIHA-F14	F	3; 10	Failed	0; 1.5	Unknown	BI	Y	0; 7	Simultaneously	L	Phonak Naida S V SP	R	N6	0; 7
CIHA-F15	F	5; 0	Failed	0; 1.5	Unknown	BI	Y	1; 0	Simultaneously	L	WEDEX SV-38	R	N5	1; 0
CIHA-M1	M	5; 4	Pass	1; 6	LVAS	BI	Y	2; 6	1; 0 post-operation	L	Unitron Max 6 SP	R	Opus 2	1; 6

CIHA-M2	M	4; 8	Unknown	2; 6	Unknown	NA	NA	1; 0	0; 6 post-operation	L	Widex Bravissmo	R	N6	0; 6
CIHA-M3	M	5; 5	Unknown	2; 6	Unknown	R	0; 3	1; 9	0; 6 post-operation	L	SIEMENS -pure carat 701	R	Freedom	1; 3
CIHA-M4	M	4; 11	Failed	1; 9	Hereditary	BI	0; 4	2; 0	0; 6 post-operation	L	Phonak Naida Q90 UP	R	N5	1; 6
CIHA-M5	M	5; 3	Pass	1; 6	Unknown	BI	Y	2; 6	1; 0 post-operation	R	Phonak Naida V UP Jr	L	Opus 2	1; 6
CIHA-M6	M	5; 4	Unknown	2; 3	Unknown	NA	NA	2; 0	1; 0 post-operation	L	Phonak Naida Q90 UP	R	Freedom	1; 0
CIHA-M7	M	4; 1	Failed	0; 10	Unknown	NA	NA	2; 0	0; 4 post-operation	L	Widex D-FS 220	R	Freedom	1; 8
CIHA-M8	M	5; 3	Unknown	2; 8	Unknown	R	0; 3	1; 9	0; 3 post-operation	L	Lisound KHAN 88	R	Freedom	1; 6
CIHA-M10	M	4; 8	Unknown	2; 7	Unknown	BI	Y	0; 9	0; 6 post-operation	R	SIEMENS -pure carat 701	L	Opus 2	0; 3
CIHA-M12	M	3; 5	Failed	2; 0	Unknown	BI	Y	0; 9	0; 3 post-operation	L	Widex D-FA P 330	R	Opus 2	0; 6
CIHA-M13	M	4; 1	Failed	1; 6	Unknown	BI	Y	2; 0	0; 6 post-operation	R	Unitron Max 6 SP	L	N5	1; 6
CIHA-M15	M	5; 6	Failed	1; 7	Unknown	BI	Y	2; 6	1; 0 post-operation	R	Widex M2-19	L	Opus 1	1; 6
CIHA-M16	M	4; 10	Unknown	2; 6	Unknown	BI	Y	1; 4	0; 3 post-operation	R	SIEMENS-Motion P	L	N6	1; 1
CIHA-M17	M	5; 10	Pass	4; 3	Unknown	BI	Y	0; 7	Simultaneously	L	Widex D-FA P 220	R	Neptune	0; 7
CIHA-M18	M	3; 11	Failed	0; 1.5	Mondini deformity	BI	0; 3	1; 11	0; 3 post-operation	L	Unitron Max 20 SP	R	Opus 2 xs	1; 8
CIHA-M19	M	4; 3	Unknown	1; 2	Unknown	BI	Y	2; 2	1; 6 post-operation	R	Oticon Safari SP	L	N5	0; 8
CIHA-M20	M	4; 8	Failed	0; 2	Mondini deformity	R	Y	1; 9	0; 3 post-operation	R	Phonak sky Q90 SP	L	Freedom	1; 6
CIHA-M21	M	5; 6	Unknown	2; 7	Unknown	NA	NA	2; 6	2; 3 post-operation	L	Phonak sky Q90 UP	R	NSP-60B	0; 3
CIHA-M22	M	3; 6	Pass	2; 6	LVAS	BI	0; 4	0; 6	0; 1 post-operation	L	Widex D-FA P 330	R	N6	0; 5

Note. BI = binaural ears; F= Female; L = left ear; LVAS = large vestibular aqueduct syndrome; M = Male; NA = not applicable; R = right ear; Y = yes; y; m = year and month;

Appendix B

Pure-tone Threshold Data Collection

Table B1 ***Audiometric Thresholds (dB HL) of Participants in the HAHA Group***

Participant	Ear		Frequency (Hz)					
			250	500	1000	2000	4000	8000
HAHA-F1	L	unaided	70	65	75	80	70	75
		HA	30	30	35	30	30	NA
	R	unaided	70	75	75	75	65	70
		HA	20	35	35	35	35	NA
HAHA-F2	L	unaided	90	85	80	75	75	80
		HA	35	30	35	35	45	NA
	R	unaided	90	85	85	70	80	85
		HA	35	30	25	40	40	NA
HAHA-F3	L	unaided	80	75	85	80	80	85
		HA	60	35	35	40	35	NA
	R	unaided	90	85	80	95	95	100
		HA	70	45	40	40	45	NA
HAHA-F4	L	unaided	85	90	95	95	85	95
		HA	40	40	40	45	45	NA
	R	unaided	75	70	80	75	65	80
		HA	40	30	45	40	40	NA
HAHA-F7	L	unaided	75	70	60	50	50	55
		HA	45	35	30	35	35	NA
	R	unaided	70	70	65	60	65	70
		HA	45	35	35	40	45	NA
HAHA-F8	L	unaided	85	85	85	80	70	70
		HA	30	30	35	45	30	NA
	R	unaided	80	65	75	70	70	70
		HA	35	25	35	40	35	NA
HAHA-F9	L	unaided	85	85	90	100	85	100
		HA	65	75	30	40	45	NA
	R	unaided	80	80	85	85	85	100
		HA	65	45	40	45	55	NA
HAHA-F11	L	unaided	50	35	25	20	30	105
		HA	30	15	10	15	20	NA
	R	unaided	40	35	20	35	40	105
		HA	25	15	10	15	15	NA
HAHA-F12	L	unaided	55	75	75	75	75	95
		HA	35	35	25	40	45	NA
	R	unaided	55	50	55	70	60	60
		HA	50	40	25	40	40	NA
HAHA-F13	L	unaided	55	60	60	65	65	75
		HA	25	20	25	20	25	NA
	R	unaided	75	75	85	80	90	85
		HA	30	35	40	35	35	NA
HAHA-M1	L	unaided	70	75	90	85	75	85
		HA	30	35	35	30	30	NA
	R	unaided	60	65	65	75	75	85
		HA	25	35	35	40	40	NA
HAHA-M2	L	unaided	65	80	85	110	120	105
		HA	35	45	45	50	80	NA

	R	unaided	85	100	100	105	110	105
		HA	35	50	50	50	70	NA
HAHA-M4	L	unaided	85	100	110	120	120	105
		HA	45	45	50	60	60	NA
	R	unaided	65	65	70	80	105	105
		HA	35	35	45	45	50	NA
HAHA-M5	L	unaided	50	60	75	70	75	85
		HA	30	35	35	40	40	NA
	R	unaided	85	85	85	70	75	75
		HA	40	45	45	40	45	NA
HAHA-M6	L	unaided	75	85	85	80	75	85
		HA	35	45	45	50	50	NA
	R	unaided	85	80	85	85	80	90
		HA	30	30	35	50	40	NA
HAHA-M7	L	unaided	70	80	100	110	120	105
		HA	40	35	55	80	80	NA
	R	unaided	75	65	75	80	80	85
		HA	40	30	35	40	60	NA
HAHA-M8	L	unaided	100	100	85	75	70	80
		HA	45	40	30	40	40	NA
	R	unaided	70	85	85	75	50	55
		HA	30	35	40	35	40	NA
HAHA-M9	L	unaided	60	60	80	70	80	85
		HA	35	30	30	35	35	NA
	R	unaided	55	65	65	75	75	80
		HA	40	35	35	35	35	NA
HAHA-M10	L	unaided	90	85	85	95	100	105
		HA	45	35	25	40	50	NA
	R	unaided	65	55	55	95	100	105
		HA	40	30	25	40	45	NA
HAHA-M11	L	unaided	50	45	55	55	45	55
		HA	35	15	15	20	20	NA
	R	unaided	65	55	50	50	55	65
		HA	40	25	25	25	20	NA
HAHA-M12	L	unaided	60	60	70	85	115	105
		HA	30	30	30	35	35	NA
	R	unaided	100	125	115	125	125	105
		HA	45	50	45	55	55	NA
HAHA-M13	L	unaided	65	80	105	125	125	105
		HA	50	50	70	80	80	NA
	R	unaided	55	70	100	120	105	105
		HA	40	40	60	60	60	NA
HAHA-M14	L	unaided	50	55	75	80	110	105
		HA	15	30	25	25	35	NA
	R	unaided	55	70	80	85	100	105
		HA	20	30	20	25	40	NA

Note. HA = hearing aid; L = left; R = right; NA = not applicable. Maximum output level for unaided thresholds is 100 dB HL at 250 Hz and 8000 Hz, and 120 dB HL at 500-4000 Hz. Maximum output level for aided thresholds is 65 dB HL at 250 Hz and 8000 Hz; 70 dB HL at 500 Hz; 75 dB HL at 1000-4000 Hz.

Table B2 ***Audiometric Thresholds (dB HL) of Participants in CIHA Group***

Participant	Ear		Frequency (Hz)					
			250	500	1000	2000	4000	8000
CIHA-F1	L	unaided	90	90	90	90	110	105
		HA	40	35	30	50	55	NA
	R	unaided	90	105	105	105	125	105
		CI	15	30	20	25	25	70
CIHA-F2	L	unaided	100	125	115	125	125	105
		HA	70	75	55	80	80	NA
	R	unaided	105	115	125	125	125	105
		CI	10	25	20	25	15	20
CIHA-F3	L	unaided	80	90	95	105	110	105
		HA	40	40	50	50	50	NA
	R	unaided	95	105	115	125	125	105
		CI	25	35	30	30	30	35
CIHA-F4	L	unaided	100	105	115	125	125	105
		HA	35	45	35	45	50	NA
	R	unaided	90	115	125	125	125	105
		CI	20	30	30	40	35	35
CIHA-F5	L	unaided	105	125	125	125	125	105
		CI	35	30	15	20	25	25
	R	unaided	105	115	115	120	120	105
		HA	65	60	55	75	80	NA
CIHA-F6	L	unaided	100	110	120	125	125	105
		HA	40	45	50	80	80	NA
	R	unaided	95	115	125	125	125	105
		CI	10	20	25	25	20	25
CIHA-F7	L	unaided	70	70	100	110	115	105
		HA	55	40	50	55	70	NA
	R	unaided	95	105	115	125	125	105
		CI	30	30	30	25	30	45
CIHA-F8	L	unaided	105	110	115	115	125	105
		CI	35	25	30	35	35	30
	R	unaided	100	90	90	110	125	105
		HA	45	35	30	65	80	NA
CIHA-F9	L	unaided	105	105	110	120	115	105
		HA	50	50	40	60	80	NA
	R	unaided	105	125	125	125	125	105
		CI	35	30	30	30	25	50
CIHA-F10	L	unaided	75	110	105	110	110	105
		HA	45	45	40	55	80	NA
	R	unaided	95	115	125	125	125	105
		CI	35	25	25	35	30	35
CIHA-F11	L	unaided	75	80	90	120	125	105
		HA	35	25	30	80	80	NA
	R	unaided	105	125	125	125	125	105
		CI	40	40	35	40	40	25
CIHA-F12	L	unaided	105	115	120	120	125	105
		HA	55	55	40	55	45	NA
	R	unaided	105	125	125	125	125	105
		CI	35	30	30	30	35	50
CIHA-F14	L	unaided	90	100	110	110	115	105
		HA	35	35	35	40	35	NA
	R	unaided	100	120	125	125	125	105
		CI	30	20	25	25	20	20
CIHA-F15	L	unaided	105	115	105	100	95	105

		HA	70	60	65	70	75	NA
	R	unaided	105	120	115	115	125	105
		CI	35	30	40	35	40	70
CIHA-M1	L	unaided	60	80	95	95	100	105
		HA	30	40	40	55	45	NA
	R	unaided	70	75	95	110	110	105
		CI	40	35	35	30	35	15
CIHA-M2	L	unaided	55	90	100	110	115	105
		HA	15	40	30	55	50	NA
	R	unaided	100	100	105	115	125	105
		CI	25	25	15	25	20	40
CIHA-M3	L	unaided	95	100	110	120	125	105
		HA	50	55	65	70	80	NA
	R	unaided	95	115	125	125	125	105
		CI	25	25	25	30	35	30
CIHA-M4	L	unaided	105	115	115	115	120	105
		HA	45	55	60	80	80	NA
	R	unaided	100	120	125	125	125	105
		CI	20	25	15	15	20	70
CIHA-M5	L	unaided	80	110	120	125	125	105
		CI	30	30	20	25	20	15
	R	unaided	90	105	105	115	120	105
		HA	35	40	30	35	35	NA
CIHA-M6	L	unaided	100	115	120	125	125	105
		HA	45	50	55	70	80	NA
	R	unaided	105	115	125	125	125	105
		CI	30	20	25	30	30	70
CIHA-M7	L	unaided	90	95	105	120	125	105
		HA	30	35	35	40	40	NA
	R	unaided	95	115	125	125	125	105
		CI	20	25	15	20	25	70
CIHA-M8	L	unaided	90	95	105	100	90	105
		HA	35	35	30	30	40	NA
	R	unaided	105	115	125	125	125	105
		CI	15	25	15	25	30	35
CIHA-M10	L	unaided	105	110	120	125	125	105
		CI	45	40	45	45	45	25
	R	unaided	95	85	85	95	90	105
		HA	50	35	35	40	65	NA
CIHA-M12	L	unaided	105	100	95	95	105	105
		HA	60	40	35	55	60	NA
	R	unaided	105	125	125	125	125	105
		CI	35	35	40	45	40	20
CIHA-M13	L	unaided	105	125	125	125	125	105
		CI	30	30	35	35	30	35
	R	unaided	95	100	105	100	95	105
		HA	50	50	40	45	45	NA
CIHA-M15	L	unaided	105	110	120	125	125	105
		CI	30	25	25	30	30	20
	R	unaided	85	95	85	90	70	90
		HA	50	45	30	35	40	NA
CIHA-M16	L	unaided	105	120	125	125	125	105
		CI	35	20	25	20	15	20
	R	unaided	105	100	95	95	95	105
		HA	70	40	45	55	50	NA
CIHA-M17	L	unaided	35	65	85	80	70	75
		HA	20	25	40	35	25	NA
	R	unaided	95	105	100	115	115	105

		CI	40	30	25	35	20	15
CIHA-M18	L	unaided	90	85	70	85	95	105
		HA	35	30	35	35	45	NA
	R	unaided	100	105	120	125	125	105
		CI	40	35	35	40	45	40
CIHA-M19	L	unaided	105	125	125	125	125	105
		CI	30	30	35	35	30	45
	R	unaided	95	100	100	95	105	105
		HA	50	50	50	55	80	NA
CIHA-M20	L	unaided	100	100	125	125	125	105
		CI	50	45	45	40	45	40
	R	unaided	100	90	80	70	50	45
		HA	35	30	30	35	30	NA
CIHA-M21	L	unaided	95	100	110	125	115	105
		HA	35	40	40	70	80	NA
	R	unaided	105	125	125	125	125	105
		CI	30	25	30	35	35	20
CIHA-M22	L	unaided	80	85	85	80	75	105
		HA	35	35	35	30	35	NA
	R	unaided	105	125	125	125	125	105
		CI	45	30	30	35	35	35

Note. CI = cochlear implant; HA = hearing aid; L = left; R = right; NA = not applicable. Maximum output level for unaided thresholds is 100 dB HL at 250 Hz and 8000 Hz, and 120 dB HL at 500-4000 Hz. Maximum output level for aided thresholds is 65 dB HL at 250 Hz and 8000 Hz; 70 dB HL at 500 Hz; 75 dB HL at 1000-4000 Hz.

Appendix C

Test sequence of Different Conditions in Speech Recognition Test in Noise

Table C1 ***Test Sequence for Participants With HAHA***

Sequence	test conditions																	
	binaural hearing condition						monaural hearing condition						monaural hearing condition					
1	NL-HAHA	NR-HAHA	NF-HAHA	NF-HAHA	NR-HAHA	NL-HAHA	NR-HAL	NL-HAL	NF-HAL	NF-HAL	NL-HAL	NR-HAL	NL-HAR	NR-HAR	NF-HAR	NF-HAR	NR-HAR	NL-HAR
2							NR-HAL	NF-HAL	NL-HAL	NL-HAL	NF-HAL	NR-HAL	NL-HAR	NF-HAR	NR-HAR	NR-HAR	NF-HAR	NL-HAR
3							NR-HAL	NF-HAL	NL-HAL	NL-HAL	NF-HAL	NR-HAL	NL-HAR	NR-HAR	NF-HAR	NF-HAR	NR-HAR	NL-HAR
4							NR-HAL	NL-HAL	NF-HAL	NF-HAL	NL-HAL	NR-HAL	NL-HAR	NF-HAR	NR-HAR	NR-HAR	NF-HAR	NL-HAR
5							NL-HAR	NR-HAR	NF-HAR	NF-HAR	NR-HAR	NL-HAR	NR-HAL	NL-HAL	NF-HAL	NF-HAL	NL-HAL	NR-HAL
6							NL-HAR	NF-HAR	NR-HAR	NR-HAR	NF-HAR	NL-HAR	NR-HAL	NF-HAL	NL-HAL	NL-HAL	NF-HAL	NR-HAL
7							NL-HAR	NF-HAR	NR-HAR	NR-HAR	NF-HAR	NL-HAR	NR-HAL	NL-HAL	NF-HAL	NF-HAL	NL-HAL	NR-HAL
8							NL-HAR	NR-HAR	NF-HAR	NF-HAR	NR-HAR	NL-HAR	NR-HAL	NF-HAL	NL-HAL	NL-HAL	NF-HAL	NR-HAL
9	NR-HAHA	NL-HAHA	NF-HAHA	NF-HAHA	NL-HAHA	NR-HAHA	NR-HAL	NL-HAL	NF-HAL	NF-HAL	NL-HAL	NR-HAL	NL-HAR	NR-HAR	NF-HAR	NF-HAR	NR-HAR	NL-HAR
10							NR-HAL	NF-HAL	NL-HAL	NL-HAL	NF-HAL	NR-HAL	NL-HAR	NF-HAR	NR-HAR	NR-HAR	NF-HAR	NL-HAR
11							NR-HAL	NF-HAL	NL-HAL	NL-HAL	NF-HAL	NR-HAL	NL-HAR	NR-HAR	NF-HAR	NF-HAR	NR-HAR	NL-HAR
12							NR-HAL	NL-HAL	NF-HAL	NF-HAL	NL-HAL	NR-HAL	NL-HAR	NF-HAR	NR-HAR	NR-HAR	NF-HAR	NL-HAR
13							NL-HAR	NR-HAR	NF-HAR	NF-HAR	NR-HAR	NL-HAR	NR-HAL	NL-HAL	NF-HAL	NF-HAL	NL-HAL	NR-HAL
14							NL-HAR	NF-HAR	NR-HAR	NR-HAR	NF-HAR	NL-HAR	NR-HAL	NF-HAL	NL-HAL	NL-HAL	NF-HAL	NR-HAL
15							NL-HAR	NF-HAR	NR-HAR	NR-HAR	NF-HAR	NL-HAR	NR-HAL	NL-HAL	NF-HAL	NF-HAL	NL-HAL	NR-HAL
16							NL-HAR	NR-HAR	NF-HAR	NF-HAR	NR-HAR	NL-HAR	NR-HAL	NF-HAL	NL-HAL	NL-HAL	NF-HAL	NR-HAL

Note. In each sequence, from left to right, test condition was conducted in turns.

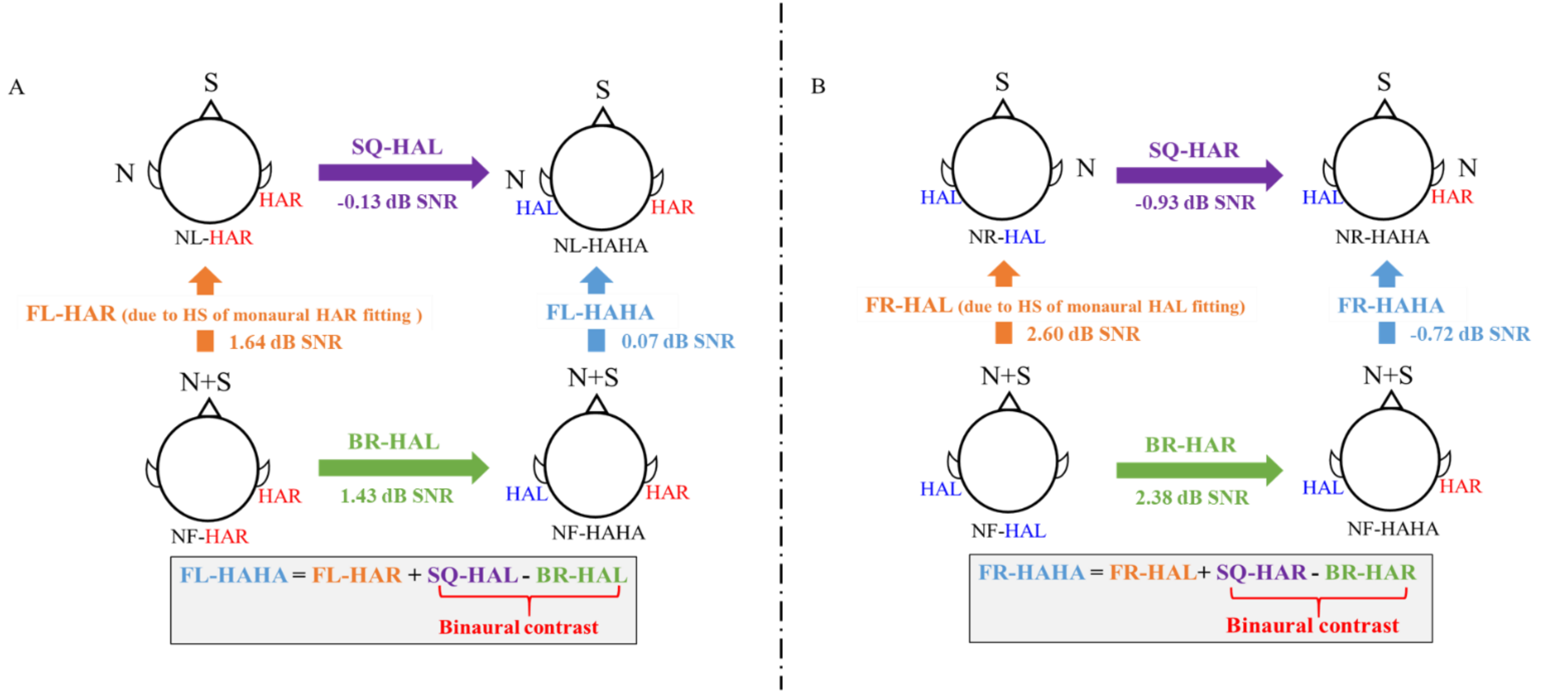
Table C2 ***Test Sequence for Participants With CIHA***

Sequence	test conditions											
	binaural hearing condition						monaural hearing condition					
1	NHA-CIHA	NCI-CIHA	NF-CIHA	NF-CIHA	NCI-CIHA	NHA-CIHA	NHA-CI	NF-CI	NCI-CI	NCI-CI	NF-CI	NHA-CI
2							NHA-CI	NCI-CI	NF-CI	NF-CI	NCI-CI	NHA-CI
3	NCI-CIHA	NHA-CIHA	NF-CIHA	NF-CIHA	NHA-CIHA	NCI-CIHA	NHA-CI	NF-CI	NCI-CI	NCI-CI	NF-CI	NHA-CI
4							NHA-CI	NCI-CI	NF-CI	NF-CI	NCI-CI	NHA-CI

Note. In each sequence, from left to right, test condition was conducted in turns.

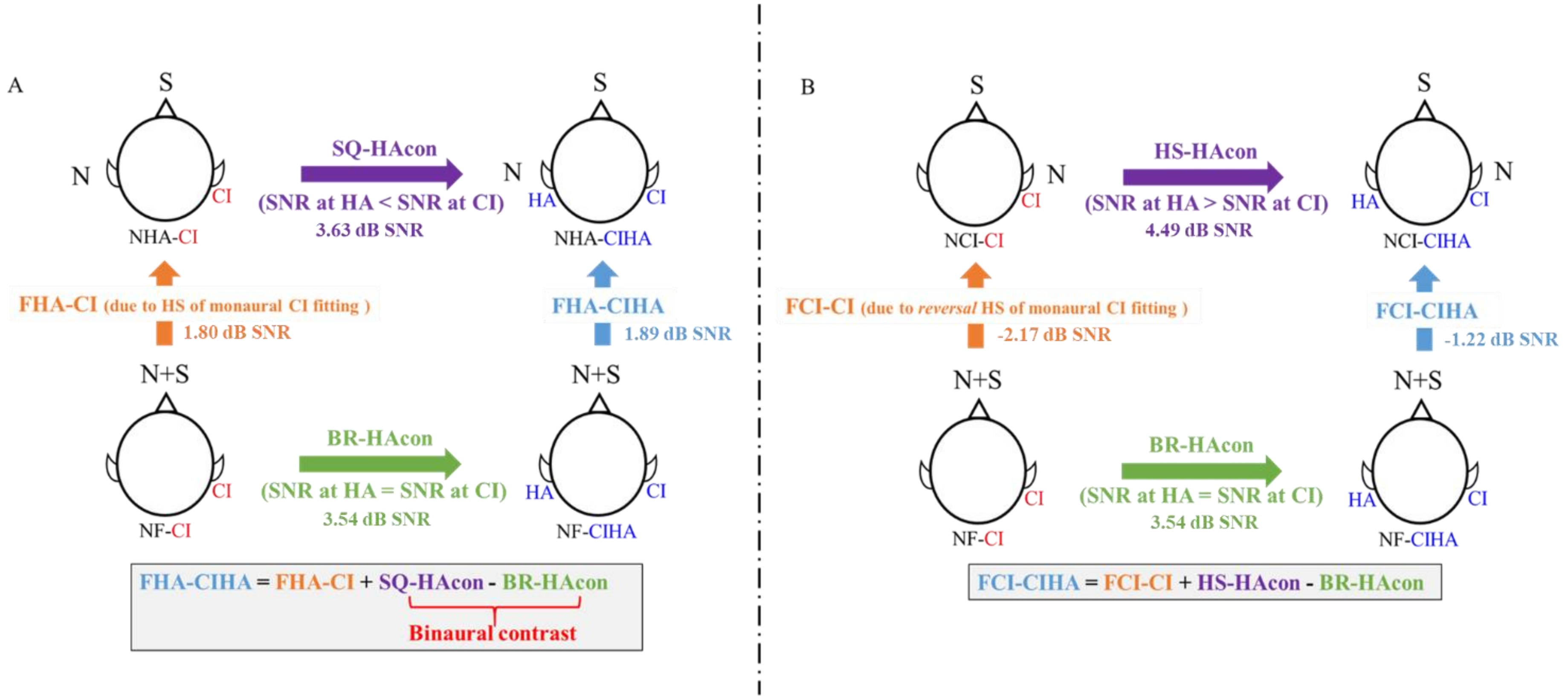
Appendix D

Figure D1 FL-HAHA and FR-HAHA of Participants with HAHA Fitting



Note. HAHA = binaural hearing aid fitting; HAL = monaural left hearing aid fitting; HAR = monaural right hearing aid fitting; N+S = noise and speech; N = noise; S = speech; NF = noise is presented from the front, NL = noise is presented from the left side; NR = noise is presented from the right side; HS = head-shadow effect, BR-HAL = binaural redundancy after adding a hearing aid on the left ear; SQ-HAL = binaural squelch after adding hearing aid on the left ear, FL-HAHA = spatial release from masking of the individual with binaural hearing aid fitting when the source of noise moved from the front to the left; BR-HAR = binaural redundancy after adding a hearing aid on the right ear; SQ-HAR = binaural squelch after adding a hearing aid on the right; FR-HAHA = spatial release from masking of the individual with binaural hearing aid fitting when the source of noise moved from the front to the right.

Figure D2 FHA-CIHA and FCI-CIHA of Participants with CIHA Fitting



Note. CIHA = bimodal fitting; HA = hearing aid; CI = cochlear implant; N+S = noise and speech; N = noise; S = speech; NF = noise is presented from the front; NHA = noise is presented at the HA side; NCI = noise is presented at the CI side; HS = head-shadow effect; BR-HAcon = binaural redundancy after adding a contralateral hearing aid; SQ-HAcon = binaural squelch after adding a contralateral hearing aid; FHA-CIHA = spatial release from masking of the individual with bimodal fitting when the source of noise moved from the front to the hearing aid side; HS-

HAcon = head-shadow effect of adding contralateral hearing aid; FCI-CIHA = spatial release from masking of the individual with bimodal fitting when the source of noise moved from the front to the cochlear implant side; SNR = signal-to-noise ratio.