The use of spatial cues by hearing-impaired listeners

in complex listening environments.

Barry Bardsley

Thesis submitted to Cardiff University

for the degree of Doctor of Philosophy

May 2019

Declaration

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

Signed .... (candidate) Date...................

Statement 1

This thesis is being submitted in partial fulfilment of the requirements for the degree of PhD.

Signed .... (candidate) Date...................

Statement 2

This thesis is the result of my own independent work / investigation, except where otherwise stated. Other sources are acknowledged by explicit reference.

Signed .... (candidate) Date...................

Statement 3

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to other outside organisations.

Signed .... (candidate) Date...................

Statement 4: PREVIOUSLY APPROVED BAR ON ACCESS

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loans after expiry of a bar on access previously approved by the Graduate Development Committee.

Signed .... (candidate) Date...................

Contents

List of Figures

List of Tables

List of Symbols

Acknowledgements

I must start by thanking John Culling my supervisor. I am aware that supervising a part-time PhD student is not always straightforward and I am incredibly grateful for all the time and effort you have put in over the years. I have also been fortunate to work in a lab that has had some very competent researchers and great friends. Jacques and Rob have been immensely supportive and having that network around me has been a real bonus. I will not forget the help I had early on from Jacques with programming. They were some very helpful discussions. I would also like to thanks Bill (Glasgow) for the assistance with coding.

Deepak thank you for your assistance with patient recruitment. Again, this would not have been possible without your input. To all the participants, I cannot thank you enough. We have published work from these studies and I hope you will get some comfort in knowing you have made a difference. I would also like to thank the charity 'Action on Hearing Loss' and the learned society 'British Society of Audiology' for their support through the respective grant schemes.

My team at Swansea have all been supportive and I feel very lucky to have been working in academia whilst undertaking this research. A special mention must go to a mentor and role-model throughout my time at Swansea. Chris, I am again grateful for all your assistance during my time in academia and during the PhD.

I have encountered some amazing friends along the way who have played a part in the culmination of this work. Paulie, Stato, Alex (Owens Park), Mike (Manchester), Richard, John (Tannery Close), Gareth, Marilyn, Donald, Queenie and Lynn (Baines Wing) thanks for the support in the 'research training' phase of my life.

Finally, to my family. My brother, father and mother have all been instrumental in different ways over the years. My father and brother kept me grounded while my mother was the inspiration for working in academia and pursing the PhD.

The biggest thank you must go to my wife Hayley and the kids. Thank you for your support and encouragement. I started this process as a father of one and end it as a father of three. Thank you for being patient and understanding. Rowan, Mason and Verity, I hope Daddy has made you proud.

Summary

People with hearing loss often struggle to understand speech in the presence of background noise. The features of the interfering noise source, and where the sounds are located in the environment with reference to the listener's position, influence the degree of difficulties faced by the listener.

Those with hearing-impairment demonstrate a substantial loss in the intelligibility of speech in the presence of interfering noise sources, when compared to their normal-hearing counterparts. The ability to use dips in the envelope of the interfering source, fundamental frequency and spatial processing all become less useful for the person with hearing loss. This deficit cannot simply be explained by a reduction in audibility.

Lip-reading provides an important cue for speech intelligibility and the advice given to those with hearing loss is to face the speaker of interest directly. The Jelfs et al. (2011) model predicts substantial benefit of orientating the head away from the target speech in normal-hearing listeners. This has since been confirmed by Grange and Culling (2016) in normal-hearing listeners. Hearing-impaired listeners were found to gain a similar level of benefit by orientating the head away from the target. This has ramifications for audiology services and the advice provided by clinicians. When interference comes predominantly from one side, the listener is advised to turn the head 30° away from the target talker and toward the interferers.

A major problem with studying the hearing-impaired population is the variability in performance on measures that underpin speech intelligibility in noise. This causes an issue when making comparisons with the normal-hearing population. An approach to examining the relevance of individual performance measures to overall speech intelligibility is to make a median split based on each measure, and then compare the speech-in-noise performance of the resulting groups. Measures of binaural temporal fine structure processing, processing of level and time differences independently and contralateral masking were used to explore the factors that lead to poor use of spatial cues by hearing-impaired listeners. No explanation for the poor use of spatial cues could be found in these measures.

1. Introduction

Hearing impairment affects 11 million people in the United Kingdom and it is expected that the number will increase to 15.6 million by the year 2035 (Action On Hearing Loss, 2015). Hearing loss is a socially debilitating condition with feelings of depression, isolation and withdrawal from society commonly reported (Dawes et al. 2015; Gopinath et al. 2012; Strawbridge, Wallhagen, Shema, & Kaplan, 2000). Hearing aids are the main source of assistance for those who develop hearing loss. The main complaint made by those with hearing loss is the poor intelligibility of speech in background noise (McCormack & Fortnum, 2013; Kramer, Kapteyn, & Festen, 1998; Tyler, Baker, & Armstrong-Bednall, 1983). Modern hearing aids provide a degree of benefit for users (Picou, Rickets & Hornby, 2013). Digital signal processing (DSP) strategies for noise reduction and directional microphones for beamforming provide benefit (Gnewikow, Ricketts, Bratt & Mutchler, 2009). However, the problem persists that hearing aid users find noisy environments very challenging (Dawes, Munro, Kalluri, & Edwards, 2013). It is believed that 6.7 million people in the UK could benefit from a hearing aid (Action On Hearing Loss, 2015) but only 2 million are hearing aid users, with only 1.4 million being regular users (Action On Hearing Loss, 2011). It has been suggested that a major factor in the decision for not using hearing aids is the performance of hearing aids in background noise (Bertoli et al. 2009; Kochkin, 2000). This thesis will investigate the reasons why hearing loss often results in difficulties understanding speech in background noise. There will be a focus on the acoustical properties of the sound sources, the environment, and strategies that improve performance.

1.1. Intelligibility of speech in noise

There is a long history of research on speech understanding in background noise. French and Steinberg (1947) considered the factors that influence the intelligibility of speech sounds. They investigated the signal intensity, addition of noise and the consequences of filtering the target or the noise on the overall intelligibility. This work led to the creation of the Articulation Index or AI (French & Steinberg, 1947). The AI was a platform for modelling speech intelligibility in a given spectrum of continuous noise and although it has undergone a number of revisions, the principle behind the AI remains relevant today. In the same year, another article was published that considered

the influence of masking fluctuations and speech interruptions (Miller, 1947). This early research shaped the landscape for future work in the area.

1.2. The 'Cocktail Party' problem

The cocktail party problem was a term first coined by Colin Cherry in 1953. It refers to the difficulties one encounters when trying to attend to one person's speech in the presence of other talkers (Cherry, 1953). In his work with the US Air Force and air traffic control, it became clear that concentrating on one message while having another message presented over headphones was extremely difficult.

1.2.1. Informational vs energetic masking of speech

Masking is the shift in auditory threshold when another sound is introduced (Miller, 1947). Miller deduced that the influence of masking on speech was dependent on the energy in the masker, its frequency components and temporal properties. Since this seminal work, a divergence has developed in what is believed to be the crucial aspect of the masker. Energetic masking has been described as masking that takes place when the target and interferer energy are presented at similar frequencies and at similar times (Brungart et al. 2001). This information is processed initially by the peripheral sensory organ of hearing, the Cochlea. When a target and masker sound source are present at the same time and with similar frequencies, they will both stimulate the same region along the basilar membrane in the organ of corti and thus, compete at the auditory nerve. Informational masking refers to any masking other than energetic. In essence, this is higher order cognitive masking that can be attributed to confusion or attention for example (Brungart et al. 2001). However, these definitions and subsequent research to support the definitions have proved deeply problematic with some referring to the energetic/information distinction as being in "total disarray" (Durlach, 2006).

1.2.2. Cues enabling the unmasking of speech in a cocktail party

The influence of background noise on speech intelligibility has adverse effects for all individuals. However, there are a number of cues available to a listener to assist them. Normal-hearing (NH) listeners use these cues very well to manage in these complex, auditory situations.

1.2.2.1.   Temporal properties of the interfering sound(s)

The changes to a masking sound over time has a significant bearing on its effectiveness as a masker. White noise, for example, is often referred to as a form of energetic masking and is a highly effective masker. It was once believed that white noise was continuous with little fluctuation in the envelope, but it has recently been suggested that white noise is "nearly continuous" and does in fact have minor fluctuations (Culling & Stone, 2017).

Sources that have modulations or gaps in the overall amplitude are less effective maskers. These modulations or gaps provide opportunities to the listener. 'Dip-listening', also known as 'auditory glimpsing' is the listener taking advantage of momentary changes in the signal-to-noise ratio (SNR) in order to capture more information about the target (Festen & Plomp, 1990).

1.2.2.2.   Fundamental frequencies of target and interfering voice(s)

The fundamental frequency (F0) of speech is the repetition rate of a voice's periodic waveform, and is the physical correlate of the perceived pitch of speech. The average male voice F0 is 100-120 Hz whereas the average female voice is around 200-210 Hz (Traunmüller & Eriksson, 1994). It has long been established that increasing the difference between the target speech F0 and the interfering speech F0 improves speech intelligibility both when identifying isolated vowels (Culling & Darwin, 1993) and listening to running speech (Brokx & Nooteboom, 1982). There are a number of explanations available for this effect, with evidence emerging to support harmonic cancellation (Deroche & Culling, 2011). It appears the harmonicity of the masker and not the target strongly influences the effect of a ΔF0. When the masker is based on a different F0 than the target, it is believed there is an internal suppression of the masker by the listener, and the target is detected in what remains following this cancellation.

1.2.2.3.   Linguistic content of interfering speech and informational masking

When using competing speech as a masking source, the content of the speech has the potential to distract or confuse the listener and so reduce performance. This would be deemed a component of informational masking as it could not be explained purely on the grounds of overlapping energy in the signals. There are a number of ways to explore this factor. One might be to use the target speech and interfering speech from the same speaker. Another approach would consist of using two different speakers talking about the same topic area. These results can then be compared with time-reversed-speech results. The time-reversed-speech shares many properties with normal speech, such as

formant transitions and modulations. However, the linguistic content is removed as the speech is unintelligible.

1.2.2.4. Spatial separation of target and interferer

The term 'spatial hearing' refers to the location of sound sources in one's environment and how these are perceived. It encompasses sound localisation and use of spatial cues to improve speech intelligibility in background noise. The head forms a roughly spherical obstacle with ears on opposite sides of its surface. This arrangement provides two acoustic cues that allow perception of sounds in space. Interaural Level Differences (ILDs) describe how sounds can be attenuated by the head and Interaural Time Differences (ITD) describe how sounds arrive at the ears at different times. These cues are important for the horizontal plane, while convolutions in the pinna provide spatial cues in the vertical plane. Spatially separating the target and masker assists with intelligibility (Peissig & Kollmeier, 1997). Much of the present work focuses on the use of these spatial cues.

1.3. Perceptual consequences of hearing loss

Hearing loss can be classified into three main categories. First, a conductive hearing loss refers to a problem associated with the outer or middle ear and diminished sound passing through the system via the air-conduction route. Second, a sensori-neural hearing loss locates the problem within the cochlea or auditory nerve. Third, a mixed hearing loss would have components of conductive and sensori-neural hearing loss. Age-related hearing loss (also known as presbyacusis) is most commonly sensori-neural hearing loss, where the hearing cells in the cochlea have become compromised. There are two types of hair cell within the cochlea, referred to as outer and inner hair cells. They perform different functions, with outer hair cells acting as biological amplifiers and inner hair cells as transducers. A sensorineural hearing loss will be caused by damage to outer and/or inner hair cells (Moore, 2007, p. 29). The outer hair cells are the most vulnerable to ototoxicity and degeneration due to ageing. The stereocillia can be distorted or destroyed, or cell necrosis can occur.

1.3.1. Loss of sensitivity

A hearing loss results in a shift in the absolute sensitivity to sounds. Audiometric descriptors have been created to describe average hearing thresholds of 0.5, 1, 2 & 4 kHz. These descriptors are general terms in decibels (dB) to use for individual ears

rather than using specific numbers at different frequencies. They are mild (21-40 dB HL), moderate (41-70 dB HL), severe (71-95 dB HL) or profound (>95 dB HL) (British Society of Audiology, 2011, p. 22). The loss of hair cell function results in hearing loss. It is believed that when outer hair cells are damaged, their amplification function is reduced or lost. This means sensitivity to weak sounds is reduced and as such, sounds need to be more intense to produce a given magnitude of response on the basilar membrane (Moore, 2007). When inner hair cells are lost the sensitivity to sounds at a specific place in the cochlea is lost also, as the mechanism for converting basilar membrane movement to neural excitation (transduction) is absent. However, sounds at the corresponding frequency are often still detected at other points along the basilar membrane.

1.3.2. Frequency selectivity

Frequency selectivity describes the ability to resolve different frequencies of sound and this is believed to be a necessary process when trying to listen to speech in background noise. The description above discusses the perception of sounds relating to the threshold of hearing but hearing impairment also leads to suprathreshold deficits. Masking experiments have been used to illustrate the frequency selectivity capabilities of the auditory system. Masking reflects the limits of frequency selectivity. If one signal with a particular frequency is masked by another signal with a different frequency (so unable to detect the first signal), then the auditory system was unable to resolve the two signals. Therefore, experiments to manipulate the attributes of one sound to just mask another allow an insight into the frequency selectivity of the auditory system.

The power-spectrum model for masking (Fletcher, 1940) suggests that the auditory system is a bank of band-pass filters (referred to as auditory filters) and the detection of a signal is determined by the amount of noise that passes through the auditory filter. The width of the auditory filter can therefore be approximated by this 'critical band', where increases in masker bandwidth past the filter boundaries has little effect on the threshold. Estimating the shape of the auditory filter can be achieved by obtaining Psychoacoustical Tuning Curves (PTCs). PTCs are plots that represent the results of masking experiments. There are two approaches to obtaining PTCs but the most common approach is to hold a pure tone constant at a certain frequency and alter noises/pure tones around the frequency of the tone in amplitude to just mask the tone. The amount of energy needed to mask the test tone is related to the excitation patterns on the basilar membrane. The typical representation of the auditory filter can be

described as 'V' shaped. There is a steep high frequency side and a shallower low frequency side. Although comparing the frequency selectivity capabilities of NH and hearing-impaired (HI) listeners is complicated by a number of factors (such as intensity level compared to hearing threshold), there is general agreement that HI listeners demonstrate broader auditory filters (Moore & Glasberg, 1986) than NH listeners. This means they have poorer frequency resolution, and loss of the active mechanism is postulated as one reason why those with hearing impairment find it difficult in background noise.

1.4.   Spatial Release from Masking

Spatial release from masking (SRM) describes the improvement in speech intelligibility when a competing source is moved away from the target source (Litovsky, 2012). Most of the work on SRM considers the target at 0°, because this was thought typical of communication (Festen & Plomp, 1986a), and the masking source moved on the horizontal axis. The typical approach is to compare a reference condition, in which the target and interferer are co-located at 0°, with at least one other condition where the target remains at 0° and the interferer is moved along the horizontal azimuth. One account for this improvement in speech intelligibility is the use of two perceptual cues; better-ear listening (BEL) and binaural unmasking (BU) (Hawley et al. 2004). Before moving on to discuss the better-ear listening and binaural unmasking field, it is worth noting another explanation for SRM. Auditory Scene Analysis was introduced by Bregman in the 1990's and he suggested that different pieces of acoustical information are separated into different 'streams' in more of a top-down higher-order cognitive process (Bregman, 1990). For a review of how Auditory Scene Analysis fits into the work on the cocktail party, the reader is directed toward the review by Bee & Micheyl (2008). The Auditory Scene Analysis explanation for the use of spatial information diverges from the better-ear listening and binaural unmasking explanation in that Bregman suggests SRM is completed by grouping sound elements from one direction and segregating them from elements of the interfering sound in different directions. The better-ear listening and binaural unmasking explanation separates the roles of ITD and ILD processing (Culling, Hawley, & Litovsky, 2004; Hawley, Litovsky, & Culling, 2004) whereas Auditory Scene Analysis suggests both cues are used in the initial determination of sound direction. Edmonds & Culling (2005) challenged this idea when they created an experiment where they manipulated the ILD and ITD cues in such a way

that they were able to present conflicting information from the cues regarding the target azimuth (in different hemifields). SRM was very similar when the cues were in conflict or coincided, evidence that favours the explanation of ILD and ITD making independent contributions to SRM.

1.4.1. Better-ear listening

Better-ear listening describes our use of ILDs to attend to the ear with the better SNR. The head acts as an acoustic barrier, so higher frequency sounds with wavelengths shorter than the diameter of the head will be attenuated. Lower frequency sounds diffract around the head and ILDs are negligible (unless the sound source is very close to the head). Frequencies greater than approximately 1.5 kHz have a differential across the ears (ILD) mainly because of this head shadow. Festen & Plomp (1986a) measured the head-shadow effect in their 2nd experiment and reported measurements for two different locations. Using a small electret microphone, they recorded at the entrance of the ear canal and the position of the microphone of a hearing aid (using a dummy hearing aid). They used eight participants and averaging across this number was believed to help address any small variations in head shape. Subjects were sat 2 m from a loudspeaker in an anechoic room and 70 dB (A) pink noise was played from the loudspeaker, both front facing and laterally in order to measure the head shadow and baffle effects. Electret microphones at both ears provided the means to measure the head-shadow, although recordings were limited to frequencies up to 8 kHz. For both ear canal and hearing aid microphone position, it was clear that the largest head shadow effects were found in the higher frequencies. This effect got larger the higher the frequency. The results were similar between the two locations, they both had a slight dip in the head shadow around 2 kHz but then the head shadow gradually increased as the frequency increased (Festen & Plomp, 1986a). The ear canal position has a higher maximum head shadow value, which can be seen at 7 kHz.

1.4.2. Binaural unmasking

Binaural unmasking is our additional ability to use differences in the time waveforms at the two ears (interaural time differences). Speech or noises that have a relatively large ITD (e.g. 0.6 ms) are perceived to be off to one side. If there is an interaural configuration which produces a signal or noise (not both) that has an ITD/interaural phase difference (IPD), this allows improved detection when compared to the condition where the signals are the same at the ears (Licklider, 1948). The mechanisms that underpin this process are still unclear, with some support being

attributed to an equalization-cancelation process (Culling, 2007; Durlach, 1963). The independent contributions of ILD and ITD to SRM have been reported as 7 dB SNR and 3.5 dB SNR respectively when using a masker at 90°, which indicates that used together they are not entirely additive (Bronkhorst & Plomp, 1988). Bronkhorst and Plomp suggested that the ILD results could be explained by the improved SNR in the high frequencies at one ear and that they are, therefore, essentially producing a monaural effect with no binaural interaction, unlike the ITD results which are exclusively binaural in origin.

1.4.3. Spatial release from masking for normal-hearing listeners

The amount of benefit attributed to spatial separation of the target and interfering sources is heavily dependent on a number of factors. Examples of such factors are interferer location, the number of interferers, the spectrotemporal properties of the interferer and level of reverberation in the test environment.

Some of the earliest studies that considered the role of interferer location were published in the 1970's. Plomp (1976) was interested in SRM using connected discourse for target material rather than single words or short sentences. He used speech-shaped noise (SSN) or connected discourse as interferers and these were moved in 45° steps along the horizontal plane, starting at 0°. The stimuli were presented over loudspeakers in a reverberation room, although he altered the reverberation time in the room by adding sound-absorbent panels. The three reverberation times used were 0.4 1.4 and 2.3 s. He used a Békésy up/down tracking method to establish the Speech Reception Threshold (SRT), which means a button was pressed when the target speech was unintelligible and released when it was intelligible. The participants were asked to maintain the target speech at a level of 'just intelligible' and that 'the more difficult words could be understood' (Plomp 1976, p.202). A headrest was used to ensure the participants faced the target source directly and all loudspeakers were equidistant from the listener. The distance was either 1, 1.8 or 2 m depending on the reverberation condition (1.8 m for anechoic). He investigated binaural performance as well as monaural performance, the latter was completed by occluding one ear. The 10 NH listeners' average SRM increased as the spatial separation increased, with 6 dB SNR benefit demonstrated in anechoic conditions and the interferer at 135°, and then reducing to 3 dB SNR at 180°. Similar SRM values were obtained between the connected discourse and SSN interferers, but the SRTs when using SSN were generally 3 dB SNR higher/poorer in all conditions. The increasing reverberation resulted in

poorer SRTs and reduced SRM, with only 1-2.7 dB SNR maximum SRM recorded for the highest reverberation time (2.3 s) and at 1 m. Binaural SRTs were 2.5 dB SNR lower/better than monaural SRTs on average, irrespective of degree of spatial separation of level of reverberation. One limitation to this study was the use of only eight loudspeaker locations at 45° steps along the horizontal place.

Plomp & Mimpen (1981) investigated SRM in an anechoic room and they considered SRM as a function of noise source location, and in this study they used a greater number of positions along the horizontal plane in one hemifield. They used a ring of loudspeakers 2m away from the listener's head in an arc spaced 22.5° apart, starting at 0° and finishing at 180°. Using speech sentences and a SSN interferer source, they used an adaptive 1-up 1-down staircase approach to collect the SRTs. They used 13 word lists for each condition. The first sentence was presented at a low SNR, which was increased until the participant responded correctly. A 2 dB reduction in SNR was used for the 2nd sentence, if there was a correct repetition of the sentence the SNR would be further reduced by 2 dB SNR, if it were repeated incorrectly then the SNR would be increased. The SRT was taken as the mean SNR for sentences 4 to 13. For 10 listeners for the collocated condition, the SRT was -7.2 dB SNR. A gradual increase in SRM was seen up to 112.5°, where the maximum SRM was 10.9 dB SNR. A gradual reduction was seen after this point up to 180°, which gave a 1.4 dB SNR SRM (Plomp & Mimpen, 1981). This study gave greater clarity to the influence of noise location with one interferer, although it remained unclear the effect of additional interferers.

Hawley et al. (2004) were interested in the type of interferer, as well as interferer numerosity and location. Thirty-two NH listeners took part and SRTs were collected using four different interferer types. These were speech, reversed-speech, SSN, and speech-modulated SSN. In using these stimuli as interferers, they could investigate informational masking, F0 processing and dip-listening. Target sentences were from the Harvard Institute of Electrical and Electronics Engineers (IEEE) corpus (Rothauser et al. 1969), convolved with Head Related Impulse Responses (HRIRs) from the AUDIS collection (Blauert et al. 1998) and presented from 0° over headphones. One, two or three interfering sources were presented either at the front with the target speech (co-located) or at a mixture of dispersed locations. These locations were on the right side at 90° (1, 2 or 3 interferers at this location), at 30° intervals on the right side (30°, 60° & 90°), or asymmetrically split (30° left, 60° and 90° right). Measurements were made both monaurally and binaurally. This resulted in a large number of conditions tested and

the authors decided to use different participants in the monaural and binaural conditions. They were paired based on the order of participation. It would have been preferable to have the same participant complete both the monaural and binaural sessions in order to minimise variability, although all were NH listeners and variability in SRTs is reasonably low.

The SRM with one interferer was highest with the speech and reversed-speech interferers. This suggested F0 processing allowed cancellation of the interferer and resulted in better SRTs. The SRM across the 3 different interferer locations (-30°, 60° and 90°) with one interferer was between approximately 5-8 dB SNR across the different interferer types, with 60° being the location with the highest SRM. It is not surprising that 90° was lower than 60° because this location is influenced by the bright-spot (Rayleigh & Lodge, 1904). An interferer on one side of the head creates a head-shadow at the opposite ear, but when the interferer moves to 90°, it is directly opposite the contralateral ear. Diffraction of sound around the head results in a bright spot of interference (Reisinger et al. 2009) at the contralateral ear and thus the SRTs are lower at 90° compared to 60°. A difference in SRM with one interferer was seen between the interferer types. SRM for SSN was higher than speech-modulated SSN. On closer inspection of the raw SRT results it is clear that this is due to lower/better SRTs for the speech-modulated SSN at the co-located position, and hence less benefit when the interferer was displaced from the target. This can be explained by dip-listening.

A similar pattern emerged with two interferers, with SRTs decreasing/improving as the interferers moved away from the target. However, the SRTs with speech interferers now gave some of the highest/poorest results suggesting that informational masking started to play a role. Consistent with this interpretation, the reversed-speech remained the lowest/best. The experimental design probably promoted informational masking by using other IEEE sentences produced by the same voice as used with the interferers. SRM values of up to 12 dB SNR were achieved with two speech or reversed-speech interferers at 60° and 90°. This was significantly different from the -30° and 60° condition, where interferers on each side of the head presumably reduce better-ear listening opportunities. The results for the three interferers were similar to those found with two interferers, with SRM up to 10 dB SNR. SRT collected with speech and reversed-speech gave these higher SRM score, although SRTs with speech interferers were once again the highest/poorest.

The difference between the SSN, and speech-modulated SSN was in the region of 2-3 dB SNR with one interferer, but this difference disappeared in the two and three interferer conditions. This is to be expected, as the dips from one interferer are filled by the energy of another interferer, and the authors suggest that the results are supportive of the concept of dip-listening but with one interferer only.

SRTs in multiple speech interferer conditions were consistently 2 dB SNR worse than those with reversed-speech. This could be considered an informational masking effect. The authors felt the experiment was unable to differentiate the effects of intrusion and attentional distraction. However, there was a suggestion that a reduction in F0 processing with the addition of a second voice-based interferer could account for some of the reduced SRT. In addition, in the multiple interferer conditions, the SRTs in the reversed-speech were not worse than SSN nor speech-modulated SSN. These results would suggest that no additional masking effect took place with the reversed-speech.

In their analysis the authors confirmed that better-ear listening was disrupted when interferers were positioned in both hemifields, but binaural unmasking remained robust with the spread of interferers. They were able to deduce this by comparing monaural and binaural results across the different spatial configurations. This surprising result went against the commonly held view at the time that the equalization cancelation theory of binaural unmasking (Durlach, 1963), which held that only one interferer with a specific interaural time delay could be cancelled at any time. The belief held was that it was unlikely that binaural unmasking could explain all the spatial advantages seen with the speech interferer. What remained unclear from this study was how much of the benefit could be attributed to the use of ILDs or ITDs.

To address this question, the same authors produced another study that investigated SRTs from target and interferers in the same locations, but on this occasion HRIRs were manipulated to remove the binaural cues (Culling et al. 2004). There were three scenarios in this experiment; both cues available, ILDs only or ITDs only. The inspiration for this follow-up study was based on parts of the data collected in Hawley et al. (2004) which were contrary to the E-C model of binaural unmasking (Durlach, 1963, 1972). The results with ITDs alone confirmed that when the interferers were spread in one hemisphere (30°, 60° and 90°) using only ITD cues, a robust SRM effect was still observed. The E-C model suggests that only one ITD can be equalized at a time and therefore the condition with the interferers spread should see poorer performance. The result removed the ambiguity in Hawley et al. (2004), because in that

study the ILD and ITD cues were intact throughout the experiment so the ILDs could have influenced some of the results, with better-ear listening still playing a part.

In experiment 1 of Culling et al. (2004), they used speech and SSN interferers with Harvard IEEE sentences (Rothauser et al. 1969). The HRIRs from the AUDIS catalogue (Blauert et al. 1998) were transformed into the frequency domain (Head Related Transfer Function) and processed in two different ways. To remove ITD information, the phase spectra of a pair of HRIRs were replaced with identical phase spectra. The replacement phase spectra linearly increased in phase with frequency, which resulted in HRIRs that had ITD information removed. Inverse Fast Fourier Transform (iFFT) was used to recreate the HRIR. To create the HRIRs with no ILD information, the amplitude spectra of a HRIR pair were replaced with identical spectra and thus removing the difference across the two channels for level. A compensation for the change in amplitude was conducted during the convolution process with the material.

Thirty-six NH listeners participated in the experiment, with twenty-four taking part with a speech interferer (two speech voices were used from the IEEE sentences 'DW' and 'CA') and 12 taking part with the SSN. The same four spatial conditions were used as Hawley et al. (2004) with three interferer conditions. These were co-located (0°,0°,0°), distributed in both hemifields (-30°,60°,90°), spread in one hemifield (30°,60°,90°), or in one location to the side (90°,90°,90°).

The results of experiment 1 in Culling et al. (2004) with the ITD cue alone gave a similar pattern of SRTs for spatial configuration to when both cues were available. However, the magnitude of the SRMs was reduced. The SRM with ITD only information was approximately 5 and 6 dB SNR when the speech interferers were at 30°,60°,90° and then 90°,90°,90°, respectively. When using the SSN interferer, the SRM with ITD only was approximately 3.5 dB SNR in both spatial configurations. The results suggest that the binaural auditory system is able to exploit ITD from interferers from multiple sources, which appeared inconsistent with the E-C model of binaural unmasking. The authors analysed this concept further in experiments 2 and 3, where a binaural advantage within frequency channels was investigated. This conceptual approach was based on the belief that it is possible to predict binaural advantage within frequency channels. This was done by using an expression of the size of a pure-tone Binaural Masking Level Differences (BMLD) within the frequency channel as a way of equating the improvement in SNR (Levitt & Rabiner, 1967).

Experiment 2 in Culling et al. (2004) measured BMLDs with the ITD-only SSNs that were created for the four spatial configurations in experiment 1 (0°,0°,0°; -30°,60°,90°; 30°,60°,90° and 90°,90°,90°). The BMLD was calculated by subtracting the detection threshold with spatialized interferers from the condition where they were co-located at 0°. Fifteen frequency bands were tested (1/3rd octave bands between 200 5080 Hz). Four NH listeners participated in the experiment. From 200 to 400 Hz, BMLDs of 8-9 dB SNR were found for the 30°,60°,90° and 90°,90°,90° conditions, whereas it was approximately 4 dB SNR for the -30°,60°,90° condition. After 504 Hz, the BMLD for 30°,60°,90° reduces to 4-5 dB SNR whereas 90°,90°,90° continues at 8-9 dB SNR. At 1600 Hz no masking release is present in any condition. Predictions from the E-C model were broadly consistent with the observed values. This can be interpreted as the E-C theory is in fact able to predict a robust BMLD for multiple, spatially distributed interferers.

1.4.3.1. Modelling spatial release from masking in normal-hearing listeners

A number of models exist today that predict speech intelligibility. Models can be monaural, binaural, microscopic, macroscopic, anechoic, or reverberant. It is beyond the scope of this thesis to review all the models developed and instead to focus on a particular binaural model that predicts SRM (Jelfs et al. 2011; Lavandier et al. 2012; Lavandier & Culling, 2010). The model contains two components. Better-ear listening and binaural unmasking are predicted from Head Related Impulse Responses (HRIRs) or Binaural Room Impulse Responses (BRIR). HRIRs are collected in anechoic conditions and BRIR from rooms. A gammatone filterbank (Patterson, Allerhand, & Giguère, 1995) filters the impulses response for the speech and interferer sources and the effect of better-ear listening and binaural unmasking are analysed independently in each frequency channel. The two components are weighted against a measure of channel importance for speech intelligibility (American National Standards Institute, 1997) and the result is summed across the frequency channels. The SRM is predicted by comparing the effective SNR at the co-located position (reference), with the spatially separated position.

Jelfs et al. (2011) validated the data against a number of studies. For instance, they used HRIRs (Gardner, Martin, William, & Martin, 1995) and found a correlation of 0.99 with the observed data from Hawley et al. (2004) and the predicted SRTs. The model has also predicted performance of Cochlear Implant (CI) users by disabling the

binaural unmasking component. It produced a correlation of 0.97 between the observed data (Loizou et al. 2009) and the predicted SRTs.

The model has also been used to systematically analyse the configurations that demonstrate the maximum SRM for CI users (Culling, Jelfs, Talbert, Grange, & Backhouse, 2012, p. 675). Figure 2 of Culling et al. (2012) is a polar plot of predicted SRM as a function of direction of the speech and noise. Although the HRIRs were collected from the front microphone of a Siemens Acuris hearing aid, the optimal orientation for the interferer for maximal SRM could be inferred. With target speech at 0°, maximum SRM is found when the one noise interferer is moved to the 60° or 110° region (either left or right side). At these locations, SRM is predicted to be 6 dB SNR. Even more SRM is predicted if the target is moved off from 0°. With the target and interferer split 60° or 120° apart, so that they are in equal and opposite in directions, and the head fixed between these two locations, there is even greater SRM predicted. In this case, it could be as high as 9 dB SNR.

1.4.4. Effect of sensorineural hearing loss on spatial release from masking

The benefits mentioned in the previous section for NH listeners are not always replicated when we consider HI listeners. There are many studies that report reduced SRM when considering HI against NH listeners. One of the first to report reduced binaural processing in HI listeners was Duquesnoy (1983). Using a female speaker as a target and either SSN or a male speaker as an interferer, 20 HI listeners were compared to 10 NH listeners. Loudspeakers delivered the target speech at 0° azimuth and the interferer at either 0° or 90°. Comparing conditions 4 and 7 in the study revealed SRM with a noise interferer was 9.6 dB SNR for the NH listeners and 2.5 dB SNR for the HI listeners. Comparing conditions 5 and 8 in the study revealed SRM with a speech interferer was 6.7 dB SNR for the NH listeners and 4.5 dB SNR for the HI listeners.

Another early study considering the deficit in SRM was conducted by Gelfand et al. (1988) who compared different groups based on age or hearing status. Four groups consisted of 23 NH young listeners, 11 NH middle-aged listeners, 7 NH older listeners and 10 HI listeners. Target speech sentences were delivered from a loudspeaker at 0°, and a 12-talker babble delivered from either 0° or 90°. SRM was 6, 6, 5 and 3 dB SNR respectvely, again demonstrating the HI listeners had signfiicantly lower SRM. These two early studies gave an impression of the deficit in SRM in those with hearing loss,

but the studies were limited in that they only considered movement of one interferer on the horizontal plane.

The early focus on one interferfer moving along the horizonal axis was extended by Ter-Horst et al. (1993) who considered SRM in both the horizontal and vertical planes, although the former is of most interest in this thesis. They investigated the effect of two interferers displaced from the target by the same angle in each hemifield. The reference was 0° for both the target speech and noise. The loudpeakers were +/- 18° and +/- 54° configurations for the two noise interferers in the spatially separated conditions. Using 15 NH listeners and 64 HI listeners, they reported an SRM of 4 dB SNR and 1 dB SNR resepctively at +/-18°. The SRM was approximately 3.5 dB SNR and 1.5 dB SNR at +/-54°, respectively. However, the results must be interpreted with caution. The symmetrically displaced maskers were correlated noise. This results in complex interference effects at certain frequencies, at positions away from 0° (Noble & Perrett, 2002). It remained unclear what the effect of an additional interferer had on the SRM in those with hearing loss.

The issues identified in the study by Ter-Horst et al. (1993) meant the questions remained as to the role of interferer numerosity and azimuth and their effects on SRM in those with hearing loss. This was investigated in a study by Peissig and Kollmeier (1997). Using eight NH listeners and eight HI listeners, simulated spatial configurations were presented over headphones to establish speech intelligibility in noise. Target speech sentences were always presented from 0° and either SSN or other talkers were used as the interfering sources in three different paradigms, although only the first and third were used to compare NH listeners and HI listeners. In the first paradigm, one interferer source was moved to 17 different locations around the 360° azimuth range (S_0N_X). In the third paradigm, the same procedures were followed as in paradigm one, but with the addition of two fixed-interferers at 105° and 255° ($S_0N_{105} N_{255}N_X$).

The spatial benefit obtained in this study was referred to as the 'intelligibility level difference'. The authors reported very large variability amongst the HI listeners, so much so that they allocated the HI listeners into three groups based on the obtained 'intelligibility level difference'. The approach of moving from a continuous variable to a categorical variable brings with it problems. Each member of the category is then deemed equal. This clearly is not a fair representation when one considers the values close to the split are treated the same as those further away from the category split. One could remove a section of the data that are close to the category boundary but the result

is a loss of data. When analysing the results, and moving from a linear regression to an analysis of variance, the result is an overall loss of power.

In the Peissig and Kollmeier (1997) study, most of the SRTs in the co-located position were only slightly poorer than the NH listeners (1-2 dB SNR) across all participants. The spatial benefit obtained by three HI listeners was close to the NH listeners, within 1-3 dB SNR for paradigm one. Two other HI listeners were approximately 5 dB SNR worse in paradigm one, compared to NH listeners. The final three HI listeners were substantially poorer in paradigm one, between 5 and 9 dB SNR poorer.

In paradigm three (S_0N_{105} $N_{255}N_X$), both SSN and speech were investigated as interferers. All HI listeners showed substantial increases in threshold at the co-located position. When moving the interferer, some HI listeners were so poor, and results so inconsistent, that scores were not recorded. Large variability was seen in these results, with some showing similar benefit to NH listeners and others being 2 dB SNR poorer. As such, interpretation of these results were difficult due to the small numbers and variability in results.

Similar to the work on SRM in NH listeners, the focused on SRM in HI listeners moved away from azimuth and numerosity of interferer, and on to the specific role of ILDs and ITDs. In a study to investigate the role of ILD and ITD in SRM, Dubno et al. (2002) used a low-pass or high-pass filtering approach. This is contrary to the approach that Bronkhorst & Plomp (1989) have taken where they specifically seperated the cues in the noise source by using fast fourier transform (FFT) and cross-correlation techniques. In Dubno et al. (2002) they accepted that filtering may not completely sepearate ILD and ITD cues. They had 8 listeners in each of three different groups. There were NH young listeners (mean age 25 years), NH older listeners (mean age 68 years) and HI listeners (mean age 72 years). They used speech sentences for target material and a SSN as the interferer. These were delivered from loudspeakers at 0° for the colocated position and then the noise was moved to 90°. There were 10 different conditions based upon the filtering cut-off frequency. One condition was left unfiltered, which allowed sounds upto 8.9 kHz to be delivered. There were four conditions with low-pass filterng. These were at freqenices of 2.24, 1.78, 1.41 and 1.12 kHz. There were five high-pass filtering cut-off frequencies at 0.56, 0.89, 1.12, 1.41 and 2.24 kHz.

For the unfiltered condition, the SRM values were 6, 4.9 and 2.7 dB SNR for the NH young, NH older and HI listeners respectively. When consideirng the filtered conditions, the NH young listeners had the highest SRM values which were obtained at the high-pass frequency of 0.89 kHz. These were in the order of 8.5 dB SNR. The lowest SRM value recorded in NH young listeners was 4.2 dB SNR at the low-pass frequency of 1.41 kHz. For the NH older listeners, the highest SRM values were obtained at the 0.56 kHz high-pass frequency in the order of 6.5 dB SNR. SRM in the 2.24 kHz high-pass could not be recorded. The lowest SRM value recorded in the NH older listeners was 2.8 dB SNR at the low-pass frequency of 1.78 kHz. In the HI listener group, the highest SRM values were obtained at the 0.56 kHz high-pass frequency in the order of 3.2 dB SNR. Like the NH older group, the HI listeners were unable to record any SRM at the 2.24 kHz high-pass condition. The lowest SRM value recorded in this group was -1.0 dB SNR at 0.89 kHz low-pass frequency. The authors concluded that HI listeners had significantly lower SRM in all the low-pass cut of frequencies compared to NH young and NH older listeners with the exception of 1.78 KHz cut-off, where HI listeners and NH older listeners were similar. For high-pass conditions, significantly lower SRM scores were found in the HI listeners with the exception of 1.12 kHz cut-off frequency where NH older and HI listener scores were similar. This study provided information about the important frequency ranges for SRM in HI listeners and one can infer from the results which cues are the most important. Having gained the most SRM for a high-pass condition which brings in a large amount of the frequency spectrum is not surprising, where information from both cues could be utilized. Having no SRM recorded with the 2.24 kHz high-pass condition suggests that ILDs are still a significant component for HI listeners to use. However, this study used SSN and only informs us of the role of an energetic interferer. What was needed was a study that considered these issues with interferers that bridged the divide between energetic and informational masking.

To address this, Arbogast et al. (2005) used cochlear implant simulation to filter material into frequency bands in order to assess the role of energetic and informational masking. The envelopes were extracted from each band and these were used to modulate pure tones. The rationale for this was that they could control the amount of spectral overlap between the target and interferer, which defines an energetic masker. It meant they had three different interferers; different-band sentence masker, different-band noise masker and same-band noise masker. They recruited 10 aged-match NH

participants (within 10 years) and 10 HI participants. They used the co-ordinate response measure (CRM) sentences as target material, which were delivered from a loudspeaker at 0°, and the interferers at either 0° or 90°. They found an average SRM of 3.7 dB SNR using the different-band noise masker and because the results were so similar between the HI & NH listeners, they only report this one average value for both sets of listeners. Similarly, they found results between the HI and NH listeners for the same-band noise masker very close, with an average SRM of 6.1 dB SNR reported. However, when using the different-band sentence masker (which they consider a predominantly informational masker), the NH listeners scored an average SRM of 15.3 dB SNR, which was significantly higher than the HI listeners, who scored an average SRM of 9.5 dB SNR. A consideration for this result is that the HI listeners have broader auditory filters and as such, are still prone to energetic masking even when attempting to control for this with different-band stimulation.

The results of Arbogast et al. (2005) became the basis for further studies on the role of informational masking in SRM with HI listeners. From this study came the suggestion that HI listeners were more susceptible to informational masking. Helfer & Freyman (2008) investigated this by attempting to control the degree of energetic masking. They recruited two groups of participants, 12 NH younger listeners and 12 older listeners. The 12 older listeners had Pure Tone Audiometry (PTA) thresholds varying from normal to a moderate, high-frequency hearing loss. The authors delivered sentences in the presence of one of four maskers. Two-talker babbles were used from the same or different gender as the target talker, as well as a speech-envelope modulated noise. The loudspeakers were at 0° and 60°. In their 'front front' condition, target and maskers were delivered from the loudspeaker at 0°. In their 'front right-front' condition, they delivered target material at 0° and the masker at both 0° and 60°. The loudspeaker at 60° had a 4-msec time lead compared to the front. When two sounds reach a listener close together in time, the person perceives one sound with a direction that favours the location of the frist sound. This is know as the precendence effect. As such, in the Helfer & Freyman (2008) study, the 4-msec lead at 60° results in the listener perceiving the sound to be off to the right. This approach was taken, and not the standard condition of simply presenting the masker at 60°, because they were looking to minimise the release of energetic masking.

Another deviation from the normal that the authors took in this study was how they recorded the SRT. They used four fixed SNRs of 4, 0, -4 and -8 dB SNR and

recorded the percentage correct. This makes it very difficult to interpret with regard to SRM. They did convert each of the participants data into rationalised arcsine units but interpretation is stilll difficult as this data is plotted as 'relative group differences'. Considering the change in percentage correct when moving from the co-located position to the perceptually separated condition, it is possible to deduce the spatial benefit. The NH young listener group demonstrated large spatial benefit in only two conditions. These were at -8 and -4 dB SNR for the same-sex masker. The group had a 45% and 18% increase in correct responses respectively. Equally, the older group (with HI listeners amongst them) only demonstrated a spatial benefit when using the same-sex masker, but the benefit was less when compared to the the NH younger listeners. They had a 22%, 27% and 13% increase in correct responses at -8, -4 and 0 dB SNR respectively. The authors confirmed a main effect was found for group, where the largest relative difference was found when using the different-sex masker. The results are surprising, given that the study was created to assess informational masking effects, no spatial benefit was found in either group for the different-sex babble masker or from the speech-envelope modulated noise. These would provide some energetic masking and moving the interferer source (partly) to 60° would have provided some spatial cues to use. The authors address the issue of confounding effects at the level of ageing and its infleunce on the precedent effect. No interaction was found between spatial benefit and group and therefore, the authors conclude that the older adults received as much spatial benefit as the younger counterparts. This study was conducted in a double-walled sound-proor booth, and clearly this lacks real-world application in which reverberation can infleunce results.

Marrone et al. (2008b) investigated the role of reverberation and hearing loss on SRM. They were interested in how higher level processing, such as selective attention, could influence SRM. They recruited 10 participants in each of four groups; NH young listeners, HI young listeners, NH older listeners and HI older listeners. The CRM speech sentences were used for target material and as an interferer. The experiment was delivered over loudspeaker in a room where the reverberant properties were changed using custom fit panels with varying acoustic reflective properties. They had two paradigms for reverberation; one was the original soundproof booth layout with carpeted floors and perforated metal on the ceiling and walls (direct-to-reverberant energy ratio of 6.3 dB SNR). In the other paradigm, a plastic, glass-substitute was fitted to all surfaces to increase reverberation (direct-to-reverberant energy ratio of -0.9 dB SNR).

Stimuli were delivered from loudspeakers at 0° or +90° or -90°. NH young listeners obtained 11.6 dB SNR and 7.8 dB SNR SRM in the standard and reverberant room respectively. The HI young listeners achieved 8.5 and 3.9 dB SNR SRM. The NH older listeners recorded 4.9 and 3 dB SNR SRM. HI older listeners demonstrated 3 dB SNR and 1.4 dB SNR. The authors found that there was a significant main effect of room type (amount of reverberation) and hearing group, although it is unclear which of the three groups are significantly different from each other as no post-hoc analysis detail was provided. The authors suggest that hearing loss increases the amount of energetic masking that HI listener's experience. They used the CRM corpus which was aimed to emphasise informational masking, yet the reduced frequency and temporal resolution of the HI listeners may have provided greater spectrotemporal overlap of the material, and hence more energetic masking.

The difficulty when looking to analyse the results of SRM in HI listeners is that there is often a poor association between hearing thresholds and SRM. As such, investigators have considered how HI individuals use the cues available in an attempt to localise the problem. As it stands, there are five broad themes as to why HI listeners do not perform as well as NH listeners. Firstly, reduced audibility because of the hearing loss limits the availability of target speech information but also limits the use of fluctuations in the masker. Another broad theory suggests that the fidelity of spatial cues is reduced by a degradation of neural coding, which is referred to under the broad title of 'temporal fine structure' (TFS) processing. The third hypothesis is concerned with the relative changes in EM and IM from hearing loss, with some believing that HI listeners are more susceptible to EM than their NH counterparts (Helfer & Freyman, 2008). The final theme suggests a reduced ability to direct spatial attention (Glyde et al. 2015). This thesis is predominantly interested in the first three themes. Each of these has a component of bottom-up processing, whereas the fourth theme is exclusively a top-down or cognitive processing theme. This final theme is covered briefly in the final experiment of chapter 4 on contralateral masking.

1.4.4.1. Reduced audibility

The common clinical measure of hearing sensitivity is PTA. This provides absolute thresholds for hearing between 0.25 and 8 kHz. It is the basis for differentially diagnosing pathological conditions and provides a platform for hearing aid fitting. A hearing loss can be attributed to a number of causes, but ultimately the thresholds will exceed the normal range (>20 dB HL) and mean the person has reduced audibility.

It is helpful to consider the impact of reduced audibility on the SRT. The most obvious influence on SRT is the reduced dynamic range of the target. Initial estimates on the dynamic range of speech were in the region of 30 dB (Dunn & White, 1940), but more recently the suggestion is that speech has a dynamic range of around 50 dB (Zeng et al. 2002). A reduced audible range because of hearing loss will make less speech available when presented in quiet. When noise is presented, a hearing loss will hinder dip-listening if the dips are below the listener's absolute threshold.

1.4.4.2. Dip-Listening

Dip-listening is also referred to as auditory glimpsing or masking release and it describes how the auditory system has an opportunity to gain more information about the target material when there are temporal gaps or dips in the interfering source. These gaps and dips are collectively referred to as modulations and it means the envelope (E) will have moments of fluctuation in the intensity of the sound. When the interferer E is in a dip, the target has more impact in the periphery (on the basilar membrane) and would be more readily detected.

Early work can be found on the influence of modulations in the interfering source (Miller, 1947). It is believed the optimum modulation frequency for NH listeners to perform dip-listening and gain maximum benefit is 10 Hz (Miller & Licklider, 1950), although others report this to be between 16 and 32 Hz (Festen & Plomp, 1986b).

Experiments conducted to explore dip-listening in HI listeners report a reduced ability to take advantage of the dips in the interferer. This has been postulated as one of the reasons for poor speech-understanding in background noise in those with hearing loss. It was believed that the reduction in compression, as a result of hearing loss, was the reason for reduced levels of dip-listening (Culling & Stone, 2017). However, there could be an experimental confound. Oxenham and Simonson (2009) found the SNR level influenced dip-listening in NH listeners. Studies comparing NH and HI are comparing groups who achieve the usual criterion of 50% correct at different SNRs.

To consider dip-listening effects separately from ageing, a study was conducted using young HI participants and SRTs measured in both a fluctuating interferer and unmodulated noise (Festen & Plomp, 1986b). The difference in SRT between these two conditions was deemed the result of dip-listening. The 20 listeners in the NH group gained a 5.5 dB SNR benefit on average from the modulations whereas the 12 young HI listeners only achieved 1.2 dB SNR benefit on average. As such, this 4.3 dB SNR

deficit in dip-listening was attributed to the hearing loss and not age-related changes in performance.

To follow this study up, the same authors conducted another study but used different types of fluctuating interferers in an attempt to investigate irregular modulations and the effect these have of speech understanding in noise. They used a number of interferer types that were intermediate between steady-state noise and running speech. The interferers in between these extremes were single-band-modulated noise, two-band-modulated noise (low and high frequency with cut off frequency of 1 kHz) and time-reversed-speech (Festen & Plomp 1990). They recruited 20 NH listeners with an age range of 16-36 years of age. They also recruited 20 HI listeners but this time did not limit the age, with an age range of 21-77 years of age. The HI listeners had higher/poorer SRTs in all conditions compared to the NH listeners and showed very little difference in the SRTs across the different interferers. The one exception to the rule was the SRTs observed when using time-reversed speech from the same talker. Both NH and HI listeners showed relatively high/poor SRTs in this condition. There was no condition using forward speech from the same talker. The average SRT differences between the two groups for steady-state noise, speech masker, single band modulation and double band modulation were 4.0, 10.3, 7.0 and 9.3 dB SNR respectively. All four of these group comparisons for the different interferer type were significantly different, although the SRTs gained when using a fluctuating interferer are far more distinct when comparing the groups. It is clear that when using the fluctuating interferer, the HI listeners have real difficulty taking advantage of the fluctuations compared to their NH counterparts and the type of fluctuating interferer appears irrelevant. They found no influence on the results from age.

Poor dip-listening in HI listeners has previously been attributed to three causes (Bronkhorst & Plomp 1992). The advantage during dips in an interferer is reduced by threshold elevation, whereby the dynamic range is reduced and so the information available in the quietest portions is inaudible. Dip-listening is generally a skill that requires temporal processing skills, and at higher rates of modulation the temporal resolution ability of HI-listeners will be poorer. Cochlear hearing loss has been proven to result in poor phase locking at the auditory nerve (B. Moore, 2007, p. 35), for reasons still unknown, and this is why the temporal resolution in HI listeners is poorer. Poor temporal resolution will, in effect, smooth the perceived masker fluctuations. Unfortunately, a hearing aid would not address these issues at the auditory nerve level.

Wearing a hearing aid provides amplification of the sound in a compressive manner but if the issue of poor dip-listening is at the auditory nerve, then a hearing aid will make little difference to the user in a complex listening environment.

The final reason refers to comodulation masking release (CMR). When a pure tone is masked by noise, the noise bandwidth can be increased and the tone threshold increases up to a critical point. Further increases in the masker bandwidth after this critical point have no influence on the threshold, if the noise remains steady state, and this is known as the critical bandwidth (Fletcher, 1940). However, if the noise contains modulations that are coherent over the entire noise band, increasing the noise past the critical bandwidth results in a decreasing tone threshold. This is known as CMR and Bronkhorst and Plomp (1992) believed it to be one of the reasons why HI listeners are unable to take advantage of dip-listening. The thought is that HI listeners show a reduced CMR (Hall, Davis, Haggard, & Pillsbury, 1988) and the advantage of masker fluctuations to speech in noise is partly caused by CMR. Thus, a deficit in CMR leads to a deficit in dip-listening, which in turn, leads to a deficit in speech intelligibility in modulated noise (compared to NH listeners).

1.4.4.3.   Temporal fine structure processing

ITD cues are a component of the overall SRM and the processing of ITD information is dependent on TFS processing. Difficulty with TFS processing has been highlighted as a potential reason for the difficulties encountered by those with HI when in the presence of background noise (Hopkins, Moore, & Stone, 2008; Lorenzi, Gilbert, Carn, Garnier, & Moore, 2006). There are a number of psychophysical measures that can be used to determine the integrity of TFS processing. Monaural detection and discrimination of low-rate frequency modulation (Strelcyk & Dau, 2009), monaural discrimination of pitch in complex harmonic sounds (Moore, Hopkins, & Cuthbertson, 2009) and monaural speech recognition with varying amounts of TFS (Hopkins & Moore, 2009) are all examples of TFS processed when the stimulus is presented to one ear only. Binaural measures that reflect (in part) TFS processing are Binaural Masking Level Difference (BMLD) (Hall, Tyler, & Fernandes, 1984) and discrimination of ITDs (Lacher-Fougère & Demany, 2005).

Binaural Masking Level Differences can be traced back to Hirsh (1948) who used three normally hearing subjects in six different conditions of tone detection in noise. A mixture of monaural and binaural presentations was used, with phase inversion across the ears for the binaural presentation of either tone or noise. The aim was to establish

which condition gave rise to the lowest threshold (optimum detection). The reference condition was tone and noise in phase in both ears (N_0S_0). The test condition where both the tone and noise were presented binaurally, but the tone was out-of-phase and the noise was in phase across the ears (N_0S_π), was the condition that allowed optimum detection (Hirsh, 1948). The difference between these two conditions is known as the BMLD and these can be as high as 15 dB SNR using a 250 Hz tone and down to 2-3 dB SNR for frequencies above 1.5 kHz tones.

One of the first studies to report BMLD findings in those with HI used a NH control group to compare BMLDs in both narrow-band noise and wide-band noise (Hall et al. 1984). Using a 500 Hz pure tone and a wide-band noise (40-1000 Hz) the HI group had on average a 5.1 dB SNR smaller BMLD, but using the narrow-band noise (475-525 Hz) this difference was on average only 2.4 dB SNR. The authors found a strong negative correlation with BMLD and the 500 Hz PTA threshold when using the wide-band noise paradigm (r = -0.81, p< 0.01), but weaker correlation when using the narrow-band noise (r = -0.65, p<0.01).

More recently, an investigation was conducted that used BMLDs, among other psychophysical measures, to assess binaural TFS processing (Strelcyk & Dau, 2009). They used a three-interval three-alternative forced-choice approach with a 750 Hz tone in wide-band noise (50-1500 Hz). They also used the classic BMLD paradigm of N_0S_0 compared to N_0S_π and presented the tones at 35 dB SPL. The six NH subjects had a mean BMLD of 10.7 dB SNR and 10 HI subjects had a mean BMLD of 9.6 dB SNR. Although the masked thresholds were significantly higher in the HI group, the difference in BMLD between NH and HI groups of 1.1 dB SNR was not significant. A critical factor to consider is the presentation level of the tone at 35 dB SPL. All the SNRs were positive so the noise spectrum was lower than 35 dB SPL and therefore much of the noise may well have been inaudible for the HI group.

It is acknowledged that the BMLD increases as the level of the masker increases. One explanation of the smaller BMLDs in HI listeners is due to the low SL caused by elevated thresholds (Staffel, Hall, Grose, & Pillsbury, 1990, p. 1720). Loudness recruitment means it is often not possible to use high SLs. This does not provide a complete explanation for the reduced BMLDs in HI listeners. BMLDs recoded in NH and HI listeners with matched SL of 60 dB still found lower BMLDs in HI listeners (Quaranta & Cervellera, 1974).

Hall et al. (1984) also investigated the discrimination of ITDs. Using a pure tone of 300-ms duration, the signal was time shifted but the left and right channels were gated on and off at the same time so that the only difference was ongoing ITD and not onset ITD. A three-interval, three-alternative forced-choice paradigm was used to measure the threshold for ITD discrimination, referred to as delta time (Δt). The NH Δt mean was 64.6 µs whereas the HI mean was 176.4 µs. It is clear that increasing hearing impairment results in larger Δt. A strong positive correlation of 0.74 (p<0.01) was found between Δt and PTA threshold at 500 Hz.

When assessing binaural TFS processing through ITD discrimination it is tempting to delay the whole waveform at one ear compared to the other. The difficulty with this approach, when using just a simple delay to the waveform across the ears, is that E or TFS cues could potentially be used as a cue. It has been suggested that a more sensitive approach is the use of amplitude modulated (AM) tones to allow investigation of the E and TFS ITDs independently. One study using this approach has used three carrier frequencies (250, 500 & 1000 Hz) with sinusoidal amplitude modulation (two modulation rates of 20 & 50 Hz). The ITDs were measured for the carrier frequency only or the amplitude modulation only (Lacher-Fougère & Demany, 2005). In doing this, the TFS task was the carrier frequency ITD whereas the E task was the amplitude modulation ITD. The results indicated a deficit in the HI group in both E and TFS ITDs. However, there was a 2.9-4.1 fold higher ITD in the E tasks for HI but a 6.5-19.7 fold higher ITD in the TFS tasks for HI. This range covers the different carrier frequency and amplitude modulation rate configurations. The largest difference found between HI and NH was in one of the TFS tasks with a 250 Hz carrier frequency and 20 Hz amplitude modulation rate (geometric mean of 3.37 degrees in NH compared with 66.28 degrees in HI, hence ratio of 19.7). In contrast to Hall et al. (1984), here the correlations between TFS ITD and 500 Hz PTA threshold were not strongly correlated (r= 0.09 and r= 0.26 for 20 Hz & 50 Hz amplitude modulation rate respectively).

TFS processing is also believed to underlie the ability to discriminate F0s in target and interfering sources (Brown & Bacon, 2010). The same ability to use F0 in discrimination tasks, concurrent vowel identification or sentence reception is generally poorer in HI listeners than NH listeners (Summers & Leek, 1998).

1.4.4.4. Use of the head-shadow with hearing-impairment

The fourth reason why hearing loss may compromise SRM is that those listeners with HI may be prevented from accessing the improvements in the SNR in the better-

ear. Better ear listening is facilitated by the head shadow effect when the competing sounds are spatially separated and it is unclear why those with hearing loss are unable to take advantage of improved SNR at the better ear to the same extent of NH listeners.

There have been attempts to isolate the ILD and ITD contributions to SRM with HI listeners. The first study to investigate the use of ILDs and ITDs independently used a simulated unilateral hearing loss in a group of NH listeners (Bronkhorst & Plomp, 1988). They reported that the use of ILDs was significantly reduced when the overall presentation level was decreased on the side with the most favourable SNR. The use of ITDs appeared unaffected when sound was attenuated at one ear. This indicates a unilateral hearing loss would significantly diminish the benefit of ILDs when the interfering noise source was in the hemisphere of the better-ear, presumably because portions of the target fall below the absolute threshold.

The authors completed a follow-up study in which they included 17 participants with a symmetrical HI (Bronkhorst & Plomp, 1989). Using an interfering source at 90°, they found the SRM to be 7.1 dB SNR and then ILD alone to 4.6 dB SNR and ITD alone to be 4.2 dB SNR. These effects of ITDs are similar to those found with NH subjects in the previous study (mean of 4.7 dB SNR) whereas the effects of ILDs are significantly different from the results found in NH (6.5 dB SNR). Interestingly, they report a large spread in the data within the ILD results, with some HI giving results close to normal and others performing very poorly.

A high frequency hearing loss may result in poor use of the high frequency cues used in better-ear listening. An inability to take advantage of ILDs, which result in a head-shadow and improved SNR at one ear, is postulated as one reason for the smaller SRM seen in HI listeners (Bronkhorst & Plomp 1989; Bronkhorst & Plomp 1992). However, the suggestion from some models is that the hearing loss has to reach a certain criterion (i.e. 50 dB HL) before this effect can be seen (Festen & Plomp, 1986a; Plomp, 1986) and other studies have been unable to find an association between hearing threshold and SRM.

1.4.4.5. The relationship between the audiogram and spatial release from masking

One of the first studies to consider the relationship between hearing loss and SRM came in 1989. Bronkhorst & Plomp (1989) had 17 symmetrical HI participants, they used 0.25, 0.5, 1, 2 & 4 kHz as well as the total PTA as dependent variables in a multiple regression analysis. They found an association between measures of spatial

benefit (which they refer to as FF) and hearing thresholds at 4 kHz. The difficulty interpreting this finding is that the PTA thresholds were averaged across the ear and the SRTs were all grouped together.

In another study, 3 years later, they again used 17 symmetrical HI participants, and multiple regression was used to study the relation between SRM performance and PTA thresholds at frequencies of 0.25, 0.5, 1, 2, & 4 kHz (Bronkhorst & Plomp 1992). Using various numbers of fluctuating maskers between one (at 90°) and six (at 30° steps), the authors claimed a moderate level of correlation of 0.58 (p=0.014) between PTA and SRM. However, the dependent variable was an average SRT across all conditions so it is difficult to specifically make associations between PTA and SRM.

Ter-Horst et al. (1993) investigated simulated SRM (over headphones) with symmetrically placed steady-state maskers. In this case, one would expect SRM due to the head-shadow effect, to be greatly reduced by the presence of another masker symmetrically displaced. With 15 NH and 64 HI subjects, correlations of SRM with audiometric thresholds at frequencies of 0.25, 0.5, 1, 2, 4 & 8 kHz plus a 4 frequency average (0.5, 1, 2 & 4 kHz) were investigated. When the target was at 0° and maskers at either +/- 18° or +/- 54°, no significant correlations were found with one exception between 4 kHz and maskers at 18° (r = -0.28, p<0.05). However, as mentioned previously, the SRM results should be interpreted with caution because they used two correlated noise sources. This has the potential for comb-filtering effects to give unreliable results (Noble & Perrett, 2002).

In another study, correlations between SRM and PTA thresholds were investigated using eight NH and eight HI subjects with varying numbers of interferers (Peissig & Kollmeier, 1997). The HI subjects were separated into three distinct groups, not based on the PTA thresholds but on the amount of spatial benefit they had demonstrated. It was reported that the degree of hearing loss was not directly related to the spatial benefit they had achieved, although no statistical information was provided in the article. The typical approach to obtaining SRTs is to use an adaptive staircase paradigm but in this study, the subjects were requested to adjust the level of the test sentence to a value that subjectively represented 50%.

It would appear the results of SRM in those with hearing impairment are heterogeneous when hearing thresholds are taken into account. Some support for a link is provided by correlations between higher PTA thresholds (2 & 4 kHz) and SRM in the account early (Bronkhorst & Plomp 1989; Bronkhorst & Plomp 1992), and one would

expect a link to high-frequency hearing thresholds. However, there seem to be a number of other studies that were unable to confirm these findings (Peissig & Kollmeier, 1997; Ter-Horst, Byrne, & Noble, 1993). Even in those who do propose a relationship, the strength of the relationship should be considered. Bronkhorst and Plomp suggest only $1/3^{rd}$ of the variance in the typical SRT can be explained by the audiogram. It appears that reduced audibility alone does not completely explain the poorer SRM in HI, and there are supra-threshold deficits.

1.4.4.6. Ageing effects

Ageing has been postulated as a suprathreshold deficit separately from hearing loss. It has been reported that ageing has a detrimental effect on our ability to understand speech in the presence of noise when we consider listeners with NH thresholds (Kim, Frisina, Mapes, Hickman, & Frisina, 2006). One of the difficulties facing researchers who investigate speech intelligibility in background noise is the confounding effects of ageing and hearing loss. It is important to recognise the relationship between hearing loss and ageing and how these may be analysed independently. For instance, the study conducted by Gelfand et al. (1988) which was reviewed in section 1.4.4. concluded that the reduced SRM in the HI listeners was attributed to the hearing loss rather than ageing.

However, there have been numerous studies that have allowed hearing loss and age to co-vary which potentially leaves them vulnerable for scrutiny regarding confounding effects. Some have attempted to control for age (Dubno et al. 2002; Hawkins & Wightman, 1980) and demonstrated spatial hearing performance is reduced in those with hearing loss. The real difficulty in controlling for both hearing loss and age is the lack of statistical power even with a large sample size.

This issue was addressed by Gallun et al. (2013), who designed a study with enough statistical power to quantify whether ageing alone had an impact on SRM. They proposed that the impact from hearing loss and ageing act at different levels of the auditory system. It was suggested that the impact of hearing loss was related to reductions in the responses at the level of the auditory nerve, whereas ageing impacted the temporal processing at the level of the brainstem. They used CRM material to measure SRM. In this test, listeners hear sentences such as "Ready Baron, go to BLUE SIX, now", against a similar competitor, such as "Ready Ringo, go to RED NINE, now". Listeners are required to recognise their call-sign ("Baron") and report the corresponding colour/number combination. In experiment 1 of the SRM study, they

created four conditions, all of which had the target speech delivered through a loudspeaker at 0°. Using one target CRM speaker and two CRM interferers, condition one consisted of all three co-located at 0°. Condition two had the two interferers split at +/- 15°. Condition three consisted of interferers at +/- 30° and condition 4 they were +/- 45°. They repeated each condition with four different gender combinations with male and female taking the part of target or interferer (male/male; male/female; female/male; female/female). They also recorded SRTs in quiet with target speech alone at 0° to familiarise the participants with the test and to ensure audibility.

They had 34 participants in experiment 1 with an age range between 25-74 years, the mean age was 50.3 years. All participants had fairly symmetrical hearing loss, with PTA thresholds below 2 kHz all lower than 50 dB HL. The high frequencies were worse, in some cases up to 95 dB HL. The authors used a within-subjects Analysis of Variance (ANOVA) where they used the target (male or female), masker (same gender or different gender) and spatial separation (0, 15, 30 and 45°) as within-subject variables. They used between-subject variables of age, and SRTs in quiet as covariates. They chose SRT in quiet as a covariate because it was the "most influential measure of hearing sensitivity based on exploratory stepwise regression with a variety of potential predictors, including individual frequency thresholds and various pure tone averages" (Gallun, Diedesch, Kampel, & Jakien, 2013, p. 3).

The analysis revealed that between-subjects factors of age and SRTs in quiet were both statistically significant. Over 32% of the variance was accounted for by age and SRTs in quiet. As such, the authors concluded that the factors of age and hearing loss were independently responsible for SRM. They came to this conclusion because the patterns of results when considering age and SRTs in quiet were very similar, yet the shared variance between the two factors was very low (<5%).

They ran a 2nd experiment with 52 participants (9 from experiment 1) where they attempted to control the hearing loss factor by varying the level of output provided over ER2 insert earphones. They used an equal sensation level signal, which was derived by obtaining the lowest level in dB HL at which the participant could just identify the target speech. They converted from dB HL to dB SPL by adding 22 and then added an extra 30 dB to give the level of the target speech. The target speech stayed constant while the interferers were adaptively altered (as was the case in experiment 1). This time around, they only tested 0 and 45° and only the male target speech. The results

from experiment two confirmed the results from experiment one in that age reduced SRM independent of hearing loss.

SRM is underpinned by an ability to use ILD and ITD cues and other researchers have focused on this level of analysis. Many of the studies investigating BMLD or ITD discrimination in those with HI have not fully considered or investigated the independent influence of ageing. One study that did consider this assessed BMLDs in 12 NH young adults (mean age of 22.3 years) and 12 older adults (mean age of 68.5 years) who had NH thresholds (< 25 dB HL) from 0.25 to 2 kHz (Pichora-Fuller & Schneider, 1992). They used the standard reference condition of S_0N_0 but then a different test condition of $S_\pi N_{\pi r}$ which meant that both the pure tone and noise were phase-reversed to the ears and they also added an interaural delay to the noise. This test condition was chosen based on a previous study they had conducted (Pichora-Fuller & Schneider, 1991) in which the $S_\pi N_{\pi r}$ condition gave larger BMLDs in younger adults compared to older adults. They hypothesised this to be due to less temporal jitters from younger adults when they realign the right and left ear inputs through an internal interaural delay line, which for $S_\pi N_{\pi r}$ has an optimum internal delay of 0 ms.

In the Pichora-Fuller & Schneider (1992) study, the results from the N_0S_0 condition was similar between young and old (54 & 55 dB SPL respectively) but the $S_\pi N_{\pi r}$ pattern of results differed significantly with the young having larger BMLDs. They tested different interaural delays in the $S_\pi N_{\pi r}$ condition and found the greatest age-related differences were present at interaural delays that provide the maximal BMLD (these were delays that were equal to odd multiples of the half period of the tone frequency). Clearly, the results from Pichora-Fuller & Schneider (1991) & Pichora-Fuller & Schneider (1992) suggest that under certain dichotic conditions, there is a difference in BMLD between young and older listeners.

A later study investigated ITD discrimination in 12 NH young adults (mean age of 26.1 years) and 12 elderly adults (mean age of 70.9 years) (Strouse, Ashmead, Ohde, & Grantham, 1998). All subjects had hearing thresholds within normal range (<20 dB HL) from 0.25 to 6 kHz. They presented two sets of 400-ms-long trains of 50-µs rectangular clicks with an interclick interval of 10 ms. The ITD was implemented through shifting signal delivery to one ear by an integer multiple of the sampling period (200 kHz sampling rate, so sampling period of 5µs). Using an adaptive 2-interval forced-choice paradigm, the first interval had 0 µs ITD (so simultaneous at each ear) and then second interval had an offset in the two channels in 5 µs intervals. The ear receiving the

30

delayed click train was selected at random and the participant indicated on a keyboard if the sound was to the left or the right. The initial trial had an ITD of 100 µs and then step size was 20 µs until the first reversal, where the step size was reduced to 5 µs. Threshold was determined after 10 reversals and estimated from the geometric mean of the ITD from the last 8 reversals. This is an unusual approach, using the geometric mean is sufficient only when the adaptive steps are logarithmic. The effect of sensation level was investigated at three different levels; 4, 8 and 16 dB SL (above threshold). The ITD thresholds for the young adult listeners were significantly lower than those of the older adult listeners at 16 dB SL, 8 dB SL, and 4 dB SL. The same study also investigated speech BMLDs and found a 2 dB SNR age effect on the BMLD. In the context of speech intelligibility, a 1 dB SNR loss can be attributed to as much as a 20% reduction in performance (Plomp, 1986).

More recently, there has been a move to compare electrophysiological and behavioural results to investigate the effects of ageing and hearing loss on neural IPD processing (Vercammen, Goossens, Undurraga, Wouters, & van Wieringen, 2018). Vercammen et al. (2018) used young, middle-aged and older participants. They had a group of NH listener and HI listeners for each age category. The six groups were tested on the Interaural Phase Modulation Following Response (IPM-FR). This is an electrophysiological measure in response to the changes in phase of an acoustic stimulus where steady state activity in the Electroencephalogram (EEG) is represented in the amplitude of the IPM-FR. They also collected behavioural data in the form of thresholds for Interaural Phase Discrimination. Reduced amplitudes of the IPM-FR were found for all groups with HI listeners. However, thresholds for Interaural Phase Discrimination were not different for the HI listeners. The explanation for this is that the electrophysiological measures suggests that binaural neural processing is altered with hearing loss, and the behavioural measure is a simple detection task and may only require a few neurons to fulfil the task. Correlational analysis revealed similar patterns of results from the two tests, which would imply that similar mechanisms underlie the measures. Ageing effects were also found in the Interaural Phase Discrimination, with older adults showing larger thresholds than younger and middle-aged listeners. The results also demonstrated that reduced amplitudes of the IPM-FR set in around middle-age. This slight difference between the effects of age could be explained by the fact that IPM-FR measured binaural TFS processing at suprathreshold levels whereas Interaural Phase Discrimination is measured at threshold level. The authors describe a "dual load" (Vercammen et al. 2018, p. 10) that could pose serious challenges on the binaural

auditory system for every day listening. They introduce the notion of binaural training as a means of addressing the deteriorations seen in binaural TFS processing.

In order to systematically quantify the associations of binaural TFS processing, hearing loss and ageing, Füllgrabe and Moore (2018) conducted a meta-analysis. They were interested in studies that reported findings from the TFS-low frequency test (Füllgrabe, Harland, Sęk, & Moore, 2017; Hopkins & Moore, 2010). Füllgrabe and Moore (2018) claim the TFS-low frequency test has small practice effects and it has been used in a number of studies with large data sets. The standard TFS-low frequency test is a two-interval, two-alternative forced-choice test. It measures the threshold for detecting changes in the interaural phase difference from bursts of pure tone at 30 dB sensation level. In the standard interval, four low-frequency pure tones are presented, each with zero interaural phase difference. In the test interval, the 2nd and 4th burst of pure tone have an interaural phase difference. The phase difference in the test interval is adaptively varied using a two-down, one-up method.

Having filtered the studies down to 16 published and three unpublished data sets, the meta-analysis confirmed previous reports that both age and hearing loss correlate with the ability to process binaural TFS information. The authors found that age was more strongly correlated with binaural TFS processing. However, the percentage of variance accounted for by hearing loss and age was relatively small (approximately 42%). The authors acknowledge a large amount of individual variability in binaural TFS sensitivity exists in the data sets, which cannot be account for by hearing loss or age.

1.4.5. Hearing aids and the influence they have on spatial release from masking

One might expect that because a hearing aid partially restores audibility, it would enable a HI listener to display similar SRM to NH listeners. However, there are a number of reasons why this may not be so. Firstly, two hearing aids process sounds separately, and therefore, there are a number of signal processing strategies that work independently. For instance, noise reduction, compression and other adaptive algorithms will alter the interaural cues available (Marrone et al. 2008a). A simulation of linked compression across the ears in NH has proven that the process improves audibility so the assumption is that this would be of benefit to hearing aid users, although clinical research on this is lacking (Wiggins & Seeber, 2013).

Secondly, HAs do not provide amplification of sound that linearly corresponds to the HL. Recruitment (which refers to abnormal loudness growth) is a problem for those with a SNHL and this means that it is only viable to provide a mirror in amplification for HL when listening at threshold. When the intensity of sound increases from threshold the gain of the HA is typically lowered. The amount of gain can vary depending on the prescription formula used.

Although HAs restore some high frequency information, the results of the studies on hearing aid users and SRM paint a confused picture. Early reports implied subjects performed better when unaided (Festen & Plomp 1986a). Others report improved SRM with a hearing aid compared to unaided so long as there is plenty of high frequency information (Ahlstrom, Horwitz, & Dubno, 2009) and the earmould used is closed and not open (William, Noble, Sinclair, & Byrne, 1997). Other reports indicate improvement with two aids when compared to one (Marrone et al. 2008a; Moore et al. 1992) although the SRM improvement with HAs does not return to the levels of NH listeners.

Some would argue that HAs are unable to restore NH levels of SRM because the HAs are unable to provide temporal and spectral resolution that NH listeners achieve. A recent article by Cubick, Buckholz, Best, Lavandier & Dau (2018) suggests that when NH listeners are fitted with HAs, their performance deteriorates. The SRM decreased with the use of the hearing aids. SRTs in the co-located conditions were similar in the aided and unaided conditions, but then then the aided performance deteriorated when the interferers were moved away from the target. An interpretation of this result could be that the hearing aids distorted the spatial cues available. However, a flaw in the approach taken in this study is that they provided a linear gain amplification through a real-time PC-integrated hearing aid processing system. Providing gain is not a fair approximation of current hearing aid processing strategies, as will be made clear in chapter 2. Kwak et al. (2018) used experienced HA users in their study and assessed spectral ripple discrimination, temporal modulation detection, speech recognition thresholds in noise and speech discrimination in quiet. They report no difference to the spectral and temporal resolution in the aided vs unaided comparison. Although no benefit was achieved with the hearing aid for spatial processing, they were not detrimental to performance either.

Poor performance of HI listeners in complex listening situations is a common occurrence. A number of factors influence performance, such as the location of the

interfering sources, the number of interferers present, the spectrotemporal properties of the interferer, and the reverberation of the environment. These factors have been studied independently and rarely together. This is the inspiration for chapter 2, where a virtual listening situation is created to replicate the real-world. To date, speech intelligibility in background noise research has largely considered the head in a static position. The reality is that people move their heads freely and in chapter 3, head orientation benefit is investigated in a virtual listening environment. Much of the work investigating HI listener's speech intelligibility in background noise report heterogeneous results. The work in chapter 4 takes the form of a forensic analysis of HI listener's use of spatial cues. The aim is to link poor use of spatial cues with an underlying mechanism in order to improve understanding.

2. The effect of masker source characteristics on speech intelligibility in a virtual restaurant

It is important to investigate speech intelligibility in noise with HI individuals because difficulty with this task is the primary complaint of this group (McCormack & Fortnum, 2013; Kramer et al. 1998; Tyler et al. 1983). There are a number of speech in noise tests available that allow clinicians to investigate functional performance of HI listeners. For instance, some of the most common measures are the Hearing In Noise Test (HINT) developed by Nilsson et al. (1994), Quick Speech In Noise test (QuickSIN) developed by Killon et al. (2004), Bamford-Kowal-Bench Speech In Noise test (BKBSIN) developed by Etymotic Research (2005), the Listening in Spatialized Noise Sentence Test (LISN-S) developed by Cameron, Dillon & Newall (2006) and the Words in Noise test (WIN) developed by Wilson (2003). These measures have greater face validity over pure tone audiometry as they use target speech material and provide interference via sources of noise. These measures vary in the specific type of target material and interferer, but they are all relatively basic in their delivery and are poor approximations of real-life listening. In fact, there have been numerous studies that have compared laboratory measures against real-life self-reported benefit of hearing aid use and many of them show disparities between the two (for instance Gnewikow, Ricketts, Bratt & Mutchler, 2009; Wu, 2010; Johnson, Xu & Cox, 2016). These studies confirm the necessity to improve the ecological validity of auditory assessments.

To investigate the factors that are involved in understanding speech in real-life, it is necessary to develop experiments that recreate a realistic listening environment. In creating more ecological valid listening scenarios, it should be possible to predict, with more accuracy, the impact of hearing impairment on the capacity to perform everyday tasks. There have been recent advances in the area of 'realism' when considering the full communication process between two speakers. Hadley, Brimijoin & Whitmer (2019) were interested in the behaviour of two people communicating and how acoustic variables, such as the level of background noise, influence speech, movement and gaze. The realistic environment was re-created in a sound attenuated room. Loudspeakers were used to present the noise, a head tracker and eye tracker for head and eye motion respectively and a microphone to record speech levels. As noise levels increased, they found that people increased their speech levels and used shorter speech utterances. They also found that people moved closer and increased gaze on the speaker's mouth when

noise levels increased. Interestingly, they found listeners did not orientate their heads to benefit speech intelligibility in noise and that when noise levels increased, gaps between speech diminished and therefore turn-taking became less efficient.

Another study that was interested in the more global aspects of conversation was conducted by Beechey, Buckholz & Keidser (2019). Their claim was that simple sentence recall tasks do not reflect the specific requirements of engaging in conversation and the challenges this brings. Namely, the static speech intelligibility tests differ from conversation in "interactivity, speech and language content, cognitive demand and intrinsic motivation". Comparing 20 NH and 20 HI participants in a referential task containing a find-a-path logic puzzle, the authors presented five different acoustic environments; open plan office, television in a room, church hall during a social gathering, reverberant café and traffic on a busy road. These acoustic environments were recorded from real-life scenarios and played back to the participants through open headphones during the task, which was conducted in a soundproof room. Microphones were used to record speech from the participants and questionnaires were completed post-task to assess subjective experiences of the conversations. The inspiration behind the referential task was that free speech has its drawbacks, variability in the task and lack of reproducibility make comparison across participants and groups more challenging. The study found no group effect on difficulty rating which they report as a surprising result, although they report that it is possible that NH listeners increased communication efforts with HI when they perceived communication difficulties. This study has it merits in that it attempts to analyse the entire communication chain but it lacks the detail required to engage which acoustical features of the different scenes are problematic for the HI listeners.

Some useful information has been gathered through monitoring of hearing aid wearers in their natural environments and reporting the typical SNR faced by those with a hearing loss with ear level recording devices (Smeds, Wolters, & Rung, 2015) and chest level recording devices (Wu et al. 2018). This 'ecological' approach has its merits, mainly that it captures the actual experiences of those with hearing loss. However, to fully investigate the factors that influence speech intelligibility in background noise, it is necessary to develop experiments that recreate the real-world in the laboratory setting. This approach allows the experimenter to manipulate the stimuli in order to investigate the role of different perceptual mechanisms in real-life listening. In recent years, there have been a number of studies that have created virtual listening experiments that combine binaural cues, room reverberation and multiple interfering sources (Culling,

2013, 2016; Westermann & Buchholz, 2015b, 2017). Only one of these studies has used a group of HI listeners so the literature is sparse when considering the impact of hearing loss in these complex listening environments. Westermann & Buchholz's (2017) restaurant was completely simulated, whereas the work by Culling (2016) was based on acoustic measurements captured from a real restaurant.

For Westermann & Buchholz (2017), the primary aim was to consider how distance of sound sources from the listener influences the performance of HI listeners and what informational masking effects are identifiable in this setting. They recruited 16 NH listeners and 16 HI listeners and sat them inside a spherical, 41 loudspeaker array with a radius of 1.85 m in an anechoic chamber. To reproduce the two nearby masking sources, 4 smaller loudspeakers were suspended inside the array at a distance of 0.85 m from the listening position. The cafeteria the authors reproduced was 15 m long by 8.5 m wide and 2.8 m high. The reverberation time (T_{60}) was approximately 1.2 s. Seven dialogues were simulated around the room at different table locations, the two nearby monologues were simulated to be either +/- 11.25° or +/- 56.25° separated from target. The target speech was either 2 m or 4 m away.

In order to partially restore audibility for the 16 HI participants, the authors used the National Acoustic Laboratory Refined-Profound (NAL-RP) prescription formula to provide linear amplification to all 45 loudspeakers. The authors accepted that this does not provide ear-specific gain adjustments that a pair of hearing aids would produce and they attempted to ameliorate the issue by recruiting HI participants with symmetrical hearing thresholds ($\leq$ 10dB HL average across the ears). This is a disadvantage to presenting the stimuli over loudspeakers; using headphones allows ear-specific gain adjustment to be made based on the participant's hearing loss on each side.

They used two types of maskers to investigate the role of informational masking, a speech masker consisting of a mixture of seven background two-talker dialogues and two nearby monologues. As such, the effect of numerosity of interferers was not examined in great detail. The other interferer used was a vocoded masker based on the speech masker, although there are other forms of interferer that can be used to tease out informational masking effects, such as using reversed-speech. They attributed the differences in SRT between using speech and vocoded interferers as informational masking. They found informational masking effects of up to 4 dB SNR with NH listeners and 2-3 dB SNR in HI listeners. In both cases, the informational masking effect was only present when the nearby maskers were present. The results of their study suggest that HI listeners are potentially less susceptible to informational masking

than their NH counterparts. One reason given for this is that the SRTs are higher/poorer in the HI listeners and this means they work at higher SNRs. It is suggested that the informational masking effect diminishes as SNRs increase above 0 dB SNR (Brungart et al. 2001). The fact that the HI listeners were operating at higher SNRs than the NH group, yet they still demonstrated a statistically significant informational masking effect, could be interpreted as them being more susceptible to informational masking. A study that allows the HI listeners to operate at different SNRs and simulates aided and unaided conditions would be insightful in this line of enquiry.

Westermann & Buchholz (2017) used the BKB speech sentences (Bench, Kowal, & Bamford, 1979) and matched the long-term spectra to a 65-minute monologue from the speaker of the sentences. This 65-minute monologue was not used to create any interferer for the study and the standard approach of matching to the Long-Term Average Speech Spectrum of the target stimuli (Byrne et al. 1994) was not followed. The authors rationale for this was to make the sounds more natural for a cafeteria environment. To determine the SRT, they kept the masker constant and varied the target material level according to an adaptive, one-up one-down staircase method. This method allowed an estimation of the SNR that yielded 50% correct performance. It used a minimum requirement of 16 presentations with a decreasing step size of 5, 2 and 1 dB SNR (Keidser, Dillon, Mejia, & Nguyen, 2013). The end of a run was determined when the standard error fell below 0.8 dB SNR or 32 sentences had been presented, however this potentially introduces some variability in that the threshold could be based on different sentences with different participants.

2.1. Aims and hypotheses

It has already been established that adding more than two interfering sources in anechoic conditions can have a detrimental effect on speech intelligibility in noise with both NH listeners and HI listeners (Peissig & Kollmeier, 1997). However, the evidence on what happens in a real-life listening environment is limited. The aims of the present study were:

i)   To investigate the hypothesis that hearing loss results in poorer performance in meaures of speech intelligibility in noise. It is expected that the SRTs of HI listeners will be higher (poorer) than those with NH thresholds. Culling (2016) published results using the same paradigm for

NH listeners, whose data will be used as a comparison to investigate the outcomes for HI listeners.

ii) To investigate the hypothesis that hearing loss leads to poorer fundamental frequency (F0) processing. The perceptual segregation of concurrent sounds can be achieved by F0 processing, and the difference in F0 is greater when using material from talkers of different gender. However, results from Culling (2016) suggest this additonal separation had little effect in a complex listening environment. One aim of this study was to examine F0 processing in HI listeners and investigate if they could exploit this to aid speech understanding in a complex, real-life environment. Due to the F0 difference between the male (approx. mean F0 of 100 Hz) and female (approx. mean F0 of 200 Hz) speakers, it is hypothesised that the masking effect will be greatest when using interferers with the same gender as the target speech. In this case, the target material is from a male so the expectation is that the male interferer will have a larger masking effect. Age-related hearing impairment affects high-frequency so there would be an expectation that this low frequency processing of F0 is not appreciably affected in those with hearing loss.

iii) To investigate the hypothesis that the characteristics of the interferring source will differentially effect performance for those with hearing loss. Using different masker types (speech, reversed-speech, modulated SSN and SSN) allows a number of perceptual cues to be investigated. Using speech and reversed-speech allows an analysis of informational masking and comparing modulated SSN with SSN allows analysis of dip-listening. It is hypothesised, based on the results from Culling (2016), that using continuous noise interferers will have the greatest masking effect and the speech interferers will have the least masking effect. It is expected that reversed-speech and modulated SSN will fall in between these two extremes, with reversed-speech being closer to the results of the speech interferer. It is likely there will be a difference between speech and reversed-speech and this could be attributed to informational masking. This will however be dependent on the SNR and is likely to be present in limited conditions.

iv) To investigate the hypothesis that those with hearing loss demonstrate less benefit when the number of interferring sources is reduced. The number of interferring souces was considered by Westermann & Buchholz (2017) who used 2 monologues and 7 two-taker dialogues as interferers. However, this study aims to investigate the effect of numerosity of interferers in greater detail. Using 1, 2, 4 and 8 interferers, it is hypothesised that there will be a degradation in performance when more interfering sources are added but this will be dependent on the type of interfering source. It is possible that the SRTs for different maskers will converge with 4 to 8 interferers. The difference in performance between the different numbers of interferers is likely to be less pronounced in the HI listeners than in the NH results of Culling (2016), due to an inability to fully exploit dip-listening and fundamental frequency differences.

v) To investigate the hypothesis that reduced audibility accounts for the poorer performance in HI listeners. Restoring audibility to counteract hearing loss allows a more direct comparison with a control group of NH listeners. Glyde et al. (2015) have shown improved performance in speech in noise tasks with gain adjustments for HI listeners. Although improvements were made in their study, performance of HI listeners never reached the same level as the NH control group. The authors propose that other suprathreshold deficits remain even after accounting for audibility. In order to scrutinise the role of audibility in a real-life scenario, a companion study will simulate the work of a hearing aid by providing extra gain in different frequency bands. The aim is to determine if the extra gain improves performance and if so, to what extent. Previous work has attempted to provide this gain adjustment (Westermann & Buchholz, 2017), but this was provided as a generic alteration for loudspeaker output. The approach here would allow frequency-specific, ear-specific gain adjustments. In this study, we will collect the results with and without the NAL-RP gain adjustments to specifically investigate the potential benefit accrued from partial restoration of audibility. It is expected that the provision of more output over the headphones will make more of the target signal audible, and

providing this gain will result in a significant improvement in performance.

2.2. Materials and methods

Aberdare Hall is a building adjacent to the Cathays Park Campus of Cardiff University with a restaurant area that is a partly wood-panelled dining hall with tables and seats. This restaurant's acoustics was used as the basis of the virtual restaurant.

2.2.1. Binaural Room Impulse Responses

Binaural Room Impulse Responses (BRIRs) were recorded from the dining area through the tone sweep method (Muller & Massarani, 2001). Tone sweeps of 20 s were presented from a B&K Head and Torso simulator and recorded from a KEMAR manikin (ear-canal resonance removed using 512-point FIR filter using data from Killion (1979)). Aberdare Hall dining area is divided into two via wooden screens. The BRIRs were recorded in the southern section of the hall with the wood screens in place. This section is carpeted and contains 14 tables for between 2 and 6 people (see Figure 2.1).
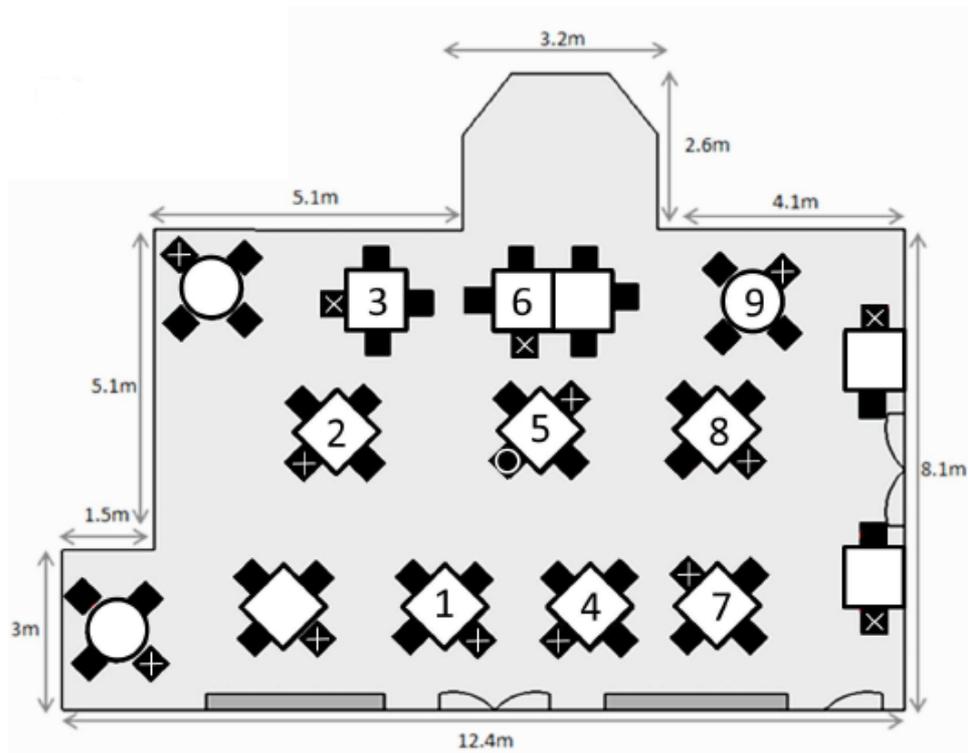
Figure 2.1 Aberdare Hall at Cardiff University where the BRIRs were recorded. Table layout and numbers are provided. The crosses represent locations of interferers and the circle is the KEMAR manikin location.

2.2.2. Interferers

Six-minute monologues were downloaded from Librivox audiobook recordings (librivox.org) from 4 male and 4 females to create the interferers. These were in mp3 format with a sampling rate of 44100 Hz. For each gender, the long-term excitation patterns (Moore & Glasberg, 1983) were equalized using custom designed 512-point FIR filters and then to published norms for male and female speech (Byrne et al. 1994). The speech interferers were used in MATLAB to create three other interferers; reversed-speech, modulated SSN and unmodulated SSN. Of particular interest is the influence of energetic and informational masking on those with hearing loss. In order to address this issue, deviations from complete realism were taken (i.e. use of reversed-speech interferer as well as the use of noise). Interferers were convolved with BRIRs from eight tables around the centre table, and added together to simulate different numbers of concurrent voices. With each additional interferer, corrections were made to keep the masker level constant. Table 2.1 provides detail on the distribution of voices in the different conditions.

42

Interferers	Male	Female
1 Male	3	
1 Female		3
2	3	7
4	3, 9	1, 7
8	2, 3, 4, 9	1, 6, 7, 8

Table 2.1 Details of the table location the number of the interferers and the gender of the voices (or noise spectra) placed at the table.

2.2.3. Targets

Target speech consisted of the Harvard IEEE corpus sentences (Rothauser et al. 1969) from a male (DA) with an American accent. Using MATLAB, these were convolved with the BRIRs collected from the same table as the listener (table 5). They were also equalized to published norms for male speech (Byrne et al. 1994). Previous studies have used BKB sentences (Westermann & Buchholz, 2017) which provides the potential for 336 sentences to be used in total. Familiarity with the test material has the potential to confound the effects under investigation. Using IEEE sentences in this study, with a potential for 720 sentences, ensured that there was no repetition of target material used during the experiment.

2.2.4. Laboratory setup

A single-walled IAC soundproof booth was used for testing. A Windows PC sat outside operating MATLAB. An external amplifier (Project Headbox SE-II) was connected via an Edirol UA-20 soundcard to the PC and this was then connected to a set of Sennheiser HD650 circumaural headphones inside the booth, via a 6mm jack socket on the interface panel. Using a monitor outside the soundproof booth provided instructions on the requirements of the task and when to respond. A microphone housed inside the booth relayed the response to the experimenter via an amplifier and a set of headphones, which the experimenter used outside the booth to score the responses.

2.2.5. Procedure

SRTs were measured using an adaptation of the (Plomp & Mimpen, 1979) method in MATLAB. The SRT was established by fixing the interferer level and adaptively varying the target sentence to provide a 50% correct word identification. Using an adaptive method limits the recognition scores to the linear portion of the psychometric function and avoids ceiling and floor effects (Crandell, 1991). At the start of each trial, the SNR was low (i.e. -28 dB SNR). Starting in an ascending manner rather than descending ensured the target sentences were used efficiently. In the descending approach, some of the target sentences would be used at higher levels of the psychometric function, but the real interest here was achieving 50% as soon as possible to ensure efficient use of participant's time. The target sentences were presented in a fixed order while the experimental conditions were rotated for each participant. Once the trial had started, the interferer would remain on throughout the 10 IEEE target sentences. The participants were asked to repeat any audible words or say 'noise' when inaudible. For the first sentence, any response indicating the speech was inaudible would result in the experimenter increasing the speech by 4 dB SNR. This continued until at least two words were correctly identified and then the 1-up 1–down adaptive tracking began using 2 dB SNR steps for the target. The remaining nine sentences of the list were presented once only. If three to five words were correctly identified then the target was reduced by 2 dB SNR, if zero to two words were identified then the target was increased by 2 dB SNR. By grouping the six different outcomes into two groups, we can be confident that using a 1-up 1–down adaptive track converges on 50% correct intelligibility. The end of the condition was reached when all 10 sentences had been presented. The SRT was estimated by averaging the presentation levels of the last eight trials. There were two practice conditions, followed by 20 conditions (4 types of stimuli x 5 numbers of interferers). Feedback was provided after the practice conditions. After 10 conditions the participants were given a break.

Participants were invited to attend two separate sessions (40 conditions in total). On visit one, the interferer level was fixed at 67 dB (A) at the tympanic membrane and the target altered adaptively as described above. To measure the output from the headphones at the start of the trial, a Sound Level Meter was attached to an artificial ear canal and then coupled to the headphone. In order to give consistent levels of output, the amplifier was calibrated to provide a set amount of output. A pure tone of 1000 Hz was generated through Audacity software and a voltmeter plugged into the jack socket of the amplifier. The laboratory is a shared facility so in order to minimise the risk of

presenting varying output levels to different participants, the output was fixed at 1.25 Volts. Anything outside this and the volume wheel on the amplifier was manually moved to match 1.25 V. This provided consistency for each participant.

2.2.6. Partial restoration of Audibility

The second visit was the same procedure descried above apart from two crucial factors. Firstly, in order to minimise the risks of participants memorising the target sentences, an entirely different set of IEEE target sentences was used. There was also a minimum of 3 weeks between the visits. The second factor related to a modification to the output at the headphones. The NAL-RP prescription formula gain adjustment (Dillon, 2012) was applied to each ear of each participant, based on their specific hearing loss. This provided amplification that addressed individual hearing losses for each ear. To ensure no excessive sounds were presented to the participants, a maximum output was set to 85 dB (A). The equation for NAL-RP is as follows;

Insertion Gain (IG) = X + 0.31 × Ht + A

Where:-

X = 0.15 * PTA   (for PTA < 60 dB HL)

X = 0.15 * PTA + 0.2 (PTA-60)   (for PTA > 60 dB HL)

Ht = Hearing threshold of the respective frequency

Pure Tone Average (PTA) = (Ht 500 Hz + Ht 1000 Hz + Ht 2000 Hz) ÷ 3

And A is a correction factor as designated by table 2.2:

Frequency (Hz)	250	500	1000	2000	3000	4000	6000
Correction Factor A	-17	-8	1	-1	-2	-2	-2

Table 2.2 The correction factor used for NAL-RP in each frequency channel.

Using a MATLAB function, the measured hearing thresholds (dB HL) were entered into the NAL-RP formula and an insertion gain in the third-octave channels was calculated. This was applied to the output of a series of 20 third-octave linear-phase finite impulse responses (FIR) filters. The filters covered the frequency range of 100 Hz to 8 kHz.

2.2.7. Participants

12 NH participants were recruited for the Culling (2016) study from the Cardiff University undergraduate population. They had no known hearing impairment and were paid or received course credits for participating. A further 12 participants with confirmed hearing impairment took part (see appendix 1 for details). This sample size was chosen to match the NH participant numbers. The age range was 56 to 86 years of age and the mean was 70.5. The gender mix was 3 female and 9 male. They were recruited from the Audiology department of the University Hospital of Wales, Cardiff. Ethical approval was obtained from the South East Wales Research Ethics Committee. Pure-Tone Audiometry and Tympanometry were measured according to national standards (British Society of Audiology, 2011, 2013). They were used to confirm the presence of sensori-neural hearing loss. Those with significant air-bone conduction gaps, significant asymmetry in hearing thresholds or abnormal tympanometry results were excluded. The defined criteria for exclusion is based on national standards (Jeffery, Jennings, & Turton, 2016). Specifically, air-bone conduction gaps of 20 dB HL or more at 3 frequencies between 500, 1000, 2000, 3000 and 4000 Hz were considered to be significant. Where necessary, masking of the contralateral ear was performed to confirm bone conduction thresholds as per recommended procedures (British Society of Audiology, 2011). Asymmetry in hearing thresholds was confirmed if the bone-conduction thresholds of the left and right ear differed by 20 dB HL or more in two or more adjacent frequencies between 500, 1000, 2000, 3000 & 4000 Hz. Abnormal tympanometry findings were related to middle-ear compliance, pressure and volume. If a flat tympanogram was recorded, with compliance less than 0.3 ml, then the person was excluded on the grounds of middle-ear effusion presence. The normative range of middle-ear pressure of +/- 50 decapascals (daPa) was used, anything outside these limits potentially indicated pathology of the middle ear (e.g. retracted tympanic membrane, eustachian tube dysfunction, glue ear) and this was a reason for exclusion. Finally, those with ear-canal volumes up to 2.5 ml were included, and those above this were excluded based on the potential presence of tympanic membrane perforations.

2.2.8. Screening criteria

The following screening criteria were used to select participants:

- Participants to be 18 years old or over, because of the different middle-ear sizes and mechanics in children and young adults that produce greater variability.

- Participants to have a strong hold of the English language in order to participate because the material included in the study is spoken English. Therefore, those who did not have English as their first language were excluded from the study.

The following criteria were used to determine participation:
- Subjects who were unable to give consent themselves were excluded from the study.
- Subjects who had an uncorrected visual impairment were excluded from the study. Subsequent studies involved participants monitoring their own head movements in a mirror. Those unable to see themselves in the mirror were excluded.
- Subjects with self-reported problems with their short-term memory were excluded. The task requires recital of speech material, which is heavily reliant on accessing short-term memory.
- Subjects who had confirmed pathological conditions (e.g. Ménière's disease) that provided atypical hearing loss configurations, other than a sloping high frequency sensori-neural hearing loss, which is typical of age-related hearing loss.

One participant was identified during testing as having developed a significant asymmetry in hearing thresholds following a reduction on one side. This participant was referred back to the hospital for further investigation and the results removed from analysis.

2.3. Results

The results of the hearing test are provided in figures 2.2 and 2.3. These graphs display the right and left ear respectively of each of the 12 participants. The typical hearing assessment via pure-tone audiometry tests between 0.25 and 8 kHz as these are the frequencies that are important for speech communication. It does not represent the full human hearing frequency range, which is 20 Hz to 20 kHz. The graphs are created like audiograms so that moving down the y axis represents increasing hearing loss.

Right ear pure tone thresholds

Figure 2.2 Plots of each participant air-conduction hearing thresholds for the right ear at the test frequencies. The dark line is the mean of the thresholds.

Left ear pure tone thresholds
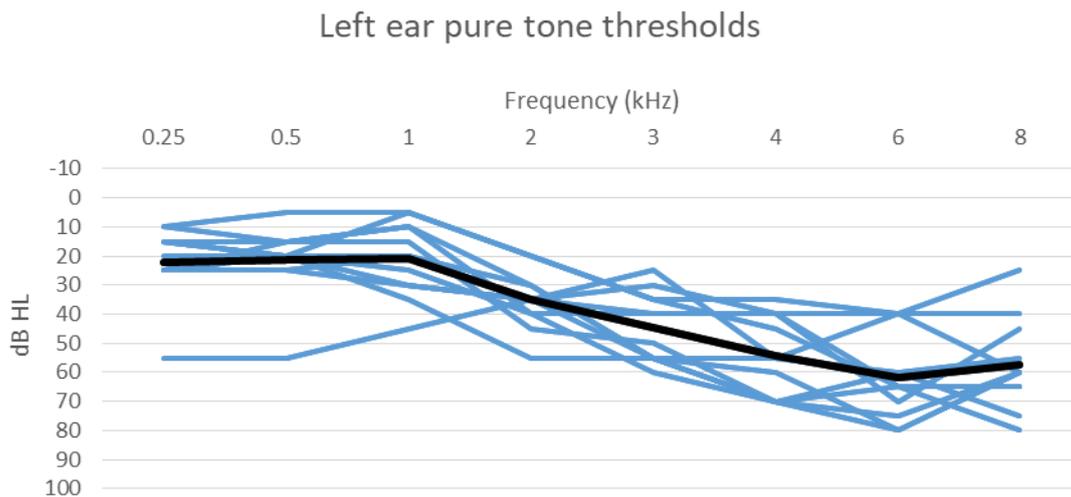
Figure 2.3 Plots of each participant air-conduction hearing thresholds for the left ear at the test frequencies. The dark line is the mean of the thresholds.

Figures 2.4, 2.5 and 2.6 are mean SRTs collected from simulation of the Aberdare Hall virtual restaurant. The figures are, respectively, for NH listeners (reproduced from Culling, 2016), HI listeners and then the same HI listeners with NAL-RP gain adjustment. The two different scales on the left and right ordinates in figures 2.4, 2.5 and 2.6 reflect a difference in the level at the source compared to the level at the ear. The left ordinate provides information on the levels at the source, with the target and interferers being different distances from the ear (different table locations). As such, this does not reflect the SNR at the ear. In order to provide an estimate of the SNR at the ear, the right ordinate is shifted. To calculate this shift, an eight-noise complex was used

to minimise interaural differences in the interferer level. Speech Intelligibility Index (SII) weighted spectra (ANSI, 1997) were used to calculate these SNRs at the head and to compensate for those difference in spectra induced by the room.
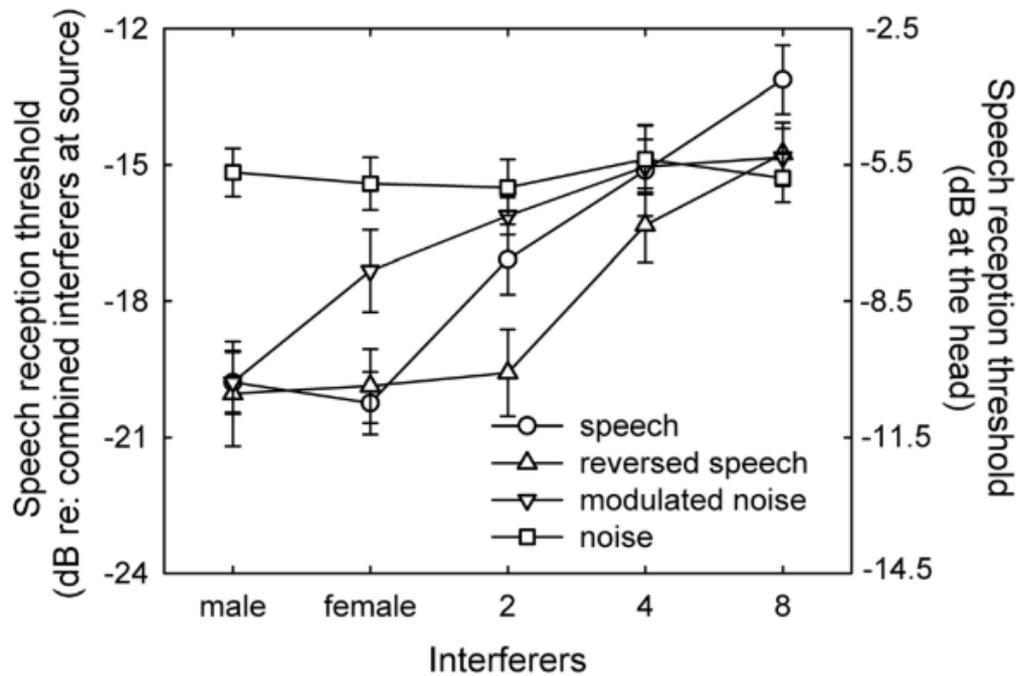
Figure 2.4 Results from the simulated restaurant. Mean speech reception thresholds and standard-error bars for a group of young normal-hearing participants are presented. With permission from Culling (2016).
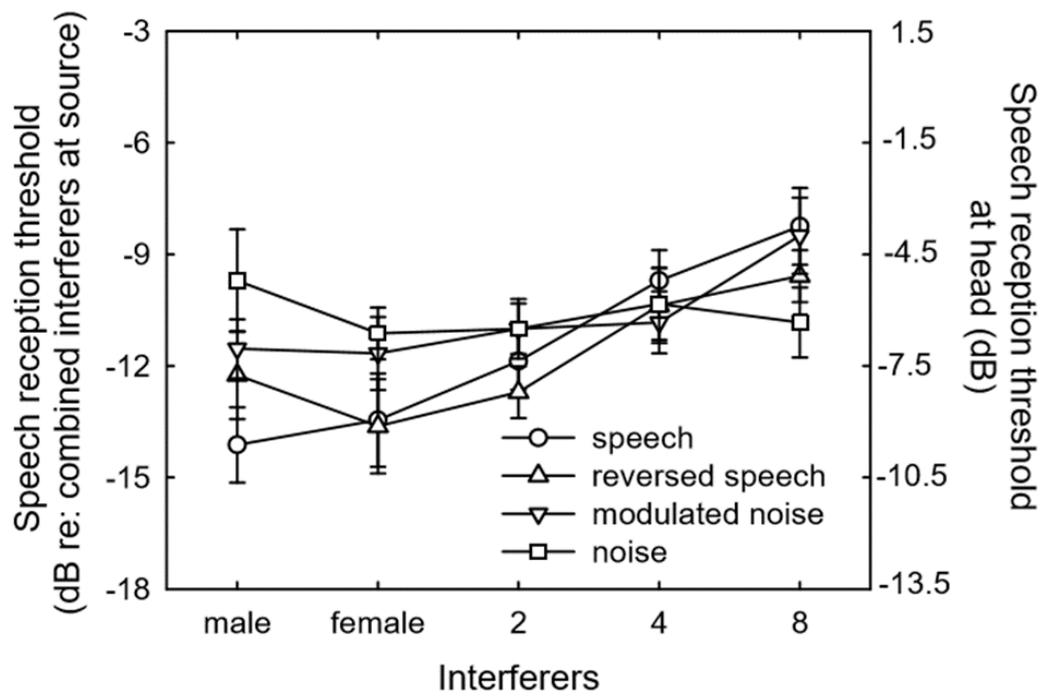
Figure 2.5 Results from the simulated restaurant. Mean speech reception thresholds and standard error bars for the hearing-impaired listeners without gain adjustment.
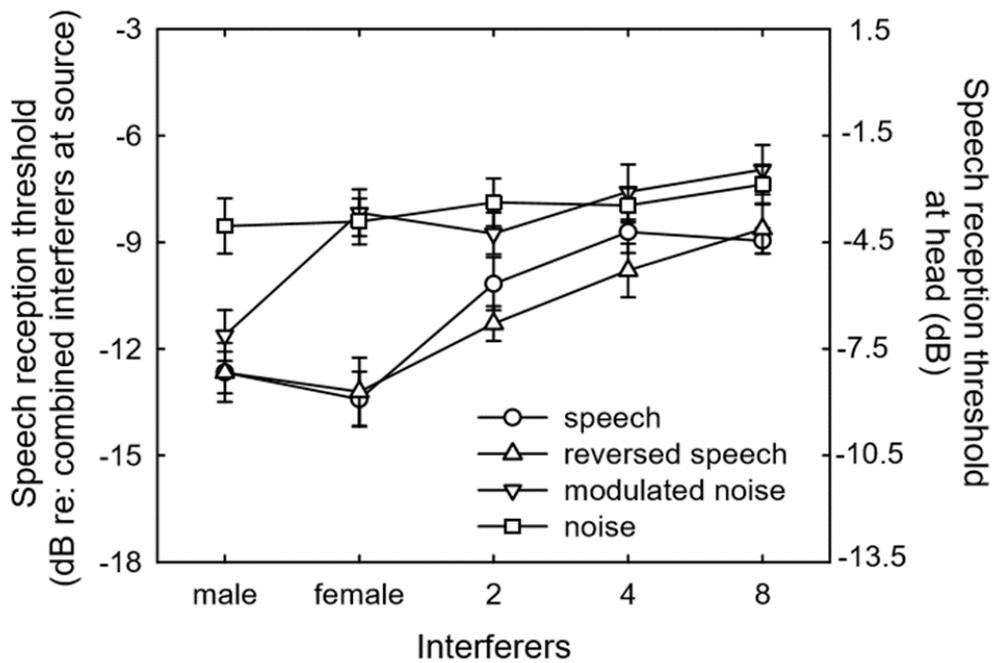
Figure 2.6 Results from the simulated restaurant. Mean speech reception thresholds and standard error bars for the hearing-impaired when the National Acoustics Laboratory Refined-Profound prescription formulae were applied to give individual gain adjustments.

A mixed Analysis of Variance (ANOVA) was used to analyse the main effects of hearing group. The data collected in this study with HI listeners without gain adjustment, was compared to the data collected in Culling (2016). In that study, they used NH listeners. The between-group measure in this analysis were NH results vs. HI results. The repeated measures were interferer type (speech, reversed-speech, modulated noise and noise) and interferer number/gender (1 male, 1 female, 2, 4 and 8).

Mauchly's sphericity test was significant for the interferer number [$\chi^2(9) = 29.60$, p<0.05]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .63$ for the main effect of interferer number). A main effect was found for the hearing status, with significantly poorer SRTs in the HI group than the NH group [$F(1,22)=36.194$, p<0.001]. A significant main effect was also found for interferer type [$F(3,66)=9.820$, p<0.001] although there was a significant interaction between interferer type and interferer number [$F(3.253, 264)=4.815$, p<0.05]. This reflects the fact that the most effective masker changed dependent on the number of interferers. The most effective masker was the SSN when only one interferer is considered, and the least effective the speech interferer. However, this finding is not as clear when there are 8 interferers. Then, the differences are less pronounced but, the most effective masker is the speech and the least effective is the SSN.

There was also a significant main effect of interferer number [$F(2.533,88)=24.888$, p<0.001], reflecting a progressively increasing trend in SRT with the number of interfering sources: the 8-mix interferers were the most effective and individual interferers the least effective as maskers. Bonferroni pairwise comparisons showed significant differences between reversed-speech and modulated noise (p<0.05), modulated noise and unmodulated noise (p<0.05) and reversed-speech and unmodulated noise (p<0.01). No significant differences were found for male *vs.* female *vs.* 2 person mix, but SRTs became significantly poorer between 2 & 4 interferers and then 4 & 8 interferers as demonstrated in table 2.3:

	Male	Female	2-mix	4-mix	8-mix
Male				**	**
Female				*	**
2-mix				**	**
4-mix	**	*	**		
8-mix	**	*	**		

Table 2.3 Post hoc table for interferer type/number with both group data considered *p<0.05 **p<0.001.

The entire HI data set (with and without gain adjustment) was separately analysed using a repeated measures ANOVA with three independent variables. These were gain adjustment, interferer type and interferer number. Again Mauchly's sphericity test was significant for the interferer number [$\chi^2(9) = 19.87$, p<0.05] and interferer type [$\chi^2(5) = 19.91$, p<0.05]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .46$ for the main effect of interferer type and .60 for the main effect of interferer number).

A significant main effect was found for comparing with and without gain adjustment [$F(1,11)=10.552$, p<0.05] reflecting the lower/better performance of the HI listeners when there was *no* correction for audibility. This occurred despite the fact that measurements of the intrinsic intelligibility of different sentence lists (Zurek, pers. comm.) suggest that the lists used without the gain adjustment tend to give SRTs about 1.6 dB SNR lower than the lists used with the gain adjustment.

Although a significant main effect was found for interferer type [$F(1.377,15.2)=3.985$, p<0.05], which would suggest a hierarchy among the interferers, a significant interaction was found between interferer type and interferer number [$F(5.406, 59.5)=7.326$, p<0.001]. This reflects the fact that the most effective masker changed dependent on the number of interferers. With a single interferer the most effective masker was the SSN and the least effective was the speech interferer. When eight interferer sources are present, the most effective masker is the speech and the least effective is the SSN (see figure 2.5). A significant main effect was found for interferer number [$F(2.399,26.4) =14.256$, p<0.001] with the 8-mix interferers being more effective than individual interferers.

A significant interaction was found between gain adjustment and interferer type [F(2.250, 24.7)=6.052, p<0.05] which implies that the effect of the interferer was greater in the SRTs recorded with gain adjustment. A significant interaction was found between gain adjustment and interferer number [F(2.804, 30.8)=3.146, p<0.05] which reflects the fact that SRTs changed less as the number of interferers increased in the paradigm with no gain adjustment.

Bonferroni pairwise comparisons for the interferer type and number are provided below in table 2.4 and table 2.5 respectively.

	Speech	Reversed-speech	Modulated noise	Speech-shaped noise
Speech			*	*
Reversed-speech			*	*
Modulated noise	*	*		
Speech-shaped noise	*	*		

Table 2.4 Post hoc table for interferer type with HI listener data. *p<0.05 **p<0.001.

	Male	Female	2-mix	4-mix	8-mix
Male				**	**
Female				**	**
2-mix				*	*
4-mix	**	**	*		
8-mix	**	**	*		

Table 2.5 Post hoc table for interferer number with HI data. *p<0.05 **p<0.001.

2.4.   Discussion

Hawley et al. (2004) were the first to investigate the role of interferer type, numerosity and location on speech intelligibility in NH listeners. What was not clear from this study was how a real room (as oppose anechoic room) with different table locations (as oppose fixed azimuth), would influence results. In this study, SRTs were measured for a group of HI listeners in a simulated restaurant experiment that measured the effect of numerosity of interferer and type of interferer. Additionally, SRTs were recorded with a gain modification to approximate the work of a hearing aid and consider the issue of reduced audibility as a result of a hearing loss. A comparison to baseline was possible through an analysis with NH listeners (Culling, 2016).

Mean SRTs for the HI listeners were significantly worse than those from the NH listeners, which was an expected result. The reduced audibility provided by the hearing loss is considered one reason for the poorer performance of HI listeners in speech intelligibility in noise tasks (Glyde et al. 2015). The rationale for including SRTs with the gain modification was to investigate this influence when using HI listeners.

The performance of HI listeners was significantly better with no gain adjustment compared to the gain adjustment (mean SRTs for the HI group were -11.1 dB SNR and -9.6 dB SNR for no gain and gain adjustment respectively) and this result would suggest that reduced audibility did not contribute to the poor results when compared with the NH listeners in the first analysis. There is a suggestion that over amplification of sounds can be detrimental when considering hearing loss and that effective audibility can often mean providing less gain at frequency regions of greater hearing loss (Ching, Dillon, & Byrne, 1998; Ching, Dillon, Katsch, & Byrne, 2001) which is a strategy now adopted by modern prescription formulae in hearing aids. However, it is interesting to note the similarity in the patter of results from the aided results to the NH listeners.

Another reason for the poorer performance of HI listeners is likely to be poorer use of spatial cues, although this is not directly tested, as there is no co-location reference condition. Both the HI (unaided) and NH listeners show a progressive deterioration in SRT as the number of interfering sources increases and one can infer that this is because more interferers results in sounds coming from more directions, which would reduce the spatial benefit. Although the interaction between interferer number and hearing group is not significant, the slopes for HI appear shallower on figure 2.5 (with the exception of noise where they are flat in both groups). There are reports that those with hearing loss have difficulty when in conditions with

reverberation (Duquesnoy & Plomp, 1980) where the use of the head shadow benefit it less likely. This is believed to be because the sound that is reflected will reach the contra-lateral ear and disrupt the head shadow.

The benefit of moving from an 8-mix interferer to 1 person interferer is 7 dB SNR and 5 dB SNR for speech and reversed-speech for the NH listeners. However, the HI listener's (unaided) average results are 6 dB SNR and 4 dB SNR for the same conditions. This would indicate that the HI listeners (unaided) are still able to make use of the spatial information in this realistic listening environment. They can take advantage of a spatial separation with a single interfering sources, when it is available, and only lose a small amount compared to the NH listeners. This is in keeping with others who have reported that HI listeners make use of spatial cues but on a smaller scale compared to the NH listener counterparts (Bronkhorst & Plomp, 1989). It may be argued that this is a spatial processing cue as opposed to a linguistic cue because both the speech and reversed-speech conditions are demonstrating the benefits of spatial processing in HI listeners. However, a counter argument to this might be that F0 processing or dip-listening advantages are more prominent with the single interferer and this is what is driving the difference. As the number of interfering sources increases, HI listeners demonstrate a progressive worsening in performance, which can be linked to more challenging spatial processing with sounds around the listener.

To investigate informational masking and incorporate contributions of harmonicity from the speech interferers, reversed-speech was a useful stimulus to include. There is a suggestion that HI listeners are less able to use F0 processing in complex listening environments. Reversed-speech has a similar harmonic structure to forward speech, but lacks the linguistic content. As such, if the speech interferers cause a significantly poorer SRT compared to the reversed-speech, then the presence of informational masking may be inferred. In the NH data from Culling (2016), the reversed-speech and speech interferers provided the lowest SRTs out of the 4 types of interferers and this benefit was thought to be based on the modulations and harmonicity of these interferers. In terms of informational masking, some evidence was presented in Culling (2016) to support the presence of informational masking, but it was in a very limited situation. Using the 2-person-mix interferer, the reversed-speech SRT was 2.5 dB SNR lower/better than the speech SRT, which was a significant finding. This was in keeping with others who have reported an informational effect when 2 interferers are presented in different hemispheres (Best, Marrone, Mason, & Kidd Jr, 2012), although

it is argued that these experiments typically employ simplified spatial configurations and speech material that promote maximum confusion for the listener (Westermann & Buchholz, 2015b).

In the present experiment with HI listeners, figure 2.5 & 2.6 show speech and reversed-speech to be far more similar than in Culling (2016). In the 2-person mix, there was a 0.83 dB SNR difference between the average HI results for speech and reversed-speech in the unaided condition. The informational masking evidence observed with the NH listeners in Culling (2016) was thus not repeated with the HI listeners in this study. The maximum difference in the HI (unaided) speech and reversed-speech results were using the 8-person mix and resulted in a 1.5 dB SNR difference between the means.

The similarity when using the modulated SSN and the reversed-speech interferer suggests that the HI listeners are also less likely to take advantage of harmonicity in the interferer. Likewise, the similarity when using the modulated SSN interferer and the SSN interferer suggests that those with HI are less likely to take advantage of the modulations in the interferer. Dip-listening is believed to be a mechanism that provides an auditory glimpse at the target when there are fluctuations in the masker. It has been suggested this is not possible in a complex listening environment with many interferers because the dips are filled by the other asynchronous interferers (Bronkhorst & Plomp 1992). Previous evidence suggests HI listeners are poorer at dip-listening (Festen & Plomp 1990) and this has been confirmed in this study, where we investigated dip-listening in a complex listening environment.

The aided results, although significantly poorer than the unaided results overall, are far more similar to the NH results in terms of the interactions and patterns of results between the different interferer types and the interferer number. In particular, the results when using one interferer demonstrate a larger separation between the two noise interferers and the two speech interferers, much like the results seen in the NH listeners. Another interesting observation with the HI aided results is the reduced variance in the average SRTs, which are indicated by the whiskers on the boxplots. It would appear that the listeners were more consistent and reliable in the SRT measured while in the aided condition. It must be noted that the aided conditions were a poor approximation of how the hearing aids provide gain, and simply providing a linear gain function has proven the point that providing this form of amplification does not improve results.

2.5.　Conclusion

A limitation to the approach taken was that due to the number of conditions involved (40 in total over two visits), the SRTs were calculated from one sentence list each only. A preferable approach would be have been to have had a 2nd or 3rd sentence list used to provide an average SRT with more confidence then given on the test-retest reliability of the results. Clearly, with this number of conditions, there is a trade-off with time and it was not possible to obtain the 2nd or 3rd SRT for reliability purposes (although this was assessed in section 4.2.4 for a different experiment).

The information gathered in this experiment can be used in the design of hearing aids. We know that simply adding gain is not helpful. With this experiment, the HI listeners performed worse with added gain. A number of characteristics of the masker source have been investigated, with the type and number of interferer influencing how the HI listener performs. The question to pose here is where the hearing aid engineers should focus their attention. Is it in the areas where HI listeners have very little benefit, which may mean they never get any benefit, or improve on the areas where some benefit has been demonstrated?

We know that HI listeners are able to perform far better in a single interferer condition and from the results, one would consider this to be predominantly driven by use of the spatial cues. Therefore, HI listeners make use of spatial cues with single interferers reasonably well but this benefit disappears when in a multiple-interferer environment. It is possible for modern hearing aids to become far more personalised and there has been a recent increase in the ability to use custom memories to meet the unique listening environments in which HI listeners find themselves. There is also work towards enhancing the spatial information provided by hearing aids. Blind source separation (Gannot, Vincent, Markovich-Golan, & Ozerov, 2017), beamforming (Kidd Jr, Mason, Best, & Swaminathan, 2015), wireless communication to enhance binaural cues and extending bandwidths (Kreisman, Mazevski, Schum, & Sockalingam, 2010) are strategies to improve the spatial information presented to the person wearing the hearing aid.

However, it is generally agreed that some of the consequences of cochlear hearing loss will not be addressed through these signal-processing techniques. It seems that frequency and temporal resolution will not benefit from technological developments in the hearing aid at the present, so issues such as poor dip-listening will remain problematic for the HI listener. This view is not held by all, with a recent study Kwak et

al. (2018) suggesting that hearing aids do in fact provide benefit in these areas when bilateral aids restore symmetric hearing levels, even when amplification effects are removed. Focusing on the reduced dip-listening benefit in HI listeners is important, however, in a complex listening environment, the dips start to reduce with an increasing number of interferers. When interferers are in both hemifields, we see a significant fall in the ability to use better-ear listening and this major cue becomes negligible. It still remains a huge challenge to hearing aid processing strategies in dealing with complex, multi-talker environments.

Signal processing advances are being made to hearing aid algorithms, but a simple answer to improving speech intelligibility might be within reach with some simple modifications to the listening strategy adopted. The following chapter investigates the role of head orientation in complex listening environments.

3. The benefit of head orientation in a complex listening environment for those with hearing loss

It is well documented that we use interaural time and level differences to aid speech understanding in background noise (Culling et al. 2004). Better-ear listening and binaural unmasking are perceptual processes that describe our ability to use spatial cues to improve intelligibility of target speech amongst other interfering sound sources in the environment. Specifically, better-ear listening is realised by the head acting as an acoustic barrier, in which a head shadow results in an improved SNR. Those with hearing impairment demonstrate a reduction in the benefit, which is not predicted very well through the Pure Tone Audiogram (Peissig & Kollmeier, 1997; Ter-Horst et al. 1993). This would suggest there is a super-threshold effect, but it is yet to be confirmed what precise mechanism is responsible.

Much of the experimental work that has been published on SRM in those with hearing loss has used a fixed-head position (Bronkhorst & Plomp, 1989; Peissig & Kollmeier, 1997). Facing the person who you wish to communicate with is socially the norm (Plomp, 1986). This provides visual cues, primarily lip reading, that aid intelligibility, and from which HI listeners benefit greatly (Grant, Walden, & Seitz, 1998). Many of the investigations into speech intelligibility in noise use target speech located at 0° azimuth and noise sources that are moved around the horizontal axis.

One study has deviated from this classical approach using target speech at 0° and 90° azimuth. Ter-Horst et al. (1993) used participants with symmetrical hearing loss and interferers varying along the horizontal and vertical planes. However, the two azimuths used for the target speech could be argued to represent ends of a spectrum and there still remain questions about the effects of smaller head orientations on speech intelligibility in noise. Grange & Culling (2016) found a benefit from moderately off-centre target speech with NH participants and with cochlea implant users, but the role of target azimuth in hearing impairment remains relatively unknown.

The benefit accrued from moving the head location to mid-point between target and interferer can bring about large benefits. If the target and interfering source are 90° apart, moving the head into the central position and splitting the two sources 45° each side is predicted from modelling to have significant benefits. Comparing the left and right polar plots in figure 2 of Culling et al. (2012), when facing a target at 0° and an interferer located at 90°, the model of Jelfs et al. (2011) predicts an SRM of 3.6 dB

SNR. However, when the head moves into the middle at 45°, this increases to over 6 dB SNR. The benefit comes from two acoustic effects. Firstly, the head-shadow effect is present and the side of the target has an improved SNR compared to the side with the interferer. In addition, with the head acting as a baffle and the pinnae increasing sensitivity of sounds from the front, sensitivity of the ear is greatest for 30-60° off centre. With the head position in the middle of a target and interferer, each 45° to either side, one ear would be placed in the region of maximum sensitivity.

A study that used HI participants to study head movement and head orientation strategies did this with asymmetrically HI participants (Brimijoin, McShefferty, & Akeroyd, 2012). Thirty-six HI listeners took part. Each person was positioned in a 24-speaker ring of loudspeakers, arranged at 15° intervals. Using an adaptive track to reduce the SNR, the undirected head movement was recorded at the lowest SNR achieved in the adaptive track. The SRT was not the main measure of interest here, but the SNR which resulted in head movements. They monitored head movements covertly using an infrared motion-tracking system. The inclusion of asymmetrically HI participants was believed to be useful in that this group of people have more of a need to complete head turns, especially when in low SNR conditions. The authors recognised that using this type of hearing loss configuration limited their study, although asymmetry in hearing thresholds does not entirely eliminate binaural hearing, it does mean the monaural cue of better-ear listening is likely to dominant. Clearly, a study that included symmetrical hearing loss cases would be investigating the monaural and binaural cues, in particular the binaural unmasking component.

The results of Brimijoin et al.'s study suggested that HI listeners do not orientate their heads based on the SNR (which is the optimum strategy) but they orientate their heads based on target signal level. In order to confirm the optimum head position, they used a combination of a mannequin and the Lavandier and Culling (2010) model. The mannequin was used to directly measure the signal level at the ear of various head positions and the Lavandier and Culling (2010) model was converted to a monaural model and used to predict the benefit of head positions. They were able to conclude that 60 degree head turns give a maximum intensity level of target to the better-ear. In a number of different masker separations from the target, the head movements were persistently in the region of approximately 50-60 degrees azimuth (when considering horizontal head turn – "yaw"). This effect was not dependent on the location of the masker in reference to the target, so the authors concluded that the strategy was target-intensity driven rather than optimum-SNR driven. They were able to predict maximum

benefit for SNR through modifying a binaural model (Lavandier & Culling, 2010). Those few participants that did orientate their heads to the positions of optimum SNR were the best performers.

A limitation to the Bimijoin study was the inclusion of only asymmetrical hearing loss particpants. A recent study (Hadley, Brimijoin & Whitmer, 2019) has used symmetrical hearing loss participants within a sample of 15 pairs of dyads to investigate, among other issues, head orientation. However, in this study they simply observed two talkers in a natural setting to assess if people with varying levels of hearing loss perform beneficial head movements. They report no significant findings for head orientation, but this study did not specifically assess the extent of head orientation benefit, but the observational that there is a lack of head orientation.

3.1. Aims and hypotheses

It has been established that head orientation benefits are seen in those with NH and cochlear implants in both directed and undirected approaches (Grange & Culling, 2016), and those with asymmetrical hearing loss (Brimijoin et al. 2012). However, those with symmetrical hearing loss have not been investigated. Further, HI listener's use of head orientation in a realistic listening environment with reverberation is unknown. The aims of the study are;

    i. To investigate the hypothesis that HI listeners will be unable to take advantage of a head orientation strategy. This will be possible by comparing the results of NH listeners (Grange & Culling, 2016) with HI listeners to reveal the extent of head orientation benefit with hearing loss. It is envisaged that HI listeners will demonstrate substantially lower head-orientation benefit. The reasoning for this is that the head-shadow effect that facilitates better-ear listening is strongest at high frequencies, where this group of listeners have their greatest hearing loss.

    ii. To investigate the hypothesis that performance will be dependent on table location. Thus, tables closer to the walls of the restaurant will have better SRTs and those more central will have poorer SRTs, because the latter would be surrounded by interferers. The result of the study would reveal the optimum seating position in the restaurant for someone with a

hearing loss, which would be useful information to share with those who use the restaurant.

3.2. Materials and methods

Mezzaluna is a restaurant in the City Road area of Cardiff. Figure 3.1 is a layout of the restaurant with table positions which have allocated numbers. Similar to chapter 2, acoustic measurements from this restaurant were the basis for a simulation. This experiment follows the methods of experiment 2 in Grange & Culling (2016).
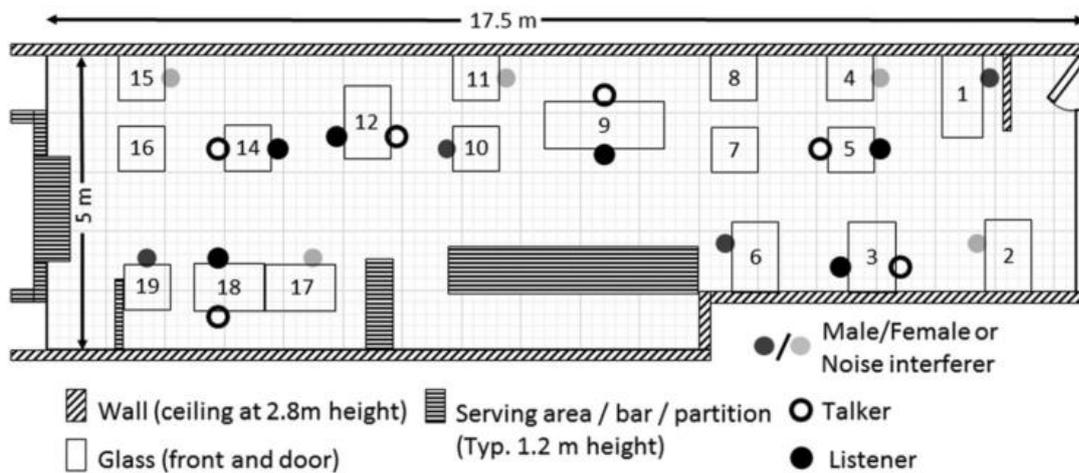
Figure 3.1 Plan view of Mezzaluna restaurant in Cardiff. Numbers in a box refer to table number. Black filled circles represent listener positions and the open circles are those of target talkers. Light grey circles are female interferers and darker grey are male interferers

3.2.1. Participants

16 young NH listeners (mean age of 21 years of age) reported in experiment 2 of Grange & Culling (2016) were used as a comparison group. 15 HI listeners were recruited for this study, the number was chosen to match the NH listener number. 8 of the 12 HI participants from chapter 2 were included and 7 new participants (see appendix 1 for details). In the HI group there were 10 males and 5 females, with an age range of 56 to 86 and a mean age of 69.6 years old. All were recruited from the Audiology department of the University Hospital of Wales, Cardiff. Ethical approval was obtained from the South East Wales Research Ethics Committee. The same inclusion and exclusion criteria were used as described in chapter 2, and collection of

audiometric and tympanometric results were completed according to national standards (British Society of Audiology, 2011, 2013).

3.2.2. Binaural room impulse responses and stimuli

The creation of the virtual restaurant was achieved by convolving BRIRs collected from the restaurant with the target and interferer signals. The recording of the BRIRs was completed during the closing hours of the restaurant and using the tone sweep method (Farina, 2007; Muller & Massarani, 2001). A Minx-10 loudspeaker (Cambridge Audio, London, United Kingdom) was used to produce a 10-second-long logarithmic tone sweep. This was delivered to a B&K 4100 head and torso simulator (Brüel & Kjær, Nærum, Denmark). The head of the B&K head and torso simulator was orientated in three different positions for each table position. Using a target facing position, the head was positioned 30° to the left, straight ahead, and 30° to the right on the azimuthal plane. This took place at 18 different table locations (see fig 3.1); every source and receiver combination BRIR was collected. This resulted in 972 impulses (18 source positions x 18 receiver positions x 3 head orientations). For the present experiment, 6 table locations were used for the target-listener interaction with a further 9 positions used for interferers, so a subset of 180 BRIRs were used.

Target speech consisted of Harvard IEEE sentences (Rothauser et al. 1969) from a male (DA) with an American-English accent. The interferers consisted of either SSN or continuous speech. Similar to chapter 2, the interfering speech was taken from monologues posted on librivox.org (five female and four female), and were distributed randomly but fixed at 9 different table locations. Target speech was always presented from the seat directly opposite. Figure 3.1 illustrates this configuration with tables 15, 19, 17, 11, 10, 6, 4, 1, 2 used for the interferers and tables 3, 5, 9, 12, 14, 18 for the listeners seating position and the target material directly opposite. In total, there were 36 conditions (6 table positions x 3 head orientations x 2 interferer type) with an additional 2 practice runs at the start.

3.2.3. Laboratory set up

Another single-walled IAC soundproof booth was used, similar to that used in chapter 2. A Windows PC sat outside operating MATLAB with a Project Headbox SE-II headphone amplifier connected to the PC via an Edirol UA-20 soundcard, and to a set of HD650 Sennheiser circumaural headphones inside the booth. A monitor was outside the soundproof booth for instructions and a microphone housed inside the booth relayed the response to the experimenter for scoring purposes.

3.2.4. Procedure

Similar to chapter 2, SRTs were measured using an adaptation of the (Plomp & Mimpen, 1979) method in MATLAB. The SRT was established by fixing the interferer level and adaptively varying the target sentence to provide a 50% correct word identification. At the start of each trial, the SNR was low (i.e. -28 dB SNR). The target sentences were presented in a fixed order while the experimental conditions were rotated for each participant. As in chapter 2, the interfering sources remained on throughout the 10 IEEE target sentences. The participants were given the same instructions as in chapter 2, where they were expected to respond to any audible words and repeat them, otherwise they were expected to say 'noise'. The target signal was increased in steps of 4 dB SNR until at least two words were correctly identified. Then the 1-up 1–down adaptive tracking began using 2 dB SNR steps for the target. The remaining nine sentences of the list were presented once only. If three or more words were correctly identified then the target was reduced by 2 dB SNR, otherwise it was increased by 2 dB SNR. The end of the condition was reached when all 10 sentences had been presented. The SRT was estimated by averaging the presentation levels of the last eight trials.

3.3. Results

The results of the hearing test are provided in figures 3.2 and 3.3. These graphs display the right and left ear respectively of each of the 15 participants via pure tone audiometry between 0.25 and 8 kHz. The graphs are created like audiograms so that moving down the y axis represents increasing hearing loss.

Right ear pure tone thresholds
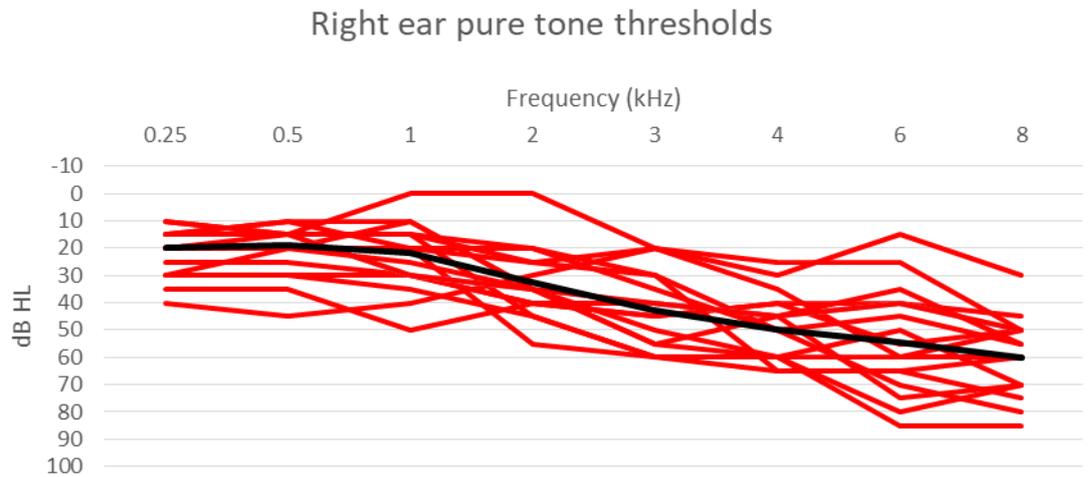
Figure 3.2 Right ear pure-tone thresholds for each of the 15 participants. Each red line indicates an individual's thresholds and the black line is the mean threshold.

Left ear pure tone thresholds
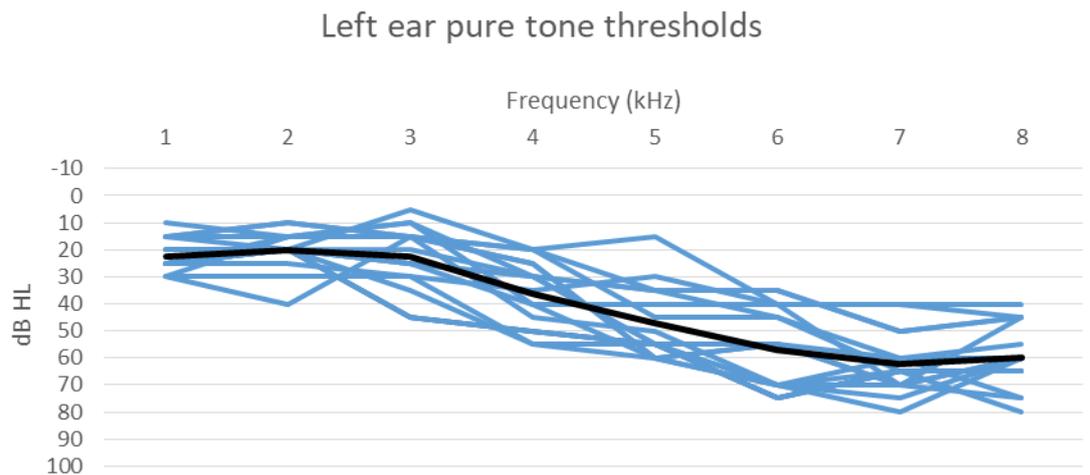
Figure 3.3 Left ear pure-tone thresholds for each of the 15 participants. Each blue line indicates an individual's thresholds and the black line is the mean threshold.

The results of the head orientation investigation are presented in figures 3.4 and 3.5. The average SRTs collected from NH listeners (figure 3.4) and HI listeners (figures 3.5) are presented at various table locations. These locations are labelled across the top of the figures and refer to the locations in figure 3.1. At each table location, three head orientations are presented (left 30°, front, right 30°). There are two sets of results based on the interferer used (speech and noise) and model predictions from Jelfs et al. (2011). The model predictions are superimposed on figure 3.5, the Jelfs et al. (2011) model does not account for hearing loss and therefore the spectrotemporal smearing that would be

associated with models who account for hearing loss. Including the model predictions on figure figure 3.5 are to facilitate a visual comparison and do not reflect expected performance in HI listeners.

Benefit of head orientation is seen in the graph as an inverted 'v' shape. The central point are the results from facing forward, which is the reference condition. If the data points to the left and right are lower, this signifies improved performance. The results of the HI listeners are presented in figure 3.5 across the six table locations, with figures 3.6 displaying an average of those results.
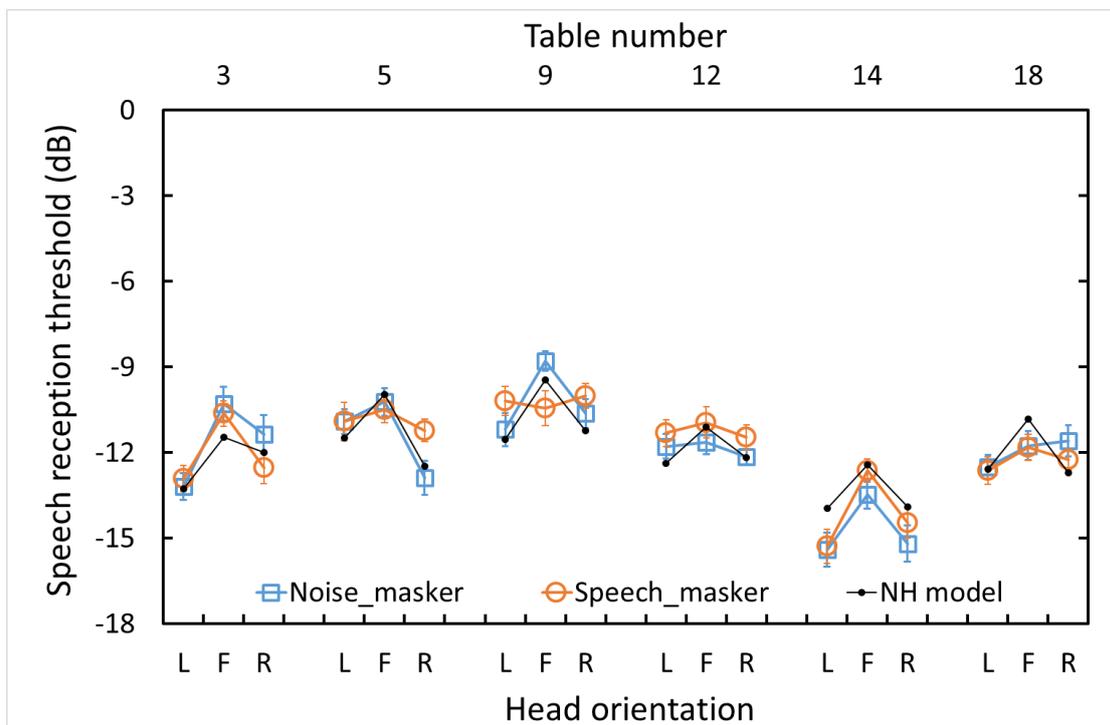
Figure 3.4 Results from Grange and Culling (2016) using NH listeners. Two interferer types (noise & speech) and model predictions from Jelfs et al. (2011). F = Facing talker, L = 30° to Left & R = 30° to Right. Table number refers to tables in figure 3.1.
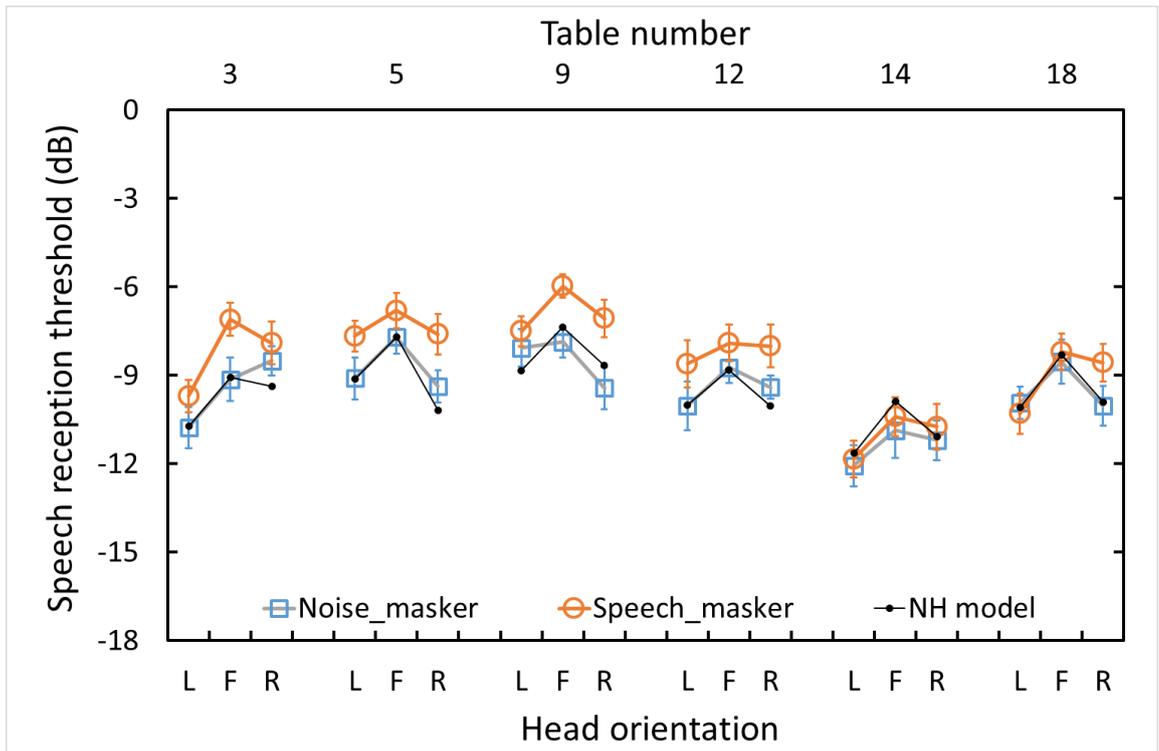
Figure 3.5 The same as figure 3.4, but for hearing-impaired listeners in the present study.
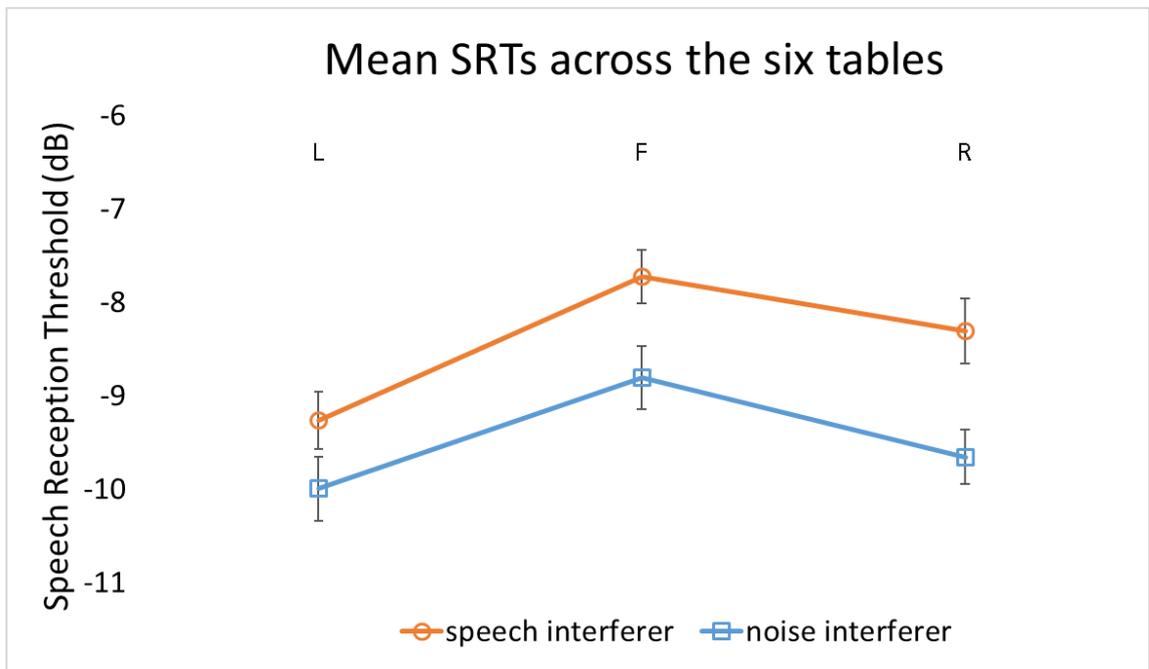
Figure 3.6 The results from figure 3.5 are presented here as an average across the six tables.

A mixed Analysis of Variance (ANOVA) was used to statistically analyse the main effects of hearing group. The data collected in this study with HI listeners, was

compared to the data collected in Grange & Culling (2016). In that study, they used NH listeners. The between-group measure was NH results vs. HI results. The repeated measures were type of interferer (speech vs noise), table number (3, 5, 9, 12, 14 and 18) and head orientation (Front, Left and Right).

A main effect was found for the hearing group, with significantly poorer SRTs in the HI listener group than NH listener group [$F(1,29)=38.215$, $p<0.001$]. A main effect was also found for the type of interferer, with significantly poorer SRTs recorded when using a speech interferer as opposed to a noise interferer [$F(1,29)=20.372$, $p<0.001$]. There was a significant interaction between interferer type and hearing group [$F(1, 29)=11.260$, $p<0.05$] which confirmed there was less effect of the interferer type for the NH listeners (SRTs for speech and noise interferers were similar), and more of an effect of interferer type with the HI listeners (SRTs when using speech interferers were poorer than obtained when using noise interferers). No other interaction effects were found.

When considering the HI group alone, the repeated measures analysis demonstrated a main effect of interferer type [$F(1,14)=29.029$, $p<0.001$], meaning that the SRTs collected for the HI listeners were significantly better/lower with the noise interferer (mean SRT was -9.5) compared to when using a speech interferer (mean SRT was -8.4). There was also a main effect for table number [$F(5,70)=33.585$, $p<0.001$], reflecting the fact that different table locations provided easier listening conditions (i.e. table 14 gave the best/lowest values). Table 3.1 below provides detail on the post-hoc results for the analysis of table number.

There was also a main effect of head orientation [$F(2,28)=18.869$, $p<0.001$]. Across all measured SRTs, the mean for left, right and front head orientations were -9.6, -9.0, and -8.3 dB SNR respectively. The left and front are significantly different at $p<0.001$ level, and all other comparisons amongst the three head positions are significant at the $p<0.05$ level.

Although these results suggest that there is a left head turn dominance in performance, the room used and the table locations have a bias towards left head turns by 0.2 dB SNR. Across the 6 table locations, the HI listeners gained a mean SRT benefit of 1.2 dB SNR when using speech interferers. This was calculated by subtracting the front SRT from the side with which the model (Jelfs et al. 2011) predicts to be the best head turn. The HI listeners also gained an SRT benefit of 1.2 dB SNR when using noise interferers.

	Table 3	Table 5	Table 9	Table 12	Table 14	Table 18
Table 3				*	**	
Table 5					**	*
Table 9	*				**	*
Table 12					**	
Table 14	**	**	**	**		**
Table 18		*	*		**	

Table 3.1 Bonferroni pairwise comparisons showed significant differences between the different tables with * denoting the significance value of $p<0.05$ and ** denoting the significance value of $p<0.001$.

3.4.   Discussion

Having proven that HI listeners had elevated SRTs compared to NH listeners in chapter 2, it is unsurprising to see a significant difference in overall SRTs between NH and HI listeners. It was hypothesised that HI listeners would demonstrate less head orientation benefit but the lack of interaction between head orientation and group would suggest this is not the case. For the HI listeners, the mean head orientation benefit was 1.2 dB SNR when using a speech interferer. The range was 0.4-2.6 dB SNR. The mean head orientation benefit when using a noise interferer was 1.2 dB SNR, the range with this interferer was 0.2-1.7 dB SNR. As such, the HI listeners gave almost identical head orientation benefit with either interferer. The NH listeners recorded mean head orientation benefits of 1.1 and 1.9 with speech and noise respectively, to give a mean head orientation benefit of 1.5 dB SNR. We can conclude that head orientation gives very similar levels of improvement to speech intelligibility in NH and HI listeners.

The significant finding for interferer type with the HI listeners is a surprising result. The speech interferer consists of nine different interfering sources and as such, should be relatively close to the noise interferer in terms of performance. We saw this in the previous chapter where the results became asymptotic across the different interferers when eight were presented. The difference across the mean SRTs for the interferers are 0.7, 1.0 and 1.3 dB SNR for left, front and right respectively. It should be noted that

these differences do not meet or exceed the benefit that has been reported for head orientation. One key factor that may have contributed to the different results between the interferers relates to the distance of those interfering sources. The nine fixed table locations are illustrated in figures 3.1. At the six table locations, the interferers are at varying distances, with 2-3 relatively nearby. It may be conceivable that these results support those of Westermann & Buchholz (2017) who deomstrated an informational masking effect, upto 4 dB, but only when nearby maskers (0.85m) were introduced. This could explain the poorer SRTs with the speech interferers.

In figures 3.4 and 3.5, model predictions (Jelfs et al. 2011) have been superimposed over the data (black dots and lines). The model predicts the direction of head turn that will give optimum benefit on each table. The model suggests left on tables 3, 9, 12 & 15 and right on 5 and 18. The model is reliable for predictions made with noise interferers. The reported benefit of 1.2 dB SNR for the HI listeners is derived by following this pattern of head orientations. It is possible to also consider what the results would be for two other conditions; least optimal and better-ear. The mean result for head orientation benefit for the least optimal head turn would be 0.6 for both speech and noise interferers. The better-ear conditions, which calculates the mean of all the highest head turn benefits, results in a 1.5 dB SNR benefit head orientation for speech and noise interferers. To summarise, the head orientation benefits are consistent between the two interferers and range from 0.6 dB SNR benefit (least optimal), to 1.2 dB SNR benefit (for model-predicted better-ear) to 1.5 dB SNR (for recorded better-ear). This 1.5 dB SNR result from the recorded better-ear of HI listeners matches the model-predicted better-ear results from the NH listeners.

One might predict that listeners would use their audiologically better ear and that this could influence the results. However, one element of the exclusion criteria for this study was asymmetrical hearing thresholds. This was determined as >20dB HL difference between two or more adjacent frequencies between 0.5, 1, 2, 4 & 8 kHz (Jeffery et al. 2016). Clearly all participants in this study had hearing thresholds that conformed to this criterion. However this is a relatively large range so an analysis of the PTA thresholds from the participants revealed that there was nonetheless a mean 3.5 dB HL difference between left and right PTA thresholds over the entire testing frequencies (0.25, 0.5, 1, 2, 3, 4, 6 & 8 kHz), with the lower thresholds found in the right ear. This can be confirmed as a very low level of variability between thresholds on the right and left side. Some degree of variability in hearing thresholds across the ears is common and

it is clear that a threshold effect is not present in this data set. The Jelfs et al. (2011) model considers noise only and using the speech interferer and comparing against the model predictions for head orientation becomes far less reliable. It predicts better SRTs for head orientation to the left based on the room acoustics.

In order to quantify the benefit of the head orientation realistically, it is important to provide some measure of success rather than an arbitrary number in dB SNR. The mean gap between the NH and HI listeners was 3.3 and 2.5 across all conditions with speech and noise interferers respectively. In other words, HI listeners performed more poorly by 3.3 and 2.5 dB SNR on average. Making a comparison of just the forward facing condition SRTs, this difference remained reasonably stable at 3.4 and 2.2 dB SNR respectively. However, when we compared the forward facing SRTs for the NH listeners, with the optimally-oriented-head SRTs for the HI listeners (left on tables 3, 9, 12 & 15 and right on 5 and 18) then the gap between the groups drops to 2.1 and 0.9 dB SNR for speech and noise interferers respectively. This could be interpreted as head orientation giving a 33% and 64% recovery of the HI listeners' deficit compared to NH SRTs for speech and noise interferers respectively. This is a direct comparison of NH and HI listeners at a set criterion of 50% intelligibility. To improve the approach and provide more detail, it would be recommended to expand the collection of data for other criteria and plot a psychometric function. This would take a significant amount of time that was not possible in the current study. There are a number of published studies on psychometric functions in speech intelligibility already, and a survey of these studies confirmed the high levels of variability of these psychometric functions based on the listening condition used (MacPherson & Akeroyd, 2014). The range of slopes reported was 1% per dB SNR (shallow) up to 44% per dB SNR (steep) with an average of 7.5% per dB SNR. Based on this average value on the psychometric function, a 1.2 dB SNR improvement would equate to a 9% increase in intelligibility. We know that people appear to be either unaware of the benefit, with a just-noticeable-difference in SNR reported as 3 dB SNR (McShefferty, Whitmer & Akeroyd, 2015), or they are unwilling to make the movement due to social consequences (Hadley, Brimijoin & Whitmer (2019).

3.5. Conclusion

Similar to chapter 2, a limitation to the approach taken was linked to the number of conditions involved (36 in total). The SRTs were calculated from one sentence list

each per condition and a decision was made on the trade-off between time and necessity to repeat the SRTs for test-retest reliability. With 36 conditions, it was not possible to obtain the 2nd or 3rd SRT for reliability purposes (although this was assessed in section 4.2.4 for a different experiment).

The benefit of head orientation in complex listening environments for HI listeners has been observed. This finding needs to be communicated widely in order to inform hearing healthcare practitioners. Far too often the advice given to HI listeners is to face the person who is speaking, this potentially prevents the HI listener from making natural head movements to improve the SNR. Grange et al. (2018) report on a survey they conducted regarding the advice provided to Cochlear Implant users. Although this is not a direct link with hearing aids, one can assume a similar finding would emerge if conducted with hearing aid users and the respective clinicians. Grange et al. (2018) used a questionnaire for the Cochlear Implant (CI) user and a separate questionnaire for clinicians who provide the service. They had a total of 95 CI users of which 44% reported they had never been advised about the benefit of head orientation. Of the 37 clinicians who completed the questionnaire, only 8% said they had ever provided advice on the benefits of turning the head away from the speaker. Some of the factors identified by the clinicians to determining their guidance for facing the speaker directly were: "ease of lip reading; microphone directionality; ease of maintaining eye contact; SNR at the better ear; training, lectures or presentations or literature; social acceptability of orientating one's head away from the speaker" (Grange et al. 2018).

It would be wise to add content to the national guidance documents held by the professional bodies (British Society of Audiology and British Academy of Audiology) used by clinicians and students. These guidance documents are intended to advise clinicians on making sure the approach to fitting and verifying hearing aids is robust and evidence based. Having content in the counselling section about head orientation would be advantageous but only if clinicians accept the evidence base to be well founded.

It would be prudent for other studies to be conducted on head orientation, possibly with and without lip-reading, in the HI listener population to fully explore the benefits. This has been conducted with CI recipients (Grange & Culling, 2016). One limitation to the work in this experiment is that it was conducted unaided. We have seen in chapter 2 that simply adding gain can be detrimental but we are unsure how hearing aids in situ would affect the head orientation benefit. With multi-channel compression hearing aids

it is possible that hearing aids could negate the better-ear listening effect by reducing the overall sound on the contralateral ear. A study looking at these effects is required. Such a study could measure SRM in the free-field with hearing aids in situ, and manipulate a loudspeaker ring to present sounds sources from different directions and imitate the work conducted in this experiment. Equally, it may be possible to use the MASTER hearing aid program (Grimm, Herzke, Berg, & Hohmann, 2006). This is a PC-based platform that was designed to evaluate DSP strategies in hearing aids. It can be used in conjunction with different programing languages, such as C or MATLAB, and this means it is possible to deliver an experiment over headphones via a PC and recreate the realistic workings of a hearing aid.

Chapter two and Chapter three have focused on speech intelligibility in complex listening environments. It is clear that HI listeners perform differently on these tasks. Some HI listeners perform remarkably well while others have significant problems. The next chapter investigates the reasons why this is the case.

4. Forensic analysis of hearing-impaired listeners

Variability in results was higher for HI listeners than NH listeners in Chapter 2 and Chapter 3. Mean standard deviation scores across all conditions were 3.2 and 2.5 for the HI and NH listeners respectively in chapter 2 and 2.5 and 2.0 for chapter 3. Analysis is made difficult with HI listeners because of the heterogeneity in the results, with a number of researchers pointing to this in their studies as a major issue when considering the results of spatial processing with hearing impairment (Peissig & Kollmeier, 1997; Ter-Horst et al. 1993).

In order to determine why we had variability in chapter 2 & 3, and to understand why some HI listeners performed more poorly, it is necessary to investigate 'individual differences'. It was Crandell (1991) who said "there remains a paucity of information concerning individual speech recognition susceptibility in hearing-impaired listeners…data are typically reported only as a mean value for heterogeneous groups of hearing-impaired subjects… mean data are of limited use…".

The approach of investigating individual differences in underlying psychophysical performance, that link to real-life functional performance, is not new. Watson, Qui, Chamberlain and Li (1996) conducted a large study comparing the relationship between speech recognition and lip-reading. Using 90 NH listeners over two experiments, they evaluated speech recognition, lip-reading, cognitive/linguistic performance and academic performance. They found a large amount of common variance between the auditory (speech recognition) and visual (lip-reading) domains. The authors propose a modality-independent source of variability that they believe may explain why other researchers have failed to find strong associations between speech recognition and measures of spectral or temporal resolution. One issue identified with the study relates to the sequence of the testing, and that all the material within each test was the same for each listener. Clearly, this does not account for training or fatigue effects.

The quest for a greater understanding of individual differences and the relationship between speech recognition and spectro-temporal resolution continued, with Surprenant & Watson (2001) completing a factor analysis. Using 93 NH participants, they found three factors with eigenvalues >1 (which is a measure of how much variance of the observed variable a factor explains). The three factors identified were i) non-speech discrimination factor, ii) speech identification factor & iii) temporal order discrimination. The factor analysis revealed a strong speech identification factor with speech tests loading on that factor with little overlap with other factors. These

speech-processing measures only correlated weakly with the measures of temporal and spectral resolution, which would confer with the results of Watson et al. (1996) that a pure modality specific speech processing explanation is unlikely, because a portion of the variance is associated with non-auditory cognitive abilities. However, the stimuli they used in the study could be called into question because the non-speech identification and discrimination tasks did not tap into the more global skills required for speech recognition.

The authors make a number of interesting claims. Firstly, they share the view that cognitive and sensory performance is normally distributed across the population, and they argue that the individual differences seen in HI listeners can be seen in the entire population but are usually obscured by the fact that NH listeners are usually performing at ceiling. They believe it is when the system becomes stressed, as is the case with hearing loss or NH listeners in adverse conditions, that the individual differences become apparent. An interesting conclusion is also shared. They provide two explanations; i) auditory spectro-temporal acuity for non-speech sounds is orthogonal to speech processing abilities or, ii) the appropriate tasks or non-speech stimuli that challenge the abilities required for speech recognition have yet to be identified.

Other studies have specifically focused on HI listeners. Humes, Kidd & Lentz (2013) focused on amplified speech with 98 older HI adults (age range 60-86 years). The rationale for this approach was that many studies beforehand with HI listeners used speech presented at conversational levels. This is 60-70 dB SPL, and many of the studies would then report that hearing thresholds would account for a large portion of variance. They used a test battery of peripheral and cognitive measures as well as speech-understanding measures. One of the peripheral measures used was the Masking Level Difference (0.25 and 0.5 kHz). Of the entire 39 variables they started with, across three domains (psychoacoustical, cognitive & speech-understanding), six predictor variables were deemed to be dominant predictors of the overall variance through a best-fitting regression model. These six variables were; Environmental Sound Test, Cognition, Text Recognition Threshold, Informational Masking, Hearing Loss & Dichotic measures.

Nuesse, Steenken, Neher & Holube (2018) have also considered HI listeners but with a stronger focus on cognitive processing. Areas such as verbal working and short-term memory, executive functioning, selective and divided attention, and lexical and semantic processing. Having recruited 46 participants, they were split into two groups based on their audiometric thresholds. These groups were referred to as 'age appropriate

hearing' or hearing impairment. They found no links between measures of speech recognition and cognition.

This chapter extends the work completed in the previous chapters and other studies mentioned above, but using a different approach with regard to the analysis. Unlike the other studies mentioned above, the focus here was identifying HI listeners with poor use of spatial information and investigating the underlying causes of this poor performance through a range of psychophysical tests. These tests were chosen because they were believed to assess underlying skills required to make speech intelligible in background noise, with particular reference to the use of spatial cues in these complex listening environments. Many of the other studies on individual difference focus on temporal and spectral resolution as oppose to spatial processing.

SRM is a measure of the ability to use spatial cues in the environment to make target speech more intelligible when it is located away from the interfering sources. The measure has a baseline when the target and interferer are co-located, and any benefit attributed to moving the sources apart can be attributed to better-ear listening and binaural unmasking. Consequently, the choice of psychophysical test for this forensic analysis focused on the use of these perceptual cues.

To address the area of binaural unmasking and the use of ITD cues, BMLDs and ITD discrimination were assessed. As discussed, the BMLD was a major predictor of aided speech recognition in Humes et al. (2013). The proposals in the literature (e.g. King et al. 2017) suggest that binaural TFS processing is a critical component of the poor performance of HI listeners, but few have investigated these binaural TFS tasks and related performance to SRM and the underpinning mechanisms.

BMLD and ITD discrimination assess one of the underpinning mechanism of SRM, binaural unmasking, but it is difficult to extrapolate these results to real-life speech in noise performance. In order to establish which of the spatial cues might be poorly processed by the poor performers, an experiment was designed that provided only ILD information or only ITD information. This addresses the question on validity, as the speech in noise task is held constant and the only changes made are to the noise interferer's binaural cues.

A further experiment has been designed to consider the influence of contralateral masking. Better-ear listening provides the largest spatial benefit and it remains unclear why some HI listeners appear unable to benefit to the same extent of NH listeners. High frequency hearing loss reduces the opportunity to use some ILD information, but Festen & Plomp (1986a) and Plomp (1986) argue that the hearing loss needs to be sufficiently

poor in the high frequencies for this to impact on performance. Therefore, there may be an alternative reason for the poor performance. It may be possible that skills in 'selective attention' (Marrone et al. 2008b; Glyde et al. 2015) are diminished. In the scenario with the target talker straight ahead and a competing speaker off to one side, the better ear is contralateral to the competing speech, because it has a better SNR than the ear closest to the competing speaker. It may be possible that a contralateral masking effect takes place with HI listeners. If the threshold for detecting a signal is raised by the presence of a contralateral sound this is referred to as either 'central masking' or 'contralateral masking'. This effect has been reported when using pure tone signals and pure tone maskers (Mills, Dubno, & He, 1996), but has not been considered with speech material and SSN.

4.1. Aims and hypotheses

The experiments in Chapter 2 and Chapter 3 were designed to replicate real-life listening scenarios, with the complex environment of a restaurant simulated in a virtual environment based on real restaurants. The experiments in this chapter were designed to investigate mechanisms behind the performance and as such were not necessarily realistic. The aims of the experiments were;

1. To investigate the link between reduced audibility from a hearing loss and the benefit of hearing aids on the use of spatial cues in understanding speech in background noise. The hypothesis is that performance will improve with hearing aids in situ.

2. To determine whether binaural TFS processing is associated with SRM performance. The hypothesis is that poor TFS processing will be associated with poor SRM.

3. To consider age as a factor in SRM and TFS performance. The hypothesis is that ageing is detrimental to TFS processing and will be seen in the HI listeners and NH age-matched controls.

4. To forensically analyse the use of ILDs and ITDs independently. The hypothesis is that the HI listeners with poorer SRM performance will be far less able to make use of ILDs.

5. To consider the role of contralateral noise in better-ear listening and whether an increased sensation level of contralateral noise interferers with better-ear listening. Some HI listeners find ILD cues less beneficial. It has been established

that better-ear listening provides benefits to speech intelligibility in noise but the overall level of noise contralateral to the better-ear has not been investigated thoroughly. The hypothesis is the HI listeners will demonstrate similar results in the monaural conditions but those with poor SRM performance will demonstrate significantly poorer SRTs in the contralateral noise condition.

6. To conduct a correlational analysis of all the variables. The hypothesis is that the measure of ILD processing will be strongly associated with poor SRM performance.

4.2.   Spatial Release from Masking

In order to complete a forensic analysis with HI listeners, it was important to initially gain baseline measures of hearing thresholds and then investigate SRM. Many researchers report group effects on SRM but the plan for this investigation was to identify poor SRM performance and consider the issues behind this poor performance on an individual level.

4.2.1. Routine audiological investigations

Hearing thresholds for air conduction at 0.25, 0.5, 1, 2, 3, 4, 6, 8 kHz and bone conduction (where necessary) at 0.5, 1, 2, 3 & 4 kHz were obtained via Pure-Tone Audiometry according to the British Society of Audiology's recommended procedures (BSA, 2011). Tympanometry was also performed to assess middle ear status according to British Society of Audiology's recommended procedures (BSA, 2013).

4.2.2. Participants

Nine young NH participants were recruited through Cardiff University Psychology department and were awarded course credits for their time. Inclusion criteria for the young NH group were i) upper age limit of 35 ii) hearing thresholds within 20 dB HL across all frequencies tested (0.25 – 8 kHz) and iii) first language of English. These NH listeners were recruited in order to provide a baseline of normative data for SRM.

Twenty-four HI participants were recruited through the Audiology department at University Hospital Wales. All but two of the participants that took part in the experiments of chapter 2 & 3 took part in this study (see appendix 1 for details). They were financially rewarded for their time and travel. A favourable opinion was gained from the East Wales Research Ethics committee as well as R&D clearance from Cardiff

and Vale University Health Board for recruitment through the hospital. Inclusion criteria for the HI group were i) aged 50-85 ii) first language of English. Exclusion criteria for the HI group were i) those unable to give consent themselves ii) uncorrected visual impairment iii) self-reported difficulties with short-term memory iv) unilateral or significantly asymmetrical hearing losses (> 20 dB HL difference between 4 frequency mean of 0.5,1,2,4 kHz for right and left ear and v) confirmed pathological conditions not related to presbyacusis. One participant (HI18, see appendix 1) was referred in error and was under the age criterion of 50-85. An exception was made for this participant and the result included in the overall analysis.

Nine subjects with ages typical of the HI group and with NH thresholds up to 3 kHz were recruited through the Cardiff University Community Participation Panel and again were financially rewarded for their time and travel. The 3 kHz criterion was used because it is very rare to find people aged 50 years and above with all hearing thresholds (0.25 to 8 kHz) within the 20 dB HL range. As such, there was a slight deviation of the criteria to 25 dB HL. The inclusion criteria for the age-controlled normal hearing were i) aged 50-85 years of age ii) hearing thresholds within 25 dB HL across a range of frequencies tested (0.25 – 3 kHz) and iii) first language of English. All participants had confirmed normal middle ear function through tympanometry. This group were recruited to consider age effects on SRM.

4.2.3. Spatial release from masking procedure

The test facility was a 3.2 m × 4.3 m sound-deadened room (RT_{60} = 60 ms) with a 24 channel MOTU digital-to-analogue converter, Auna solid-state amplifiers and Cambridge Audio Minx speakers. The centre of the speakers were 1.18 m from the ground and the face of the speaker was 1.3 m from the centre of the listener's seating position. MATLAB software using the Playrec toolbox was used for stimulus creation, presentation and response scoring. An adjustable swivel chair with weights to fix it in place was used to ensure the participant was unable to shift position and a mirror below the centre speaker with a target ensured minimal head movements, because participants were instructed to keep their reflection symmetrical in the mirror.

The Harvard IEEE sentences from speaker 'DA' were used as target sentences (Rothauser, Chapman, & Guttman, 1969). These are semantically plausible but unpredictable sentences with five key words in each sentence such as 'the BOX was THROWN BESIDE the PARKED TRUCK'. The interferers were SSN filtered to the long-term spectrum of the target sentences. Overall presentation level was 65 dB (A)

and this was maintained through an adaptive procedure so the overall presentation level remained at 65 dB (A) regardless of SNR. Listeners were required to repeat as many of the words from the sentence as possible. Speech reception thresholds (SRTs) were measured in an adaptive up-down procedure (Levitt, 1971), starting at a SNR of -16 dB and increasing towards positive SNR in 4 dB steps until 2 key words were correctly repeated. Each subsequent response with 0-2 keywords correct increased the SNR by 2 dB; responses with >2 keywords dropped the SNR for the next trial by 2 dB. This adaptive procedure provided an estimated 50%-correct threshold. Each condition consisted of 10 IEEE sentences with the SRT calculated as the mean of the final 8 sentences. A counterbalanced design for conditions was used to minimise training effects.

SRTs were recorded in three different conditions and repeated three times, from which a mean SRT could be obtained. As mentioned in sections 2.5 and 3.5, repeating the SRTS with different material allows an analysis of test-retest reliability. Two practice conditions were performed at the start for familiarisation. The reference condition consisted of speech and noise presented from a loudspeaker 1.3 m away from the participant and directly ahead (0 degrees azimuth). The split condition consisted of two speakers at +60 and -60 degrees azimuth from the front speaker. Two uncorrelated noise sources were used at each speaker. A correction in the output for each speaker was made to ensure the overall level at the participant's ear was the same in all the conditions and this was verified using a sound level meter in place of where the listeners head would be situated. The combined condition consisted of both noise sources moved to +60 degrees azimuth.

Spatial release from masking was calculated by subtracting the SRT in the reference condition from the SRTs in the spatially separated conditions. As such, two different SRM measures were derived; one for the split condition and one for the combined condition. In order to facilitate analysis on an individual basis, the data from the nine NH participants was used to create a correction for sentence intelligibility. The IEEE sentence lists 51:59 were used for this part of the experiment and these are referred to as 1 to 9 unaided. These sentences are referred to as unaided because they have been used by both the NH listeners and the HI listeners, but in the latter group, the sentences were presented without hearing aids. We were also interested in performance of the HI listeners when they wore their hearing aid(s). The above experiment was repeated with IEEE sentence lists 60 to 68 and these are referred to as 1 to 9 aided. It

was necessary to use different sentence lists in order to avoid confounding the results due to HI listeners being familiar with the material. However, the principle comparison was made with NH listeners and the same material was used across the groups, which is important considering the unpublished reports of differences in sentence intelligibility for the IEEE corpus (Zurek, 1996). For the aided condition, HI listeners wore their monaural or binaural hearing aids for the experiment and were asked to ensure the hearing aids were on the standard program for 'everyday listening'. This is typically the default program when switching a hearing aid on.

The starting condition and the subsequent order of testing were rotated across the three different conditions for each participant. The counterbalanced design of this study resulted in three NH subjects having the co-located position (0°) for each of the nine sentence lists. A correction was obtained by calculating the mean SRT across all nine sentence lists at the co-located condition. Each sentence list then had a correction based on the deviation from the mean and this was applied to all SRTs recorded with the subsequent sentence list (table 4.1). The mean SRT was -2.9 dB SNR across the nine sentence lists at the co-located position and the range was -4.6 (sentence list 1) to -1.0 (sentence list 3). The correction was applied to each of the measured SRTs to equate for the differences in sentence intelligibility. In the case above, a correction was applied to all results from sentence list 1 results. This means 1.7 dB SNR was subtracted from the score (i.e. a -7 dB SNR score is converted to -5.3 dB SNR) and all sentence 3 list scores gained an extra 1.9 dB SNR (so a -7dB SNR score is converted to a -8.9 dB SNR score).

	S1	S2	S3	S4	S5	S6	S7	S8	S9	mean
0° mean	-4.67	-2.33	-1.00	-3.67	-2.67	-2.50	-3.00	-1.83	-4.67	-2.93
standard error	0.60	1.36	0.33	0.44	0.60	0.87	0.29	0.44	0.73	0.63
correction	-1.7	0.6	1.9	-0.7	0.3	0.4	-0.1	1.1	-1.7	0.00

Table 4.1 A summary table of the corrections applied to all SRTs recorded for SRM. S1-S9 refers to the unaided sentence lists, which are sentence lists 51 to 59 of IEEE corpus. The mean 0° SRT was recorded from three NH listeners from the reference condition where speech and noise are co-located at 0°.

4.2.4. Results

The average SRTs were obtained from three SRTs measured in the same condition but with different target sentences being used. This allowed an analysis of test-retest reliability. The six different conditions consisted of aiding (unaided vs aided) and the three speaker locations (target and interferer co-located at 0° azimuth, target at 0° azimuth and interferer at 60° azimuth, target at 0° azimuth and interferers at 60° azimuth and 300° azimuth). The intraclass coefficients for the six conditions were as follows;

Unaided 0° azimuth = 0.71 with 95% confidence interval (0.52, 0.85)

Unaided 60° azimuth = 0.83 with 95% confidence interval (0.70, 0.92)

Unaided 60° & 300° azimuth = 0.79 with 95% confidence interval (0.64, 0.90)

Aided 0° azimuth = 0.71 with 95% confidence interval (0.51, 0.85)

Aided 60° azimuth = 0.88 with 95% confidence interval (0.78, 0.94)

Aided 60° & 300° azimuth = 0.68 with 95% confidence interval (0.48, 0.83)

Correlation coefficient values closer to 1 represent stronger reliability (Koo & Li, 2016), with five of the six results within the acceptable to good rating for reliability. The value for aided 60° & 300° is just below 0.7 and therefore the reliability for this measure may be questionable.

The following tables represent the baseline hearing thresholds of the participants along with their SRM results for the three groups of listeners. The aided and unaided data from the HI listeners is also presented.
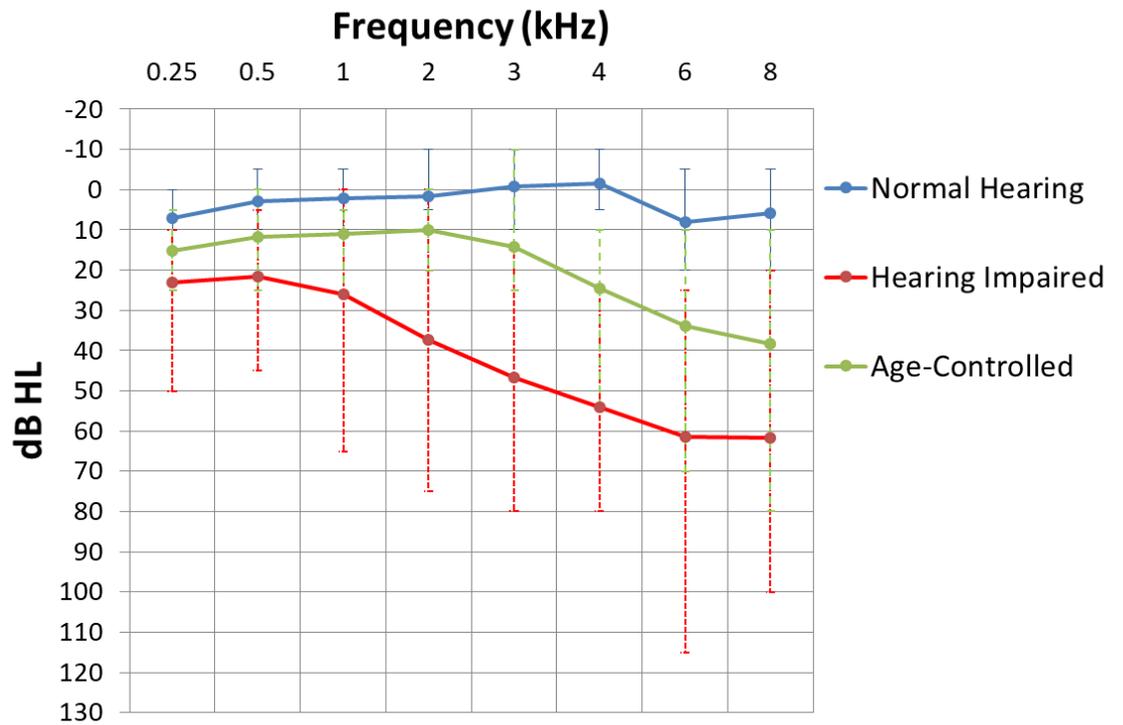
Figure 4.1 Mean PTA thresholds of the combined left and right ears at each of the test frequencies. The blue, green and red depict the NH young, NH age-matched and HI listeners respectively. These colours are also used in figures 4.2, 4.3 and 4.4.
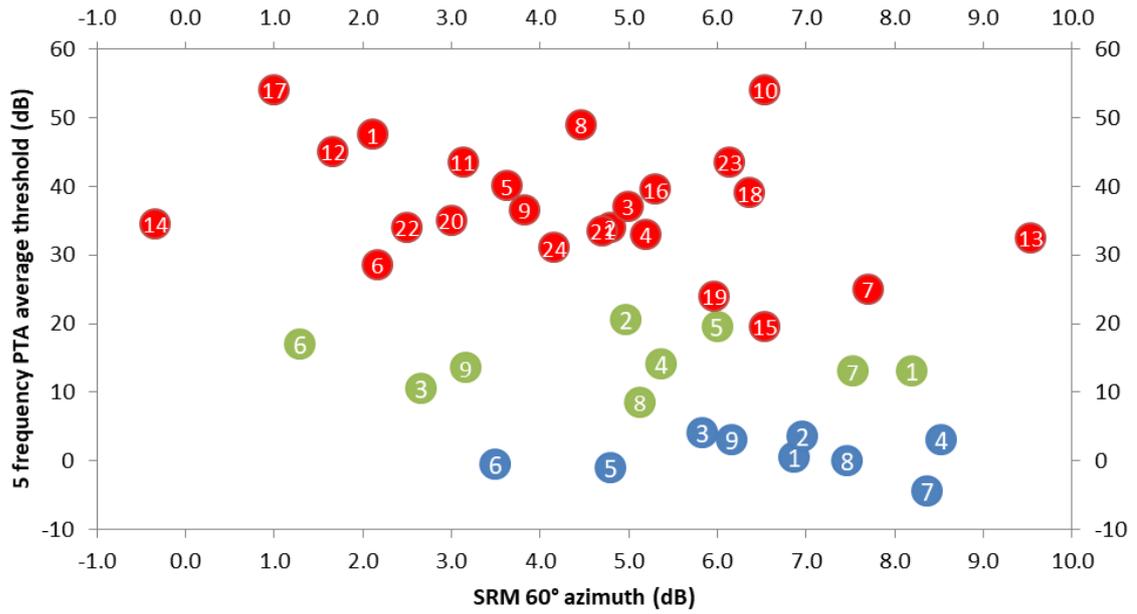
Figure 4.2 The five frequency (0.5, 1, 2, 3, 4 kHz) pure tone audiogram mean vs the benefit in speech intelligibility by moving the masking sound from 0° to 60° (SRM60). For visualisation purposes, the dependent variable (SRM) is plotted on the x-axis.
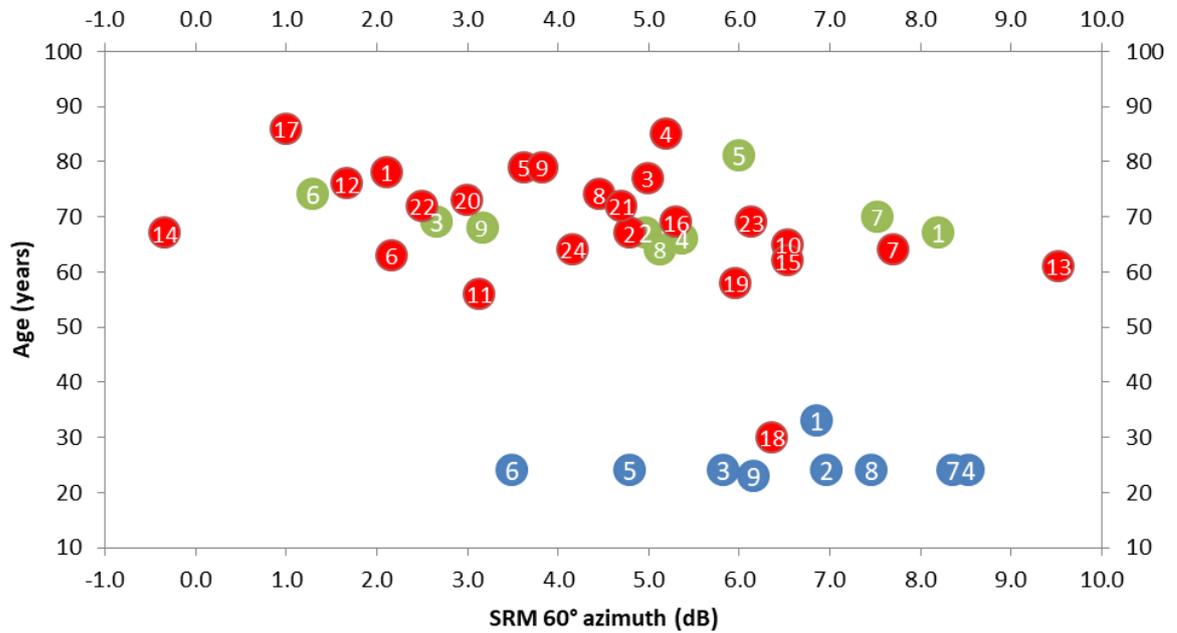
Figure 4.3 The age of the participants in years vs the SRM60 results.
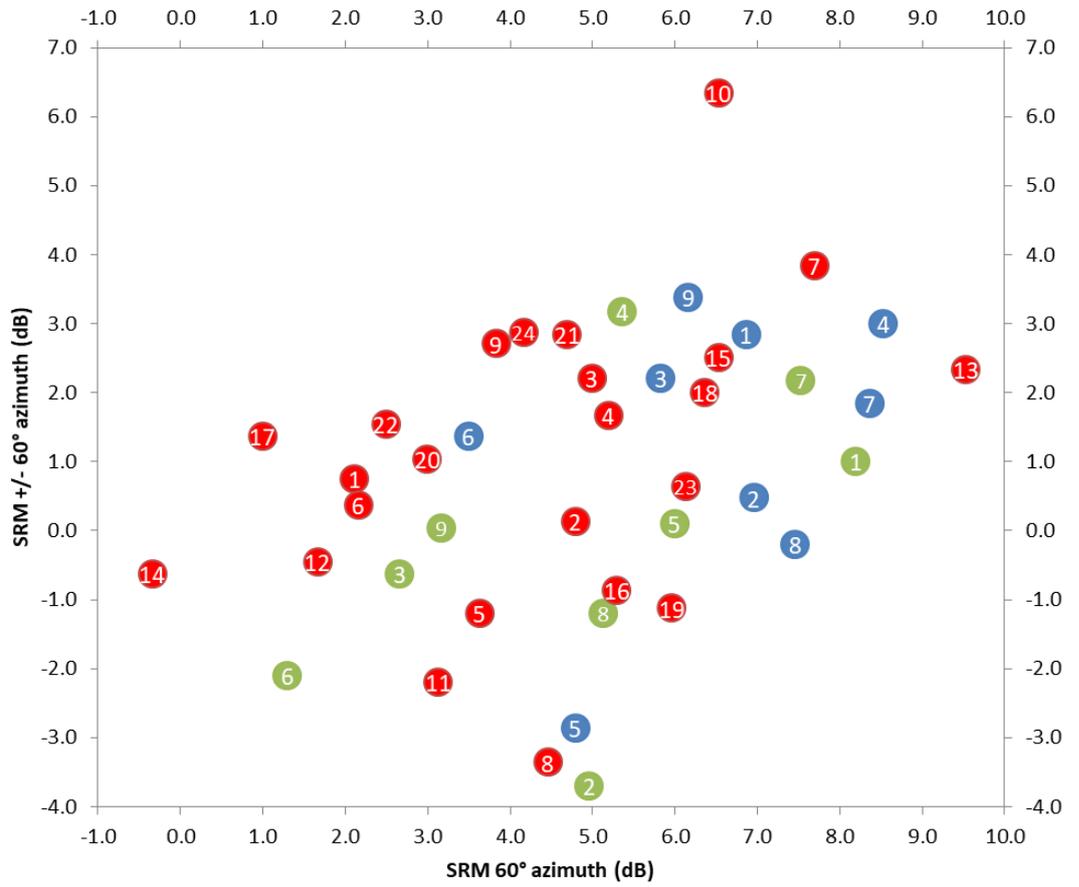
Figure 4.4 The benefit in speech intelligibility when moving the noise source from 0° to +/- 60° (SRMsplit) vs the benefit in speech intelligibility when moving the noise source from 0° just 60° (SRM60).
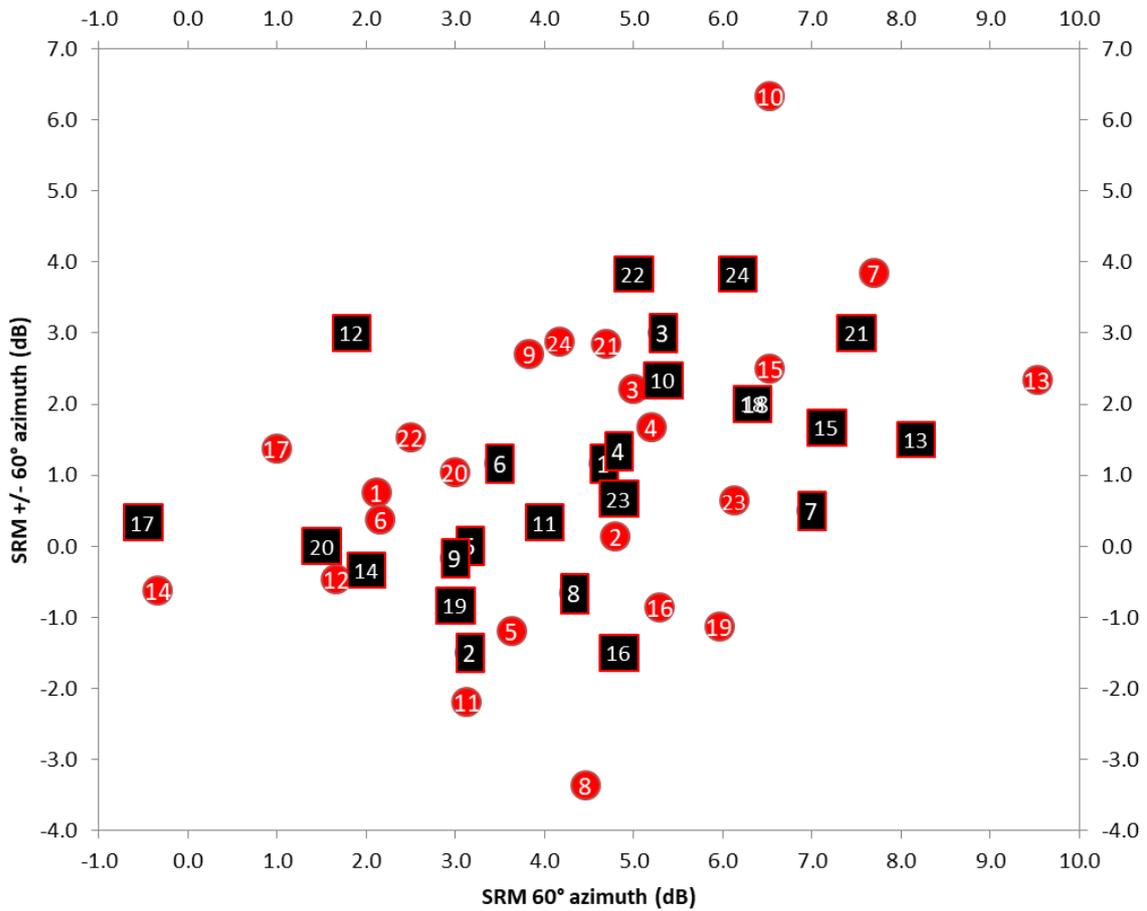
Figure 4.5 The same as figure 4.4 but only HI data presented. The red circles are the same as 4.4 but the black squares are with the HI listeners with their hearing aids in situ.

	SRM60 unaided	SRM+/-60 unaided	SRM60 aided	SRM+/-60 unaided
SRM60 unaided	1			
SRM+/-60 unaided	.395	1		
SRM60 aided	.745**	.446*	1	
SRM+/-60aided	0.31	.536**	.429*	1

Table 4.2 A correlation table for the variables in figure 4.5. Pearson correlation values. *p<0.05 and **p<0.001. For ease of reading, only one side of the correlation matrix has been completed.

4.2.5. Discussion

The correlational analysis in table 4.2 confirms that SRM performance in HI listeners is related to each of the four different measures. Mean SRM values for aided and unaided performance are remarkably similar, within 0.1dB SNR in SRM60 and SRM+/-60 conditions. This could be interpreted in two different ways. The first interpretation might suggest that the hearing aids have given little spatial benefit to the HI listener, and the possible reasons were discussed in section 1.4.5. However, another perspective could be that the hearing aids have not destroyed the ability to use the spatial cues, which is the preferred explanation.

There are many references in the literature to heterogeneity in performance of HI listeners in their use of spatial cues (Peissig & Kollmeier, 1997; Ter-Horst et al. 1993) and this makes the typical group analysis more difficult to interpret. We know that the PTA is not a consistent predictor of performance in speech in noise tasks (Peissig & Kollmeier, 1997; Ter-Horst et al. 1993). In order to address these issues, we decided to conduct a forensic analysis of the HI listeners. To facilitate this analysis, we grouped the HI listeners based on the SRM performance in a similar approach to that taken by Peissig & Kollmeier (1997).

It is accepted that conducting a median split and moving from a continuous to categorical scale is not the preferred method as it has the potential to lose power. The rationale for taking this approach was multi-factored. We were hoping to comparing results from the HI group to two other groups (young normal-hearing and hearing-impaired age-matched controls) and it seemed sensible to have categorical data for this comparison. In addition, there were variable numbers of participation from the HI listeners in the different measures. An exploratory factor analysis (or principle component analysis) would have been preferable but the participant numbers for some of the measures were too small to make this meaningful. Appendix 1 details the number of participants, in some cases this is as low as 14. As a compromise, a correlation analysis of the measures covered in chapter 4 for HI listeners are provide in section 4.7. Previous guidance on factor analysis was to ensure that the number of participants was greater than the number of variables under consideration. In the correlational analysis in section 4.7, we were interested in 17 variables. It is recognised however that newer techniques, such as regularised factor analysis, could be an option in these cases (Jung, 2013).

87

To achieve the median split, we used the SRM results from the condition where the interferers were co-located at 0° and then 60° azimuth. Figure 4.2 provides results of this experiment along with a five frequency mean PTA threshold. Along the X-axis, we can see that the mid-point between the red circles (HI listeners) is approximately 4.5 dB SNR SRM. The HI listeners left of this point are deemed to be poor at using spatial cues in speech in noise task: 14, 17, 12, 1, 6, 22, 20, 11, 5, 9, 24, 8. The other 12 HI listeners are deemed to be better users of spatial cues in speech in noise tasks.

4.3.   Temporal fine structure: Binaural masking level difference

One theory for the poor use of spatial cues by HI listeners is that they have poorer TFS processing (see section 1.4.4.3). BMLDs are believed to assess binaural TFS processing, so a relationship between SRM and BMLD might indicate a mediating role for TFS.

4.3.1. Participants

The same nine NH listeners and nine age-matched NH listeners participated in the BMLD experiment. One of the HI listeners (HI 24) did not take part (see appendix 1 for details). The HI listeners were split into two groups based on performance in the SRM task. Therefore, there were four groups; nine NH young listeners (group 1), nine NH age-matched listeners (group 2), 12 HI listeners with better SRM (group 3) 11 HI listeners with poorer SRM (group 4).

4.3.2. BMLD procedure

BMLDs were recorded with 2 kHz wideband random noise (0-2000 kHz) with pure tones of three frequencies; 0.25, 0.75 & 1.25 kHz. Two conditions were used, N_0S_0 as the reference and N_0S_π as the test condition. Using the three different frequencies, the BMLD was calculated as the difference between the two conditions. A practice run was provided and test order was randomly assigned so that half of the group started with 0.25 kHz and an ascending order or 1.25 kHz and a descending order. To establish a detection threshold, a 2-interval forced-choice paradigm was adopted with one interval noise only, and one interval with the pure tone present amongst the noise. The starting level for testing was -10 dB SNR and the sound duration was 1 second with an inter-stimulus interval of 200 ms. Successful identification of the tone reduced the SNR by 2

dB whereas an incorrect response increased the SNR by 2 dB. The mean of eight reversals was taken as the detection threshold.

A PC running MATLAB facilitated the production and presentation of stimuli. An Edirol UA20 audio interface was connected to Sennheiser HD650 headphones, which were housed within a single-walled IAC sound booth. A keyboard within the booth captured responses and a small screen could be seen through the window of the booth, which presented visual feedback on responses. Presentation level through headphones was controlled across test sessions using a voltmeter and a 125 mV output from the amplifier. This was measured to provide a 65 dB (A) presentation level.

4.3.3. Results
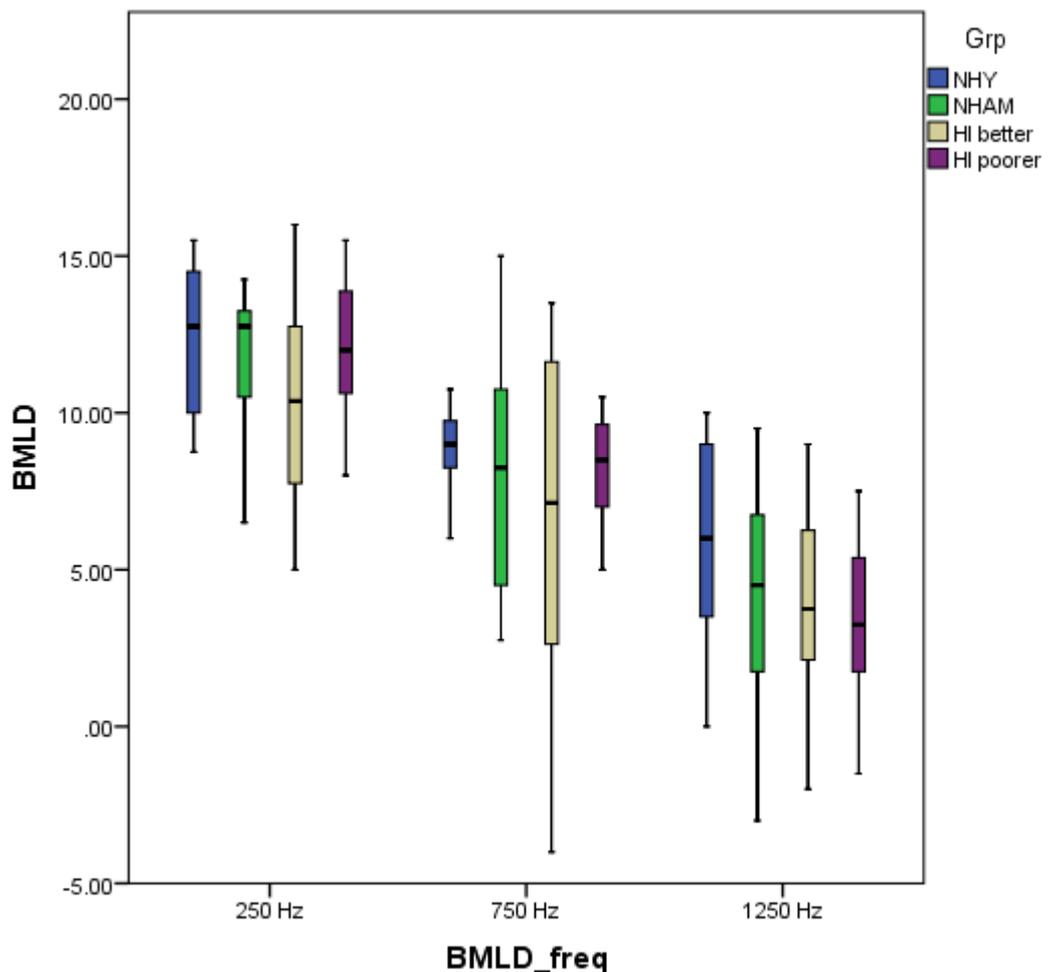
Figure 4.6 The boxplot results from the BMLD experiment with the four groups compared at each of the four test frequencies.

Of the 122 BMLD results, seven scores were identified as outliers with respect to their group and BMLD frequency. These were all changed to within one unit of the next

highest or lowest score within the distribution. This data transformation is known as winzorisation and is an accepted approach taken to reduce univariate outliers (Dixon, 1960; Tabachnick & Fidell, 2013, p. 111). For BMLD scores for 250 Hz, the Levene's test for equality of variance was not violated between the four listener groups ($F_{(3,37)}$ = 0.849, p >0.05). There was also no violation for the 1250 Hz scores between the groups ($F_{(3,37)}$ = 0.948, p >0.05). However, there was a violation of Levene's test for 750 Hz and resulted in significant differences between the groups, ($F_{(3,37)}$ = 5.619, p< 0.05). The analysis conducted here is between variables and as such, there was a necessity to attempt a transformation of the data for the BMLD 750 Hz for each of the four groups. The full 750 Hz data set gave a skewness value of -1.093 and a standard error of skewness of 0.369. By converting the skewness scores to z-scores (dividing the skewness value by the standard error) we could confirm this was a significant skew score (2.96 is greater than 1.96, p<0.05). To correct the data, a number of transformations were trialled. Initially, all numbers were converted to positive values by adding a value to the entire data set for 750 Hz (5 in this case because -4 was the most negative value in the data set). A reversed score transformation was then conducted (because it was a negative skew) followed by a square root transformation followed by another reversed score transformation (to return the values back in the correct order). This resulted in the skew reducing to -0.103 and standard error of .0369, which is no longer significant. However, Levene's test was still violated after the transformation ($F_{(3,37)}$ = 4.536, p< 0.05). Therefore, it was decided that Welch's ANOVA would be used for the 750 Hz data. The transformed mean data is plotted below for the 750 Hz data set.
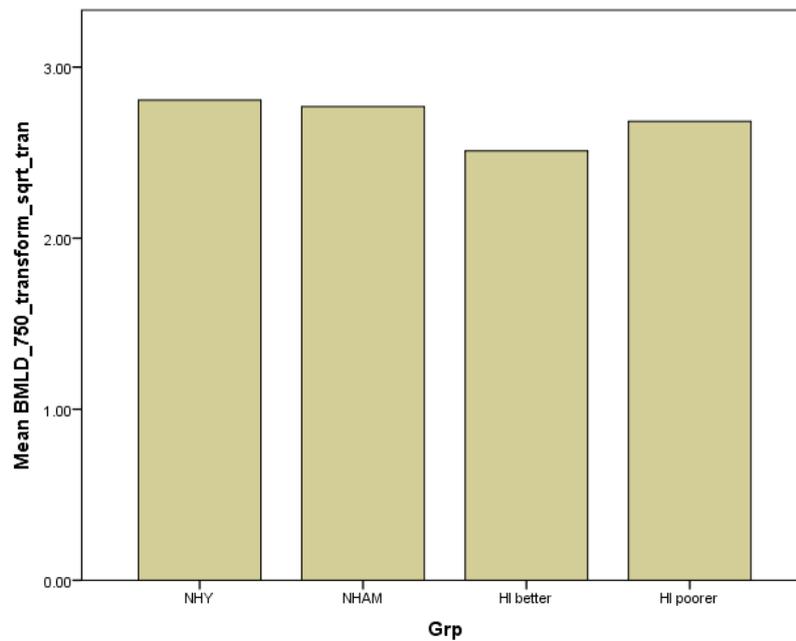
Figure 4.7 The transformed data for the 750Hz BMLD.

The 250 Hz and 1250 Hz data were assessed with a standard mixed ANOVA and the 750 Hz data with a Welch's ANOVA. For the mixed ANOVA, the BMLD score was the dependent variable, the group was the independent between-subjects variable and the BMLD frequency was the within subjects variable. No significant difference was found between the four groups at 750 Hz using Welch's ANOVA [$F(3,19.119)=0.457$, $p>0.05$]. From the mixed between-within ANOVA, there was no interaction between BMLD frequency and group, Wilks' Lambda = 0.93, [$F(3,37)=0.902$, $p>0.05$, partial eta squared = 0.068]. There was a substantial main effect of BMLD frequency, Wilks' Lambda = 0.28, [$F(1,37)=133.6$, $p<0.001$, partial eta squared = 0.783]. As such, all four groups showed a substantial reduction in the BMLD scores between 250 Hz to 1250 Hz, consistent with the BMLD literature (Hirsh and Burgeat, 1958). No significant difference was found for the between-group analysis [$F(3,37)=1.165$, $p>0.05$, partial eta squared = 0.086].

4.3.4. Discussion

No significant differences were found between the four groups of listeners at any of the three frequencies tested. In keeping with previously reported research (van de Par & Kohlrausch, 1999), the BMLD did reduce as centre tone frequency increased. We can confirm BMLD was not significantly different between our two groups of HI listeners so we must conclude that this particular measure of binaural TFS processing has been

unable to predict performance for SRM in our group of HI listeners. Age does not influence the results in this set of data, with the age-matched NH group mean thresholds similar to both HI listener groups.

4.4.   Temporal fine structure: Interaural time difference discrimination

Another measure of binaural TFS processing is ITD discrimination, so the possible role of TFS was further examined using this measure.

4.4.1. Participants

The same nine NH listeners and 9 age-match NH listeners who participated in the SRM and BMLD experiment took part in the ITD experiment. The one HI listener who did not take part in the BMLD experiment (HI 24) took part in the ITD experiment (see appendix 1 for details). Once again, the HI listeners were in the same groups based on performance in the SRM task (same groups as BMLD with HI24 now participating and added to the group with poorer SRM performance). Therefore, there were four groups; nine NH young listeners (group 1), nine NH age-matched listeners (group 2), 12 HI listeners with better SRM (group 3) 12 HI listeners with poor SRM (group 4).

4.4.2. ITD discrimination procedure

ITD discrimination thresholds were obtained over headphones using a 2-interval forced-choice paradigm. The signals used were noises with a bandwidth from 0 to 2000 Hz. A standard noise (with an ITD of zero) and the test noise were randomly assigned in order of presentation. The instruction to the participant was that they would hear two noises. If the second sound was to the left of the first sound, they were asked to press 1 on the keyboard, if it was to the right of the first sound they were asked to press 2 on the keyboard. This is the standard approach to recording ITD discrimination (Wright & Fitzgerald, 2001). The duration of each noise was 500 ms with an inter-stimulus-interval of 300 ms. The starting ITD was 1000 µs. Two correct responses at the same ITD was the rule for reducing the ITD with a total of 10 reversals required for the trial to end. Feedback was provided via a monitor outside the soundproof booth, which indicated if a correct or incorrect response was achieved. A multiplicative factor was used to adapt the ITD, which was dependent on the response for the participant. The ITD was divided by 1.259 following two correct responses and multiplied by the same

number following an incorrect response. The delayed wave was implemented using phase shifts in the frequency domain. The mean of the last eight reversals was taken as threshold for ITD discrimination. The same process was used to quantify headphone output as for the BMLD task.

4.4.3. Results
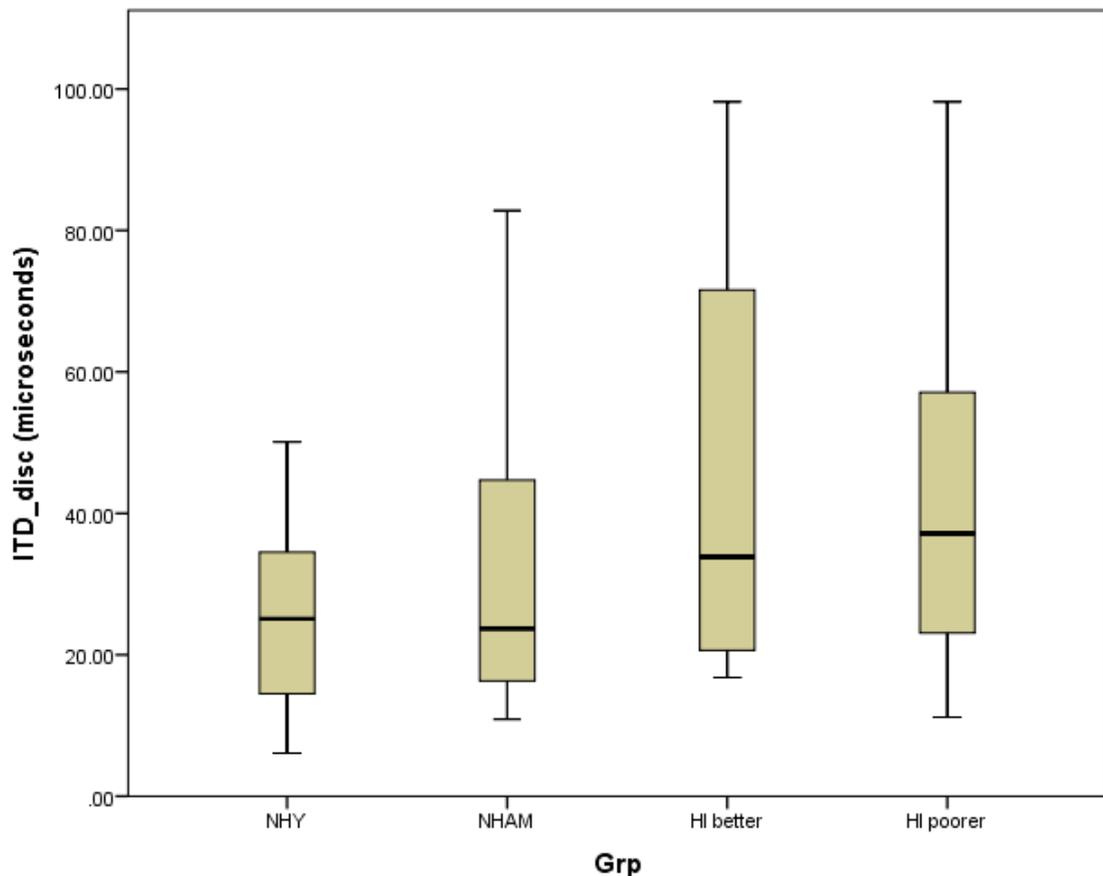
Figure 4.8 Boxplot results from the four groups for ITD discrimination thresholds in microseconds.

Four outliers were identified in the 42 mean thresholds collected, three from the HI listeners (two from the group with better SRM performance and one from the group with poorer SRM performance) and one from the age-matched NH group. These were winzorised to within one unit of the highest values within their respective groups. The full data set for ITD discrimination had a skewness of 1.167 and the standard error of skewness was 0.365. This is a significant skew when we convert to z-scores (3.19 is greater than 1.95, $p<0.05$). However, with sample sizes greater than 30 then one-way ANOVA is robust against this violation of normal distribution (Pallant, 2016, p. 208). Levene's test of homogeneity of variance was not violated [$F(3,38) = 1.628, p>0.05$]. A one-way between-groups ANOVA was conducted and there was no significant different

between the four groups [$F_{(3,38)} = 1.133$, $p>0.05$]. Moreover, while figure 4.8 suggests that there may be some difference between HI and NH listeners, the means for HI listeners who were poorer and better HI at exploiting SRM were very similar.

4.4.4. Discussion

Similar to BMLDs, there was no difference between the groups and as such, we can confirm that the ITD discrimination thresholds in this group would not predict SRM performance. Age does not influence the results in this set of data, with the age-matched NH group mean thresholds similar to both HI listener groups.

4.5. Independent use of interaural level and time differences

There is clear heterogeneity in the SRM results presented in section 4.2.4 and this was the reason behind the creation of two different groups of HI listener. Although the TFS abilities have been measured, it is not clear how the HI listeners process different spatial cues in a speech-in-noise task. The inspiration for the next experiment was Bronkhorst and Plomp (1989) and Culling et al. (2004). Bronkhorst and Plomp investigated the use of ILD and ITD independently in HI listeners. However, the experiment detailed here differed from Bronkhorst and Plomp (1989) in a number of ways. Firstly, they used the spatial locations of 0°, 30° (ITD only) and 90°. They used these angles based on the findings of their study with NH listeners (Bronkhorst & Plomp, 1988). These locations are not optimal for spatial benefit. We know that using 90° is not ideal in that the benefit can be reduced because of the bright spot (Reisinger et al. 2009). The optimal locations for speech facing conditions would be a comparison of 0° with 60° or 112° (Culling et al. 2012). The 60° configuration was used in this experiment.

Another difference in approach between Bronkhorst and Plomp and the present study is concerned with the presentation level of the noise. They were interested in how HI listeners would perform in monaural listening conditions as well as binaural. Unlike the study with NH listeners in 1988 where the noise was fixed at 60 or 65 dB (A), with HI listeners in the 1989 study they fixed the noise level but this was dependent on the degree of hearing loss. This varied from 75 and 95 dB (A). In the present experiment, the noise was fixed at 70 dB (A).

4.5.1. Participants

12 NH and 17 HI listeners took part. All 12 NH listeners were new participants and had not taken part in any previous experiment. The age range for the NH listeners was 21-27 with mean age of 22 years. The 17 HI listeners had all participated in the SRM experiment, 6 from the group with poorer SRM performance and 11 from the group with better SRM performance (see appendix 1 for details). The group numbers were therefore uneven so in order to facilitate a fair analysis, the two poorest performer from the group with better SRM performance were switched into the group with poorer SRM performance. These were HI21 and HI2 from figure 4.2 (these are overlapping on the figure, they had 4.7 and 4.8 dB SNR of SRM at 60° respectively).

4.5.2. Experimental set-up

Using manipulation in the frequency domain within MATLAB it was possible to use the HRIRs from the two locations, 0° and 60°, and swap the phase and amplitude spectra between the two. Similar to Culling et al. (2004), the alteration to the HRIRs are such that the interaural differences in intensity or time delay were eliminated. For instance, imposing the phase spectra for the 0° location on the 60° HRIR will eliminate the ITDs. This manoeuvre provided signals to the ears that contained only ILD or only ITD information, equivalent to Bronkhorst and Plomps dL and dT respectively (Bronkhorst & Plomp, 1989). Harvard IEEE sentences (Rothauser et al. 1969) were used for the target speech. A SSN was used as the interferer; the noise had a spectrum that was shaped according to the long-term average spectrum of the sentences. Three SRTs were recorded to give a mean SRT for each of the four condition. Target speech was always at 0°. The four conditions were;

1. Noise co-located at 0°

2. Noise at 60° (SRM_both)

3. Noise with only ILD information for 60° (ILD_60)

4. Noise with only ITD information for 60° (ITD_60)

The same procedure for recording SRTs was used as that described in section 3.2.4. The only difference was in the presentation of the interferer. Rather than have the interferer run for the entire sentence list (10 sentences), the interferer was presented 0.5 seconds before the IEEE sentence started and continued until 0.5 seconds after the end of the sentence.

4.5.3. Results
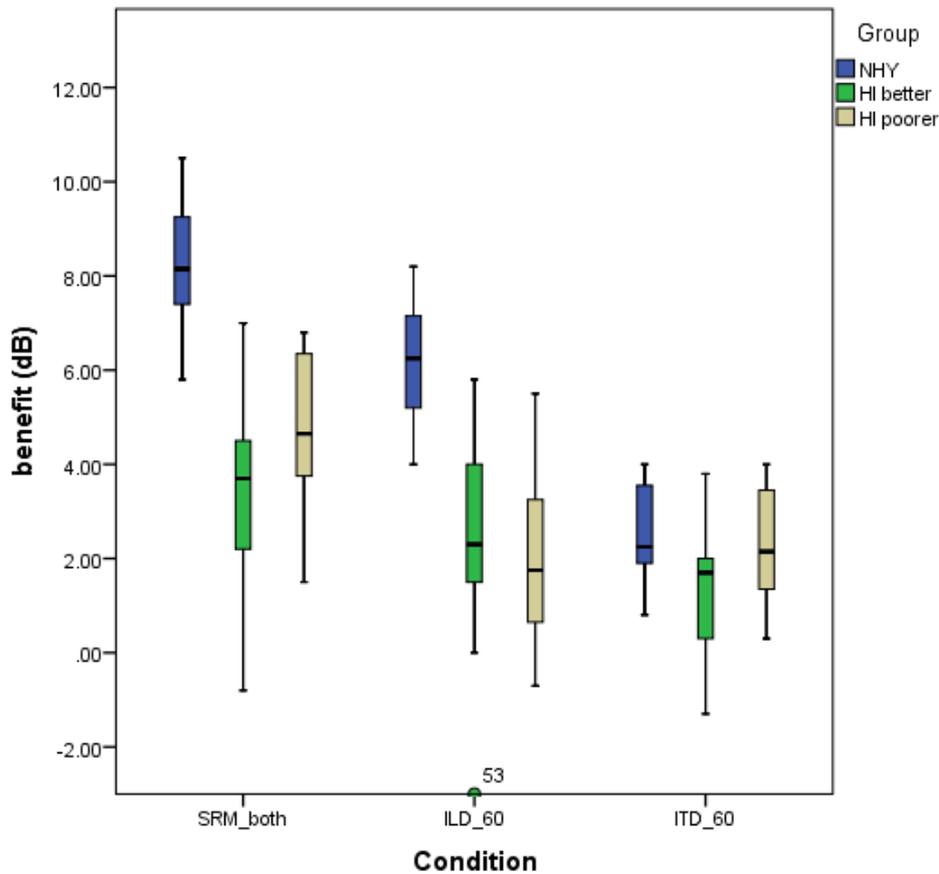
Figure 4.9 Boxplot results of benefit in SRT (in dB SNR) from both cues, or ILD or ITD only. Three groups are displayed, NH young, HI better or HI poorer.

Of the 87 mean SRTs recorded, one outlier was identified in the HI 'better' group. This was winzorised to within one unit of the highest value in the respective data set. Levene's test of homogeneity of variance was not violated when both cues available (SRM_60) [$F_{(2,26)}$ = 1.241, $p > 0.05$], with ILDs only [$F_{(2,26)}$ = 1.065, $p > 0.05$] and ITDs only [$F_{(2,26)}$ = 1.054, $p > 0.05$]. A mixed ANOVA was conducted, with the benefit in SRT the dependent variable, the group was the independent between-subjects variable and the condition was the within subjects variable. There was a significant interaction between group and condition, Wilks Lambda = 0.37, $F_{(4,50)}$ = 8.11, $p < 0.05$, partial eta squared = 0.394. Results from the condition with both cues are dispersed more than when only ITDs were present. Mauchly's sphericity test was significant for the condition [$\chi^2(2)$ = 10.513, $p < 0.05$]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = .74 for the main effect of condition). There was a significant main effect of condition [$F_{(1.489,38.711)}$ =60.621, $p < 0.001$], reflecting a hierarchy of performance. Highest scores were achieved when

both cues were present and the lowest scores were achieved when only the ITD cue was available. There was a significant main effect of group [F(1,26) =15.142, p<0.001]. Bonferroni pairwise comparisons showed significant differences between NH listeners and the HI 'better' group (p<0.001), as well as significant differences between NH listeners and the HI 'poorer' group (p<0.05). The two HI groups were not significantly different.

4.5.4. Discussion

A comparison of the NH listener's data with that of Bronkhorst and Plomp (1988) reveals that the mean benefit from ILD and ITD is substantially different. In their study with 17 NH listeners, they report mean ILD benefit for 60° as 6 dB SNR and mean ITD benefit as 5.1 dB SNR. In the present experiment with NH listeners, we found mean ILD benefit to be 6.2 dB SNR, but the ITD benefit as 2.5 dB SNR. Like Bronkhorst and Plomp, these effects were not completely additive. They found that when using both cues, the SRM was 9.4 dB SNR when moving the noise to 60°. In this experiment, the SRM was 8.2 dB SNR. It is encouraging to see the results of ILD benefit to be almost identical to those seen in the NH listeners in Bronkhorst and Plomp (1988). However, the NH listeners in this experiment failed to obtain the ITD benefit that Bronkhort and Plomp report.

To investigate the differences between the results with NH listeners, it is wise to revisit the SRT values. The mean SRTs Bronkhorst and Plomp report for 0° and 60° ITD are -6.4 dB SNR and -11.6 dB SNR. The benefit they report for the ITD only condition, which is the difference between these SRTs, is double the value recorded in this experiment. The standard deviation for their 0° and 60° ITD SRTs was 1.5 and 1.6 respectively. In the present experiment, the mean for the SRTs were -12.3 and -14.8 dB SNR, and the standard deviations were 1.3 and 1 dB SNR respectively.

Comparing the absolute mean SRTs scores for NH listeners may be unhelpful when the speech material and the procedures to collect the SRTs are different. Jelfs et al. (2011) model predictions for moving a noise source away from the co-located position with the target at 0°, to 60°, results in a 10 dB SNR overall benefit, 6.4 dB SNR for better-ear listening and 3.6 binaural unmasking benefit. Therefore, the results of this study are far closer to the model predictions than the results from Bronkhorst and Plomp (1988), whose results appear inflated when considering the ITD cues.

A further explanation for the difference in ITD benefit in NH listeners from Bronkhorst and Plomp and the current study may be found when we consider the

presentation level. Bronkhorst and Plomp (1988) had presentation level of the noise as 60 or 65 dB (A) whereas in this experiment, the noise was fixed at 70 dB (A) for both the NH and HI listeners. It was fixed at this level to ensure the HI listeners had sufficient sensation of the noise. However, this may have resulted in unexpected results with the NH listeners. An initial explanation might point to having presentation levels affecting the binaural masking component and thus the ITD only condition. However, it has been reported that BMLDs vary with the presentation level of the masker, with higher presentation levels of noise increasing the BMLD (Staffel et al. 1990).

When considering the HI listeners, the first result of interest is from the SRM_both condition. The HI groups were divided initially on performance in an SRM experiment in the free field with the interferer moved from co-located position (with the target) to 60° and the results from this determined the grouping. The SRM_both condition from the present experiment is almost identical to the initial SRM experiment, altering only in the mode of presentation (to headphones) and use of different sets of IEEE sentences. No significant difference was found between the two different groups of HI listeners in this experiment over headphones, even though they were separated based on SRM performance over loudspeakers. See section 4.7 for an individual correlational analysis (variables 1 and 11).

Bronkhort and Plomp (1989) varied the presentation level of the noise based on the hearing thresholds of the HI listener and then adaptively varied the target to obtain an SRT. They varied the noise level because they feared threshold effects in the conditions in which they attenuated one channel. This other analysis (monaural presentation) was not part of our interest and as such, the threshold effects were less of a concern in our experiment as it was binaural in its entirety. Having the noise fixed at 70 dB (A) gave a consistent presentation level to all HI listeners, all of whom shared reasonably similar PTA thresholds.

The significant interaction effect between group and condition must be interpreted with caution. The HI listeners are worse overall, but they cannot be worse by the same extent in dB SNR in every condition. The reason for this is that there is potentially less SRM available in different conditions. The NH group show a gradual decline in performance as we move from both cues, to ILD only, to ITD only. Although the two groups of HI listeners are not significantly different across the three conditions, both groups are significantly different from the NH listeners. Results of ITD only are however, reasonably similar across the three groups. The large differences are in the

ILD only condition and when both cues are present. There are a number of ways of interpreting the lack of use of ILDs in the HI groups. It is possible that they simply are unable to take advantage of the improved SNR on the side of the head shadow. Another view could be the HI listeners are unable to suppress the higher levels of noise on the side contralateral to the better SNR. The latter idea was investigated in the next experiment.

4.6. Contralateral noise

The results from section 4.3 and 4.4 do not support the theory that reduced SRM was based on TFS processing. Equally, results in section 4.5 suggest very similar results for NH and HI listeners in ITD only SRM. If the problem is not TFS processing, then it suggests the problem lies with ILD processing. In order to pursue this line of enquiry further, another study was conducted to test whether listeners were affected by the level of noise at the ear with the poorer SNR. Zwislocki (1972) presented data to support a theory on contralateral masking which he referred to as central masking. He demonstrated that the threshold of a pure-tone signal is elevated by the presence of a pure tone signal presented to the contralateral ear. The rationale for this experiment is that this contralateral masking effect (or central masking) is present with more complex signals than pure tones, such as speech. It may be possible that some individuals find it difficult to ignore or suppress a louder noise on one side and this becomes distracting when they are attending to the ear with the better SNR. It is possible to have a distracting noise source closer than the target talker in real-life scenarios and it is possible that some HI listeners will have more of a problem with dealing with such intense contralateral noise.

4.6.1. Participants

Fourteen HI participants took part in this experiment. Of the 17 from the previous experiment, 13 took part in this experiment (see appendix 1 for details). The two HI participants that moved group in the previous task (HI2 and HI21) were returned to the original group and this gave an equal split of seven in each group.

4.6.2. Experimental set-up

Similar to previous experiments, responses were vocalised by the participants and this was picked up by a microphone and scored by the experimenter who sat outside the soundproof booth. Each condition was repeated three times and a mean of the three

scores calculated. Like previous experiments, IEEE sentences were the target material and the interferer was a SSN. The signal to the headphones was monitored to ensure that there was no digital distortion introduced through peak clipping, and that the sound pressure levels presented to the either ear were not excessive (over 85 dB A).

Four conditions were created in MATLAB. Conditions 1 and 2 provided the target IEEE speech sentences and SSN monaurally to the left and right ear, and SRTs were measured according to the approaches detailed in the previous experiment. Conditions 3 and 4 were the same except for the presence of contralateral noise. This noise was independent of the noise at the ear with the target sentences and 20 dB more intense. The 20 dB was decided upon because it avoided distortion at the headphone, was within the boundaries of interaural attenuation when using circumaural headphones, and would be large enough to demonstrate an effect, but was thought unlikely to trigger an acoustic reflex in the contralateral ear. The conditions can be summarised as:

1. Left ear presented with speech in noise. No presentation to right ear

2. Right ear presented with speech in noise. No presentation to the left ear

3. Left ear speech in noise plus an independent, contralateral noise presented to right ear, which was 20 dB more intense.

4. Right ear speech in noise plus an independent, contralateral noise presented to left ear, which was 20 dB more intense.

Each condition was repeated 3 times and a mean score taken for the condition. The participants had two practice trials, one from a monaural condition (1 or 2) and the other from the contralateral noise condition (3 or 4). The sentence lists remained in the same order but the conditions were rotated.

4.6.3. Results
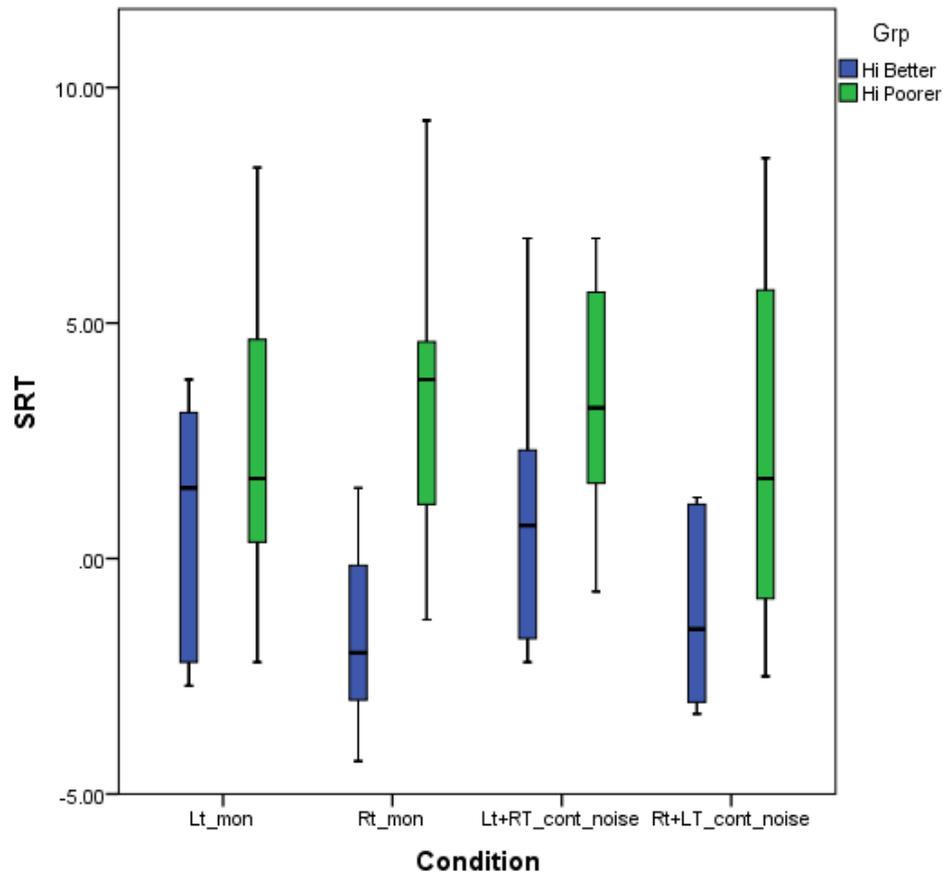
<u>Figure 4.10 Boxplot of the SRTs for the two groups of HI listeners, over 4 different</u>
<u>conditions. Two conditions are monaural and two condition have an added contralateral</u>
<u>noise added. The boxplot presents the median values as small lines within the box.</u>

Of the fifty-six mean SRTs recorded, one outlier was identified in the HI 'poorer' group. This was winzorised to within one unit of the highest value in the respective data set. A mixed ANOVA was conducted, with the mean SRT as the dependent variable, the group as the independent between-subjects variable and the condition was the within subjects variable. Levene's test of homogeneity of variance was not violated in the left monaural condition [$F_{(1,12)} = 0.157$, $p>0.05$], right monaural condition [$F_{(1,12)} = 0.962$, $p>0.05$], right contralateral noise condition [$F_{(1,12)} = 0.58$, $p>0.05$] or left contralateral noise condition [$F_{(1,12)} = 4.256$, $p>0.05$]. Mauchly's sphericity test was significant for the condition [$\chi^2(5) = 20.716$, $p<0.05$]. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .48$ for the main effect of condition). There was no significant main effect of condition [$F_{(1.444,17.328)} =1.392$, $p>0.05$]. There was a significant main effect of group [$F_{(1,12)} =5.322$, $p<0.05$]. No significant interaction effect was found between condition and group. The mean

SRT results for the HI poorer group ranged from 2.5 to 3.4 dB SNR whereas the mean SRT results for the HI better group ranged from 0.9 dB SNR to -1.6 dB SNR, reflecting superior performance across the four conditions in the HI better group.

4.6.4. Discussion

At first glance, the significant difference found between the two HI groups is encouraging. This difference considers SRTs across all four conditions. However, on closer inspection, the most significant findings are the monaural conditions. If a contralateral masking effect was taken as the reason for the poorer group's performance, one would expect similar results for the monaural SRTs between the two groups. In these conditions, there is no contralateral noise. The results illustrate that there is a large difference between the two groups across the conditions. The lack of a significant interaction between condition and group reflects a separation that persists across the conditions and opposes the hypothesis that a contralateral masking effect could account for the poor use of ILDs. The pure tone thresholds of the right and left ears of all the participants are all classed as symmetrical so it is unlikely to be a result of a threshold effect.

It would appear that the ability to ignore a louder contralateral noise while concentrating on an ipsilateral speech signal was not a feature that separated the two HI listener groups. Spatial attention has been postulated as a reason for HI listeners struggling to understand speech in background noise (Glyde et al. 2015). Spatial attention was, to some extent, measured in the present experiment, as the listeners were required to ignore a loud noise on one side and listen to the ear with the better SNR. It has been suggested that age can play a role in spatial attention (Singh, Pichora-Fuller, & Schneider, 2008), but the analysis performed in this study concentrated on differences within HI subjects only and as such, did not include other groups (i.e. NH young, NH age-matched). The only difference here compared to other speech in noise tasks in this chapter was that speech was exclusively presented to one ear. The spatial attention explanation does not hold for this set of results because the monaural results were dissimilar between the two groups.

Another effect that might play a role in the results may be found in the 'right ear advantage' literature. This came from early work (Kimura, 1961) with dichotic listening experiments where different acoustical items were delivered to the left and right ears, over headphones, at the same time. The results in the Kimura study suggested an asymmetry, with the material presented to the right ear being dominant. The

conclusions drawn postulated that the contralateral pathway between the right ear and the left hemisphere of the brain is a pathway that has a strong focus on processing speech information and this was the reason behind the results. There has been a large support in the literature in the past fifty years, which has proven that dichotic listening tasks confirm the right ear advantage (Hugdahl, 2011). However, there is a growing body of evidence that questions the right ear advantage (Westerhausen & Kompas, 2018). No evidence can be found in the results of this study that would support the right ear advantage theory with regards to the effect on intelligibility, with no interaction between group and condition found.

4.7.   Relational analysis

A number of different variables have been measured in this chapter. The aim was to complete a median split of the HI listeners in their SRM performance and then investigate these different groups in a number of psychoacoustical tasks. An alternative approach is simply to correlate the different variables across listeners. The following variables were included in this analysis, which is presented in table 4.3:

1. Spatial release from masking from 0° to 60° in the free-field (SRM60)

2. Age of the participant (age)

3. Pure Tone Audiogram threshold at 0.5, 1, 2, 3, 4 kHz (5freqPTA)

4. The mean SRT of the three trials with speech and noise at 0° in the free field (meanSRT0FF)

5. Spatial release from masking from 0° to split interferers at 60° and 300° in the free-field (SRMsplit)

6. Binaural Masking Level Difference with pure tone of 250 Hz (BMLD250)

7. Binaural Masking Level Difference with pure tone of 750 Hz (BMLD750)

8. Binaural Masking Level Difference with pure tone of 1250 Hz (BMLD1250)

9. Interaural time difference discrimination (ITD_discrim)

10. Mean SRT of the three trials with speech and noise at 0° over headphones for the independent cues analysis (meanSRT0H)

11. Spatial release from masking from 0° to 60° over headphones with both cues available (SRM60both)

12. Spatial release from masking from 0° to 60° over headphones with only ILD cue available (ILD_only)

13. Spatial release from masking from 0° to 60° over headphones with only ITD cue available (ITD_only)

14. Mean SRT for three trials of monaural presentation of speech in noise to the left ear (Lt_Mon)

15. Mean SRT for three trials of monaural presentation of speech in noise to the right ear (Rt_Mon)

16. Mean SRT for three trials of speech in noise to left ear and contralateral noise to the right ear (Lt+Rt noise)

17. Mean SRT for three trials of speech in noise to right ear and contralateral noise to the left ear (Rt+Lt noise).

	SRM 60	Age	5freq PTA	Mean SRT0FF	SRM split	BMLD 250	BMLD 750	BMLD 1250	ITD discrim	Mean SRT0H	SRM 60both	ILD only	ITD only	Lt Mon	Rt Mon	Lt_Mon +Noise	Rt_Mon +Noise
SRM60	1																
Age	-.404	1															
5freqPTA	-.317	.282	1														
MeanSRT0 FF	.021	.217	.618**	1													
SRMSplit	.401	-.065	-.121	.029	1												
BMLD250	-.202	-.440*	.117	.246	-.224	1											
BMLD750	-.070	.220	-.152	-.079	-.025	.208	1										
BMLD1250	.070	-.263	-.552**	-.496*	.130	.137	.233	1									
ITD Discrim	-.055	.217	-0.83	-.200	-.007	-.352	-.020	-.239	1								
MeanSRT0 H	-.424	.420	.784**	.717**	.108	.240	-.219	-.330	-.110	1							
SRM60 both	.179	-.141	-.484*	-.312	.104	.033	.571*	.528*	-.278	-3.84	1						
ILD_only	.296	-.206	-.517*	-.258	.240	-.215	.316	.403	-.247	-.459	.850**	1					
ITD_only	.001	.198	-.025	-.019	-.047	.203	.620*	.464	-.366	.183	.598*	.293	1				
Lt_Mon	-.346	.080	.565*	.408	-.644*	.034	-.466	-.574*	-.081	.580*	-.686**	-.504	-.344	1			
Rt_Mon	-.690**	.354	.550*	.095	-.256	.276	.019	-.258	-.053	.678*	-.496	-.577*	-.015	.414	1		
Lt_Mon +Rtnoise	-.446	.007	.497	.230	-.568*	.158	-.214	-.635*	-.134	.602*	-.622*	-.350	-.316	.889**	.490	1	
Rt_Mon +Ltnoise	-.607*	.360	.555*	.371	-.102	.380	.068	-.335	.004	.646*	-.489	-.678*	-.105	.426	.896**	.426	1

Table 4.3 A correlation table for all the variables. Pearson correlation values provided with * denoting a statistical significance value of <0.05 and ** a statistical significance value <0.01. All correlational values that were statistically significant have been highlighted.

As mentioned in section 4.5.4, the SRM60 result and SRMboth are essentially the same measure but delivered through loudspeaker or headphones and these are not correlated. However, it is reassuring that the SRT0FF and SRT0H are correlated. These are the absolute measures in each of the experiments when the target sentences and noise are co-located at 0°. This relationship would be expected, as they are the same task with the only difference being the method of presentation (headphones vs. loudspeaker). This provides a level of trust in the results, even if the actual benefit achieved (the SRM values) in each method of presentation are not correlated. The amount of reverberation in the free-field room has a potential to explain the result in that reverberation present over loudspeaker (in a room) was not present over headphones. However, the room used had a reverberation time of only 60 ms, which makes this explanation for the results seem unlikely.

The dependent variable in the experiments earlier in the chapter was SRM60. The variables that demonstrated a relationship with SRM60 were Rt_Mon and RT+Ltnoise. The scatterplots are presented below:
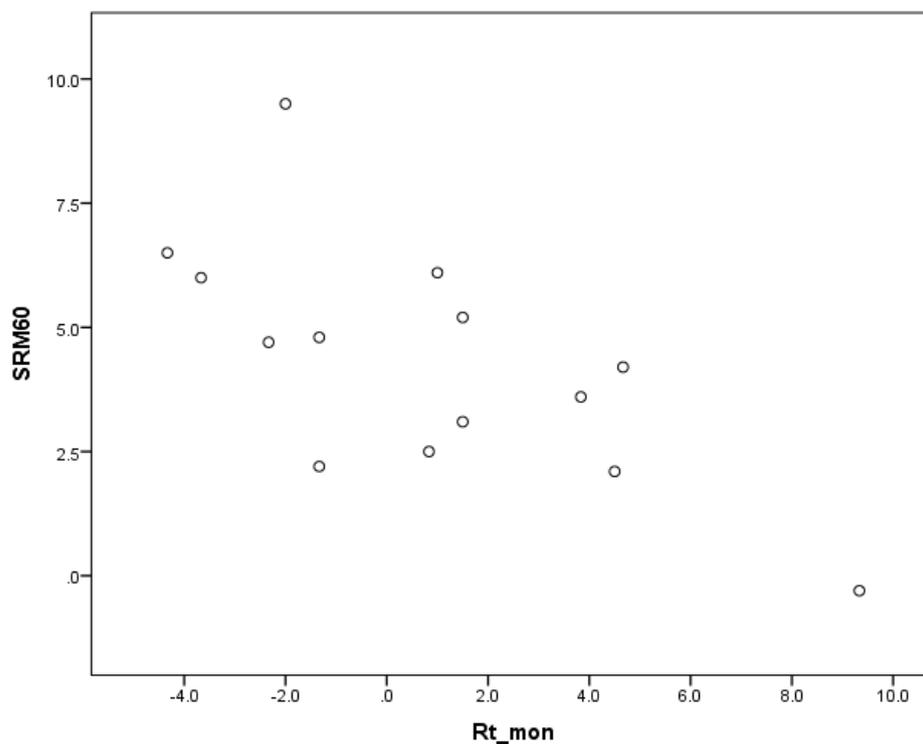
Figure 4.11 Scatterplot of the HI-Listeners data from SRM 60 in the free field vs the right monaural condition under headphones. A larger score on SRM indicates superior

performance in that task whereas a lower SRT for the right monaural reveals superior performance.
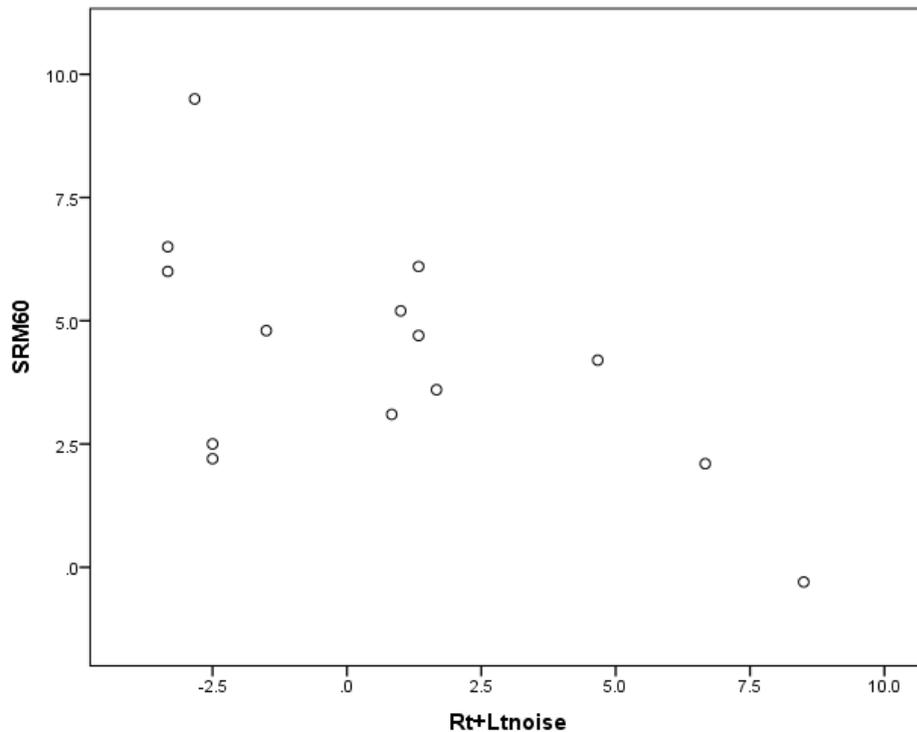
Figure 4.12 Scatterplot of the HI-Listeners data. The Y-axis is from SRM 60 in the free field. The X-axis is the SRT values obtained under headphones when the right ear had speech in noise and the left ear had contralateral noise.

Using a Pearson product-moment correlation coefficient, there was a strong, negative correlation between SRM60 and RT_Mon (r=-.690, n=14, p<0.01) and strong negative correlation between SRM60 and RT+Ltnoise (r= -.607, n=14, p<0.05). This implies that those with better SRM performance had lower/better SRTs when speech and noise was presented to the right ear, regardless whether there was noise on the left ear. This is unlikely to be a threshold effect (i.e. poorer PTA thresholds in the left ear) because of the nature of the inclusion criteria and the necessity for symmetrical hearing loss.

There was a strong positive correlation between BMLD750 and ITD_only (r=.620, n=16, p<0.05). This suggests the larger the BMLD750 score, the larger the SRM was for ITD_only. This result would be expected because both tests are underpinned by binaural unmasking. The BMLD750 also correlated with SRM60both (r=.571, n=16, p<0.05), which can be explained by the fact the binaural unmasking is a

component of the overall SRM measure. This would indicate there is some effect of TFS processing that affects SRM, even if it is limited to these conditions. It is unclear why BMLD250 did not demonstrate a similar relationship with SRM. There was a larger BMLD on average recorded at 250 Hz (11.15 dB SNR) compared to 750Hz (7.1 dB SNR) which is an expected result based on the literature (e.g., Hirsh & Burgeat, 1958). However, BMLD250 and SRM60both are not correlated. One explanation for this result is that the 250 Hz region is less important for clarity of speech in background noise (Fletcher & Galt, 1950).

ITD_discrim and BMLD were not correlated at any frequency, but this is not unexpected in that the physiological mechanisms behind each measure may be different. It has been suggested that the Inferior Colliculus and Auditory Cortex play large roles in the encoding of BMLDs (Gilbert, Shackleton, Krumbholz, & Palmer, 2015), although the thalamus and its communication with the insula have also been proposed as critical to BMLD processing (Wack et al. 2012). In the case of ITD discrimination, the information is believed to be encoded at the level of the Superior Olivary Complex (SOC), with the medial SOC responsible for the initial coding (Palmer, Shackleton, & McAlpine, 2002).

Some other interesting relationships were uncovered during the analysis. Age was found to be marginally, non-significantly correlated to SRM60 ($r= -.404$, n= 24, p=0.05). The variable that has the most correlations with other variables is the 5freqPTA. The recommended procedures for PTA (BSA, 2011) advise to test the intermediate frequencies of 3 & 5 kHz, and the typical approach for the average is to take values between 0.5 and 4 kHz. For the average hearing threshold to be related to so many measures would suggest there is a threshold effect, although when this was addressed in chapter 2 and when threshold effects were mediated through gain adjustments, little change was reported. There were also many examples of studies with PTA measures poorly correlated with other psychoacoustical measures, as discussed in section 1.4.4.5.

4.7.1. Discussion

It has been proposed that HI listeners are less able to make use of ITD cues (King et al. 2017; Strelcyk & Dau, 2009). It was expected that when completing a median split of the HI listeners based on SRM performance, those identified with poorer SRM would also demonstrate poorer binaural TFS processing. In the experiment reported here, this has not been the case. The HI and NH listeners' performance on the tasks with ITD

information is not significantly different (see figures 4.8 and 4.9). We can therefore not link poor TFS processing with poor speech intelligibility in noise.

The independent cues experiment confirmed that HI listeners are poorer at using spatial cues than their NH counterparts. The comparison of the mean scores from the two groups of HI listeners showed similar results and once again no significant difference. We are left to conclude that the ability to make use of ILD and ITD cues (over headphones) individually, or combined, may not be a useful indicator to poor SRM performance in the free-field.

The lack of significant findings in TFS pointed to the issue being ILD in nature and this was the inspiration behind the contralateral noise experiment. The ITD aspect had already been investigated with ITD discrimination, BMLD and ITD only SRTs. The contralateral noise experiment was conducted in order to establish whether the HI listeners with poorer SRM performance had difficulty using an ear with an optimum SNR in the presence of a louder contralateral noise. When considering the two different groups (HI better vs HI poorer), they did perform significantly differently. The HI poorer group had significantly higher SRT thresholds, with and without the contralateral noise. These results can be seen in figure 4.10. However, to confirm a contralateral masking effect one would have expected an interaction to be present with the monaural conditions being similar between the groups and then the contralateral conditions different. This was not the case. It remains unclear why the HI poorer group found the monaural conditions more challenging than the HI better group.

An explanation for the findings might have already been provided. Crandell (1991) suggested three possible reasons why it is difficult to find strong associations between psychoacoustical tasks and speech recognition with HI listeners. One explanation suggests that individuals may process speech different at a cognitive level. This would result in different degrees of efficiency or susceptibility to disruption. In other words, given an optimal signal, some might perform perfectly, but once noise is added or there some degree of hearing loss, then difficulties are encountered. Therefore, individual differences seen in HI listeners would be a manifestation of the differences seen in the population of NH listeners. The benefit of this explanation is that it does not require any relationship between psychoacoustical performance and speech-processing performance. The caveat is that some non-auditory cognitive tasks that utilise the same abilities may be affected by the same variables. This explanation could fit the results found in this chapter. It is possible that the measures were sensitive on teasing apart

spatial processing, but that the general spread of performance in cognitive processing has manifested itself in variable performance. The argument is that this spread is a natural characteristic of the normal distribution of the population.

5. General discussion

5.1. Summary of findings

The fundamental aim of this thesis was to analyse how HI listeners struggle to understand speech in background noise. The motivation for the study came from a number of sources. Firstly, much of the research focusing on HI listener's speech intelligibility in background noise has been completed in ideal situations such as a sound-deadened room or from HRIRs recorded from an anechoic chamber. There have been very few attempts to recreate real-world listening experiences in the laboratory. Equally, much of research focuses on one variable at a time. It was felt that there was a gap in knowledge about how HI listeners perform in complex listening environments and the work in chapter 2 was inspired by Culling (2016).

It was also noted that almost all the studies investigating speech intelligibility in noise used a fixed head position, which typically has target speech directly ahead at 0° azimuth. This does not reflect the natural behaviour of people in complex listening environments. Inspired by Culling et al. (2012), Grange and Culling (2016) and the model predictions from Jelfs et al. (2011), chapter 3 investigated head-orientation strategies in HI listeners.

The experiments in chapters 2 and 3 recreated real-world, complex listening environments. This provided a platform to analyse functional performance. However, it did not completely address a fundamental question as to how HI listeners struggle to understand speech in complex listening environments. There is a lack of agreement in the literature as to the mechanisms that deteriorate when a hearing loss develops so the inspiration for chapter 4 came from studies such as Peissig and Kollmeier (1997). They were one of the first to amend their approach and analysis based on the heterogeneity in results from HI listeners, such as a median split not on the PTA thresholds, but on SRM performance. However, they only split the group to describe the results of the SRM task and there was no further analysis of performance linked to SRM. This split-group approach was the inspiration for chapter 4. The 'forensic' analysis was performed by undertaking a median split based on SRM performance so that the HI listeners were grouped as 'better SRM performers' or 'poorer SRM performers'. A series of experiments were then created to attempt to identify the underlying mechanisms for the poor use of spatial information.

Study 1: The effect of masker source characteristics on speech intelligibility of HI listeners in a complex listening environment.

Findings and conclusions

- Performance of the HI listeners was significantly poorer than NH listeners. All SRTs were elevated, across all test conditions. This supports the hypothesis that hearing loss leads to poorer speech intelligibility in noise in complex listening environments.

- It appears HI listeners are able to take some advantage from F0 processing, evidenced by the fact that their performance was superior when the masking sources were either speech or reversed-speech. However, this is the case with single interferers and when more interferers are added this effect disappears. The hypothesis that the difference in gender of the interferer would influence the results has not been supported.

- There was a significant interaction effect between interferer type and interferer number in both the analysis of NH vs HI (unaided) and the analysis of HI (unaided) vs HI (aided). This demonstrates how the most effective masker and least effective masker with one interferer, SSN and speech respectively, actually reverses when there are eight interferers. With the eight interferers, speech becomes the most effective masker and the SSN the least. These results do not support the hypothesis that the speech interferer would be the least effective as it is only the case with the low number of interferers. No informational masking effect was found as the speech and reversed-speech interferers provided very similar SRTs. Unlike Culling (2016) who found an information masking effect in the 2-talker condition with NH listeners, this was not the case with the HI listeners.

- The results suggest that the spatial cues provided by separating the interferers might be the most beneficial cue for HI listeners of all the cues available. This was confirmed in the results with one interferer, where performance in the HI listeners was closest to NH results. However, this performance deteriorates when interferers are spread across both hemifields. In this scenario, the opportunity for better-ear listening is significantly reduced. The experiment demonstrated that HI listeners are

112

unable to take advantage of modulations in the masker, consistent with other studies. It has been proven that modulations are a significant cue for NH listeners when there are single interfering sources, and this benefit disappears as the environment becomes more complex and more interferers are added. The addition of extra interfering sources fills the modulations. However, this study confirms that HI listeners are unable to take advantage of the modulations even with single interfering sources.

- The poorer results of the HI listeners cannot be attributed to reduced audibility alone. There is a suprathreshold deficit, which influences results. This can be confirmed as the experiment had a second trial in which each HI listener was provided ear-specific gain adjustments to correct for hearing loss. No increase in performance was measured after this correction was made, which does not support the hypothesis, so it can be confirmed that loss of audibility through the hearing loss does not account for the poorer results in the HI listeners.

Study 2: Head Orientation benefit in HI listeners.

Findings and conclusions

- There is confirmation that moving the head away from the target by up to 30° can provide significant benefits for HI listeners. The hypothesis was that HI listeners would not be able to take advantage of head orientation strategy but this has proven to be the case. The hypothesis was based on the concept that high frequency hearing loss would lead to impaired use of the head shadow. However, the benefit observed with distributed maskers occurs due to the reflections of target sounds from the head, which would be more broadband. The results confirm that the head orientation benefit is 1.2 dB SNR for HI listeners. This has significant implications regarding the way that HI listeners are advised and counselled concerning listening tactics. For the work to have impact, these results need to be disseminated to the public and the Audiology community to ensure HI listeners are given the best advice on head orientation. For a long time the assumption has been the best strategy is to look straight at the speaker, for obvious reasons concerning lip-reading. The work that comes from this thesis

suggests that one can still benefit from lip-reading and increase intelligibility of target sentences by orientating the head, even if one has a hearing loss. Generating impact and dissemination of these findings can be found in the recent publication in the British Academy of Audiology Magazine (Culling, 2018) which is disseminated to all members. Indeed, Sara Coulson referred to the article in the editorial section "Cardiff University has conducted research into the best head position for optimal hearing that turns our traditional advice on its head".

- Performance was dependent on table location and this would support the hypothesis that there are preferential seating options for HI listeners. The SRTs recorded at table 14 were the superior scores and this was in the corner of the room. This supports the hypothesis that more central sitting locations are more problematic because the listeners is then sat in the middle of all of the interferers and then unable to using any spatial information. Table 9 was the most central of all table locations and this resulted in the poorest SRTs for the HI listeners. It would be prudent for restaurant staff to have this information to hand should it be requested.

Study 3: Forensic analysis of the mechanisms underpinning poor use of spatial cues in HI listeners.

Findings and conclusions

In order to investigate the mechanisms behind the poor performance in HI listeners, a forensic analysis was undertaken. This is a novel way of approaching the issues seen in so many studies with HI listeners. Many researchers group HI listeners together and complete a group analysis, often comparing to NH listeners. However, this has inherent issues. A large heterogeneity in the results is often reported, and it is often the case that performance is not predicted very well by PTA thresholds. The forensic analysis consisted of a median split of the HI listeners based on SRM performance and a correlational analysis on a number of psychophysical tasks. These psychophysical tasks were chosen because they were believed to assess the mechanisms that underpin the use of spatial information. The median split grouped the HI listeners into one of two groups: HI 'poorer' or HI 'better'. NH listeners were also split into two groups based on their age to investigate the influences of age on performance. Conclusions were;

114

- Aided and unaided SRM results for the HI listeners were well correlated although performance was not significantly improved by the presence of the hearing aids. This contradicts the hypothesis that hearing aids would improve performance.

- Binaural Masking Level Differences were similar between NH young, NH older, HI 'poorer' and HI 'better'. ITD discrimination was similar between NH young, NH aged-matched controls, HI 'poorer' and HI 'better'. This result indicates that poorer SRM performance that we observed was not associated with either of the binaural TFS measures. It also confirms that age has not influenced the results. These two findings oppose the hypotheses stipulated in section 4.1.

- The use of ILD and ITD cues independently for speech intelligibility in noise were similar for the HI 'poorer' and HI 'better' groups. NH young listeners had superior performance compared to both HI listener groups. A significant interaction effect was found for condition and group. Although the NH group were superior in all three measures, the HI 'poorer' group actually performed marginally better than the HI 'better' group when both cues were present and when only ITD cues were present. The overall results were not significantly different and as such, the hypothesis that those with poorer SRM performance would have inferior performance on the use of ILDs has not been supported.

- The contralateral masking experiments did find a significant difference between the HI 'poorer' and HI 'better'. However, the results were surprising. Even in the reference conditions (right monaural SRTs) the HI 'poorer' listeners were demonstrably less able to recover speech from the noise. It is unclear why this was the case. If the contralateral hypothesis were to be supported, the results of monaural SRTs would have been similar and contralateral SRTs vastly different. This has not been the case so the results do not support the hypothesis.

- The correlational analysis from 17 variables gave an insight into potential future areas of exploration. The five-frequency pure tone average threshold had an association with the highest number of other variables. The hypothesis that ILD processing would be associated with SRM performance was not confirmed.

115

5.2. Foreseen extensions of this thesis

There are a number of constraint when conducting speech in noise testing. There is often the trade-off between time and data. This is partly the reason for using 50% correct criteria threshold for the SRT. If time were not a constraint, it would be far more informative to collect thresholds at different criteria to plot psychometric functions but this was not possible for the work in this thesis. Linked to this is the lack of realism in certain parts of the thesis, even though this was a primary aim of the 2nd and 3rd chapters. For instance, the target speech was often fixed in level while the interferer was adaptively adjusted based on the responses of the participant. The target speech was unchanged while these changes were made in noise. The target sentences were pre-recorded in ideal circumstances with little noise present and as such, were presented at normal vocal level. However, we know that vocal effort does vary depending on the level of the background noise, and speakers raise their voice in the presence of noise, in what is referred to as the Lombard effect (Lombard, 1911). These acoustical changes to the target speech are not reflected in the current approach and it remains unclear if this would have a significant effect on intelligibility. The only feasible way assessing this with the approached described in this thesis would involve different recordings from the same speaker under different levels of background noise. These could then be used at different SNRs in the experiment adaptively.

A further deviation from reality was the intentional use of reversed speech in chapter 2. It may be argued that using reversed-speech does not completely represent the phonetic flow of typical speech. A suggestion for future work may be the use of nonsense sentences that mix-up typical English syllables into an incorrect order. This would provide the platform to investigate informational masking without the changes to acoustical properties of the material. However, mixing English syllables into a random order may be equally unreliable as a predictor for real speech because of influences from coarticulation that are present in running speech.

The results from chapter 3 have served notice to the scientific community and clinicians alike, that there are significant benefits to head orientations away from 0° azimuths. The work from this thesis is a first of its kind to systematically assess head orientation benefit in a complex listening environment with symmetrical hearing loss participants. Using virtual reality to assess performance in complex listening situations can be extended. The methods employed in chapter 2 and 3 of recording Binaural Room Impulses Reponses is adequate for the purposes of recreating a virtual listening

environment. What was not investigated was the option of visual feedback and free-head orientation. It is within modern technology to advance the approaches taken in this thesis and record multiple audio and visual inputs from 360°. In doing so, it may be possible to render 360° audio and visual information through a mixed-reality platform. This would be a further step in creating the most realistic, sensory experience for those with hearing loss.

Another extension to the work completed in chapter 4 might be a collection of more cases to support the analysis through regression or factor analysis. Another area of interest is better-ear glimpsing. There has been a lot of attention paid to this recently in the literature (for instance Culling & Mansell, 2013; Rana & Buckholz, 2016; Rana & Buckholz, 2018). The work from chapter 4 with independent cues consisted of SRTs recorded from noise sources from either 0 or 60°. However, in the real world, interfering sources intermittently arrive from different directions. Use of better-ear glimpsing has been studied in NH listeners but less so in HI listeners. The natural extension of the independent cues study of chapter 4 would be an investigation of better-glimpsing and how quickly those with hearing loss are able to perform this function.

5.3. Concluding remarks

The most significant finding of this thesis to clinicians is the benefit of head orientation because they have the power the make changes to the way information is conveyed to a large body of the HI community. However, to embed these changes there needs to be a national campaign to promote the work from the thesis and some form of top-down policy change.

To address this at a national level, one could consider the quality assurance tools used in the UK. The 'Adult Quality Standards' or 'Improving Quality in Physiological Services', are used by health boards to assess Audiology service delivery. Taking Wales as an example, the Adult Quality Standards are used as an audit tool for adult hearing services in the National Health Service (NHS). The audit is conducted in two stages over two years. Year 1 is a self-audit where the department report and score their own service. Year 2 is external audit, with the audit conducted by senior clinicians from other, independent health boards as well as an independent third sector auditor to ensure consistency across audits. The reports are sent to the chief executive of the health board.

The reports are also sent on to Audiology Standing Specialist Advisory Group (ASSAG) and then on to the Welsh Government via the Cabinet Secretary for Wales.

There are nine standards in total in the Adult Quality Standards. Six focus on the service user journey and three on the infrastructure unique to Audiology services. To fully implement changes on a national level, it would be advisable that the Adult Quality Standards be modified to include head orientation advice. Standard four consists of the 'Individual Management Plan' (IMP) and this would seem the natural place for head orientation advice. Once it becomes nationally recognised in the recommended procedures and it forms part of the Audit tool and the IMP, we are then likely to see significant shifts in the advice offered to HI listeners. This has far wider implications than first expected. One of the major complaints from hearing aid users is the lack of benefit they receive in complex listening scenarios. This means many hearing aid users return to the Audiology department or simply refuse to wear the hearing aid. Head orientation can give an extra 1.2 dB benefit in SNR. I t is possible to compare this to NH performance and equate a recovery percentage based on this benefit in dB SNR. The 1.2 dB SNR improvement through head orientation provides a recovery of 33% and 64% toward NH performance, for speech and noise interferers, respectively. It is possible to create simulated head orientation strategies using virtual reality to encourage users to orientate their head to an optimum position when in challenging conditions. Although 1.2 dB SNR has been recorded here, with a simulated virtual reality training programme it would be preferential to artificially increase the benefit achieved to 3 dB SNR, as this is the just-noticeable-difference for SNR (McShefferty, Whitmer & Akeroyd, 2015). By creating this elevated benefit, it is possible to train HI listeners to incorporate the head orientation strategy in real-life scenarios. This has the potential to significantly reduce the number of people returning to the Audiology department as the functional performance is improved through head orientation strategies. The reduced number of hearing aid users returning to the audiology department has the potential for significant financial savings for the health board, at a time when the NHS funds are increasingly squeezed.

References

Action On Hearing Loss. 2011. *Facts and figures on hearing loss and tinnitus*.

Action On Hearing Loss. 2015. *Hearing Matters*.

Ahlstrom, J. B., Horwitz, A. R., & Dubno, J. 2009. Spatial benefit of bilateral hearing aids. *Ear and Hearing*, 30(2), pp.203–218.

American National Standards Institute. 1997. American National Standard: Methods for Calculation of the Speech Intelligibility Index. S3.5-1997 (R2012).

Arbogast, T.L., Mason, C.R., & Kidd Jr, G. 2005. The effect of spatial separation on informational masking of speech in normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America*, 114(4), pp.2169-2180.

Bee, M. A, & Micheyl, C. 2008. The cocktail party problem: what is it? How can it be solved? And why should animal behaviorists study it? *Journal of Comparative Psychology,* 122(3), pp.235–51.

Beechey, T., Buchholz, J. M., & Keidser, G. 2019. Eliciting naturalistic conversations: a method for assessing communication ability, subjective experience, and the impacts of noise and hearing impairment. *Journal of Speech, Language and Hearing Research*, 62(2), pp.470-484.

Bench, J., Kowal, A., & Bamford, J. 1979. The BKB (Bamford–Kowal–Bench) sentence list for partially hearing children. *Britsh Journal of Audiology*, 13, pp.108–112.

Bertoli, S., Staehelin, K., Zemp, E., Schindler, C., Bodmer, D., & Probst, R. 2009. Survey on hearing aid use and satisfaction in Switzerland and their determinants. *International Journal of Audiology*, *48*(4), pp.183–195.

Best, V., Marrone, N., Mason, C.R, & Kidd Jr, G. 2012. The influence of non-spatial factors on measures of spatial release from masking. *The Journal of the Acoustical Society of America*, *131*(4), pp.3103–3110.

Blauert, J., Brueggen, M., Bronkhorst, A., Drullman, R., Reynaud, G., Pellieux, L., Krebber, W. & Sottek, R. 1998. The AUDIS catalog of human HRTFs. *The Journal of the Acoustical Society of America*, 103, pp.3082.

Bregman, A. 1990. *Auditory Scene Analysis: The Perceptual Organization of sound*. Cambridge, Massachusetts: The MIT Press.

Brimijoin, W. O., McShefferty, D., & Akeroyd, M. A. 2012. Undirected head movements of listeners with asymmetrical hearing impairment during a speech-in-noise task. *Hearing Research*, 283(1–2), pp.162–8.

British Society of Audiology. 2011. *Recommended procedure. Bone-conduction threshold audiometry with and without masking*.

British Society of Audiology. 2013. *Recommended Procedure. Tympanometry*.

Brokx, J. P. L., & Nooteboom, S. 1982. Intonation and the perceptual separation of simultaneous voices. *Journal of Phonetics*, 10, pp.23–36.

Bronkhorst, A., & Plomp, R. 1988. The effect of head-induced interaural time and level differences on speech intelligibility in noise. *The Journal of the Acoustical Society of America*, 83(4), pp.1508–1516.

Bronkhorst, A., & Plomp, R. 1989. Binaural speech intelligibility in noise for hearing-impaired listeners. *The Journal of the Acoustical Society of America*, 86(4), pp.1374–1383.

Bronkhorst, A., & Plomp, R. 1992. Effect of multiple speechlike maskers on binaural speech recognition in normal and impaired hearing. *The Journal of the Acoustical Society of America*, 92(6), pp.3132–9.

Brown, C. A., & Bacon, S. P. 2010. Fundamental frequency and speech intelligibility in background noise. *Hearing Research*, 266(1–2), pp.52–59.

Brungart, D. S., Simpson, B. D. B., Ericson, M. A., & Scott, K. K. R. 2001. Informational and energetic masking effects in the perception of multiple simultaneous talkers. *The Journal of the Acoustical Society of America*, 110(5), pp.2527-2538.

Byrne, D., Dillon, H., Tran, K., Arlinger, S., Wilbraham, K., Cox, R., Hagerman, B., Hetu, R., Kei, J., Lui, C., Kiessling, J., Nasser Kotby, M., Nasser, N.H.A., El Kholy, W.A.H., Nakanishi, Y., Oyer, H., Powell, R., Stephens, D., Meredith, R., Sirimanna, T., Tavartkiladze, G., Frolenkov, G.I., Westerman, S & Ludvigsen, C. 1994. An international comparison of long-term average speech spectra. *The Journal of the Acoustical Society of America*, 96(4), pp.2108–2120.

Cameron, S., Dillon, H & Newall, P. 2006. Development and evaluation of the listening in spatialized noise test. *Ear and Hearing*, 27(1), pp.30-42.

Cherry, E. C. 1953. Some experiments on the recognition of speech, with one and with

two ears. *The Journal of the Acoustical Society of America*, 25(5), pp.975–979.

Ching, T. Y. C., Dillon, H., & Byrne, D. 1998. Speech recognition of hearing-impaired listeners: predictions from audibility and the limited role of high-frequency amplification. *The Journal of the Acoustical Society of America*, 103(2), pp.1128–40.

Ching, T. Y. C., Dillon, H., Katsch, R., & Byrne, D. 2001. Maximizing effective audibility in hearing aid fitting. *Ear and Hearing*, 22(3), pp.212–224.

Crandell, C. C. 1991. Individual differences in speech recognition ability: implications for hearing aid selection. *Ear and Heairng*, 12(6), pp. 100s-108s.

Cubick, J., Buckholz, J. M., Best, V., Lavandier, M. & Dau, T. 2018. Listening through heairng aids affects spatial percetion and speech intelligibility in normal-hearing listeners. *The Journal of the Acoustical Society of America*, 144(5), pp.2896–2905.

Culling, J.F. 2007. Evidence specifically favoring the equalization-cancellation theory of binaural unmasking. *The Journal of the Acoustical Society of America*, 122(5), pp.2803–13.

Culling, J.F. 2013. Energetic and Informational Masking in a Simulated Restaurant Environment. In B. C. J. Moore, R. D. Patterson, I. M. Winter, R. P. Carlyon, & H. E. Gockel (Eds.), *Basic Aspects in Hearing.* (Vol. 787, pp.511–518). New York, NY: Springer New York.

Culling, J.F. 2016. Speech intelligibility in virtual restaurants. *Journal of the Acoustical Society of America*, 140(4), pp.2418–2426.

Culling, J.F. 2018. Turn and ear to hear. *British Academy of Audiology magazine*, 47, pp.14-16.

Culling, J.F, & Darwin, C. J. 1993. Perceptual separation of simultaneous vowels: Within and across-formant grouping by F0. *The Journal of the Acoustical Society of America*, 93(6), pp.3454–3467.

Culling, J.F., Hawley, M. L., & Litovsky, R. Y. 2004. The role of head-induced interaural time and level differences in the speech reception threshold for multiple interfering sound sources. *The Journal of the Acoustical Society of America*, 116(2), pp.1057–1065.

Culling, J. F., Jelfs, S., Talbert, A., Grange, J., & Backhouse, S. 2012. The Benefit of Bilateral Versus Unilateral Cochlear Implantation to Speech Intelligibility in

Noise. *Ear and Hearing*, 33(6), pp.673–682.

Culling, J. F. & Mansell, E. R. 2013. Specch intelligibility among modulated and spatially distributed noise sources. *The Journal of the Acoustical Society of America*, 113(4), pp.2254–2261.

Culling, J. F., & Stone, M. 2017. Energetic masking and masking release. In Middlebooks, J. C., Simon, J. Z., Popper, A. N., & Fay, R. R., (Eds), The auditory system at the cocktail party: Springer handbook of auditory research (pp.41-73). ASA Press.

Dawes, P., Emsley, R., Cruickshanks, K. J., Moore, D. R., Fortnum, H., Edmondson-Jones, M., McCormack, A. & Munro, K. J. 2015. Hearing loss and cognition: The role of hearing aids, social isolation and depression. *PLoS ONE*, 10(3), pp.1–9.

Dawes, P., Munro, K. J., Kalluri, S., & Edwards, B. 2013. Unilateral and bilateral hearing aids, spatial release from masking and auditory acclimatization. *The Journal of the Acoustical Society of America*, 134(1), pp.596–606.

Deroche, M., & Culling, J.F. 2011. Voice segregation by difference in fundamental frequency: Evidence for harmonic cancellation. *The Journal of the Acoustical Society of America*, 130(5), pp.2855–65.

Dillon, H. 2012. *Hearing Aids.* 2nd editon. Thieme.

Dixon, W. J. 1960. Simplified Estimation from Censored Normal Samples. *The Annals of Mathematical Statistics*, 31, pp.385–391.

Dubno, J., Ahlstrom, J. B., & Horwitz, A. 2002. Spectral contributions to the benefit from spatial separation of speech and noise. *Journal of Speech, Language and Hearing Research*, 45, pp.1297–1310.

Dunn, H. K., & White, S. D. 1940. Statistical Measurements on Conversational Speech. *The Journal of the Acoustical Society of America*, 11(3), pp.278–288.

Duquesnoy, A.J., & Plomp, R. 1980. Effect of reverberation and noise on the intelligibility of sentences in cases of presbyacusis. *The Journal of the Acoustical Society of America*, 68(2), pp.537–544.

Duquesnoy, A.J. 1983. Effect of a single interfering noise or speech source upon binaural sentence intelligibility of aged persons. *The Journal of the Acoustical Society of America*, 74(3), pp.739–743.

Durlach, N. I. 1963. Equalization and Cancellation Theory of Binaural Masking-Level

Differences. *The Journal of the Acoustical Society of America,* 35(8), pp.1206–1218.

Durlach, N. I. 1972. Binaural signal detection: Equalization and cancellation theory. In *Foundations of Modern Auditory Theory.* New York, Academic Press, Inc., pp-371-462.

Durlach, N. I. 2006. Auditory masking: Need for improved conceptual structure. *The Journal of the Acoustical Society of America*, 120(4), pp.1787–1790.

Edmonds, B., & Culling, J.F. 2005. The role of head-related time and level cues in the unmasking of speech in noise and competing speech. *Acta Acustica*, 91(3), pp.546–553.

Etymotic Research. 2005. Bamford-Kowal-Bench Speech-in-Noise Test user manual. Version 1.03. Retrieved from http://www.etymotic.com/pdf/bkbsin-user-manual.pdf

Farina, A. 2007. Advancements in Impulse Response Measurements by Sine Sweeps. In *Audio Engineering Society Convention*, pp.2-21.

Festen, J. M., & Plomp, R. 1986a. Speech-reception threshold in noise with one and two hearing aids. *The Journal of the Acoustical Society of America*, 79(2), pp.465–71.

Festen, J. M., & Plomp, R. 1986b. The extra effect of masker fluctuations on the SRT for hearing-impaired listeners. In *Proceedings of the 12th International Congress on Acoustics*, pp.B11-4.

Festen, J. M., & Plomp, R. 1990. Effects of fluctuating noise and interfering speech on the speech-reception threshold for impaired and normal-hearing. *The Journal of the Acoustical Society of America*, 88(4), pp.1725–1736.

Fletcher, H. 1940. Auditory Patterns. *Reviews of Modern Physics*, 12, pp.47–66.

Fletcher, H. & Galt, R. H. 1950. The perception of speech and it's relation to telephony. *The Journal of the Acoustical Society of America*, 22(2), pp.89–151.

French, N. R., & Steinberg, J. 1947. Factors Governing the Intelligibility of Speech Sounds. *The Journal of the Acoustical Society of America*, 19(1), pp.90–119.

Füllgrabe, C., Harland, A., Sęk, A., & Moore, B. 2017. Development of a method for determining binaural sensitivity to temporal fine structure. *International Journal of Audiology*, 56(12), pp.926–935.

Füllgrabe, C., & Moore, B. 2018. The Association Between the Processing of Binaural Temporal-Fine-Structure Information and Audiometric Threshold and Age: A Meta-Analysis. *Trends in Hearing*, 22, pp.1-14.

Gallun, F. J., Diedesch, A. C., Kampel, S. D., & Jakien, K. M. 2013. Independent impacts of age and hearing loss on spatial release in a complex auditory environment. *Frontiers in Neuroscience*, 7, pp.1–11.

Gannot, S., Vincent, E., Markovich-Golan, S., & Ozerov, A. 2017. A Consolidated Perspective on Multimicrophone Speech Enhancement and Source Separation. *IEEE/ACM Transactions on Audio Speech and Language Processing*, 25(4), pp.692–730.

Gardner, W. W. G., Martin, K. D. K., William, W., & Martin, K. D. K. 1995. HRTF measurements of a KEMAR. *The Journal of the Acoustical Society of America*, 97(6), pp.3907–3908.

Gelfand, S., Ross, L., & Miller, S. 1988. Sentence reception in noise from one versus two sources: effects of aging and hearing loss. *The Journal of the Acoustical Society of America*, 83(1), pp.248–56.

Gilbert, H. J., Shackleton, T. M., Krumbholz, K., & Palmer, A. R. 2015. The Neural Substrate for Binaural Masking Level Differences in the Auditory Cortex. *Journal of Neuroscience*, 35(1), pp.209–220.

Glyde, H., Buchholz, J. M., Nielsen, L., Best, V., Dillon, H., Cameron, S., & Hickson, L. 2015. Effect of audibility on spatial release from speech-on-speech masking. *The Journal of the Acoustical Society of America*, 138(5), pp.3311–3319.

Gnewikow, D., Ricketts, T., Bratt, G. W. & Mutchler, L. C. 2009. Real-world benefit from directional microphone hearing aids. *Journal of Rehabilitation Research and Development*, 46(5), pp.603-618.

Gopinath, B., Hickson, L., Schneider, J., Mcmahon, C. M., Burlutsky, G., Leeder, S. R., & Mitchell, P. 2012. Hearing-impaired adults are at increased risk of experiencing emotional distress and social engagement restrictions five years later. *Age and Ageing*, 41(5), pp.618–623.

Grange, J.A., & Culling, J.F. 2016. Head orientation benefit to speech intelligibility in noise for cochear implant users and in realistic listening conditions. *The Journal of the Acoustical Society of America*, 140(2), pp.703–712.

Grange, J.A., Culling, J.F., Bardsley, B., Mackinney, L.I., Hughes, S.E. Backhouse, S.S. 2018. Turn an ear to hear: How hearing-impaired listeners can exploit head orientation to enhance their speech intelligibility in noisy social settings. *Trends in Hearing*, 22, pp. 1-13.

Grant, K. W., Walden, B. E., & Seitz, P. F. 1998. Auditory-visual speech recognition by hearing-impaired subjects: Consonant recognition, sentence recognition, and auditory-visual integration. *The Journal of the Acoustical Society of America*, 103(5), pp.2677–2690.

Grimm, G., Herzke, T., Berg, D., & Hohmann, V. 2006. The master hearing aid-a PC-based platform for algorithm development and evaluation. *Acta Acustica United with Acustica*, 92(4), pp.618–628.

Hadley, L.V., Brimijoin, W. O. & Whtmer, W. M. 2019. Speech, movement and gaze behaviours during dyadic conversation in noise. *Scientific Reports*, 9, pp. 1-8.

Hall, J., Davis, A. C., Haggard, M. P., & Pillsbury, H. C. 1988. Spectro-temporal analysis in normal-hearing and cochlear-impaired listeners. *The Journal of the Acoustical Society of America*, 84(4), pp.1325–1331.

Hall, J., Tyler, R., & Fernandes, M. 1984. Factors influencing the masking level difference in cochlear hearing-impaired and normal-hearing listeners. *Journal of Speech, Language, and Hearing Research*, 27, pp.145–154.

Hawkins, D. B., & Wightman, F. L. 1980. Interaural time discrimination ability of listeners with sensorineural hearing loss. *Audiology*, 19, pp.495–507.

Hawley, M. L., Litovsky, R. Y., & Culling, J.F. 2004. The benefit of binaural hearing in a cocktail party: Effect of location and type of interferer. *The Journal of the Acoustical Society of America*, 115(2), pp.833–843.

Helfer, K.S., & Freyman, R.L. 2008. Aging and speech-on-speech masking. *Ear and Hearng*, 29(1), pp.87-98.

Hirsh, I. J. 1948. The influence of interaural phase on interaural summation and inhibition. *The Journal of the Acoustical Society of America*, 20(4), pp.536–544.

Hirsh, I. J. & Burgeat, M. 1958. Binaural effects in remote masking. *The Journal of the Acoustical Society of America*, 30(9), pp.827–832.

Hopkins, K., & Moore, B. 2009. The contribution of temporal fine structure to the intelligibility of speech in steady and modulated noise. *The Journal of the*

Acoustical Society of America, 125(1), 442–6.

Hopkins, K., & Moore, B. 2010. Development of a fast method for measuring sensitivity to temporal fine structure information at low frequencies. *International Journal of Audiology*, 49(12), pp.940–946.

Hopkins, K., Moore, B., & Stone, M. A. 2008. Effects of moderate cochlear hearing loss on the ability to benefit from temporal fine structure information in speech. *The Journal of the Acoustical Society of America*, 123(2), pp.1140–53.

Hugdahl, K. 2011. Fifty years of dichotic listening research- still going and going and… *Brain and Cognition*, 76(2), pp.211-213.

Humes, L. E., Kidd, G. R., & Lentz, J. J. 2013. Auditory and cognitive factors underlying individual differences in aided speech-understanding among older adults. *Frontiers in Systems Neuroscience*, 7(55), pp.1-16.

Jeffery, H., Jennings, S., & Turton, L. 2016. Guidance for Audiologists: Onward Referral of Adults with Hearing Difficulty Directly Referred to Audiology Services. *British Academy of Audiology*, pp.1-13.

Jelfs, S., Culling, J., & Lavandier, M. 2011. Revision and validation of a binaural model for speech intelligibility in noise. *Hearing Research*, 275(1–2), pp.96–104.

Johnson, J. A., Xu, J. & Cox, R. M. 2016. Impact of hearing aid technology on outcomes in daily life II: Speech underdanting and listening effort. *Ear and Hearing*, 37(5), pp.529-540.

Jung, S. 2013. Exploratory factor analysis with small sample sizes: a comparison of three approaches. *Behavioural Processing*, 97, pp. 90-95.

Keidser, G., Dillon, H., Mejia, J., & Nguyen, C.V. 2013. An algorithm that administers adaptive speech-in-noise testing to a specified reliability at selectable points on the psychometric function. *International Journal of Audiology*, 52(11), pp.795–800.

Kidd Jr, G., Mason, C.R, Best, V., & Swaminathan, J. 2015. Benefits of acoustic beamforming for solving the cocktail party problem. *Trends in Hearing*, 19, pp.1–15.

Killon, M.C., Niquette, P.A., Gudmundsen, G.I., Revit, L.J. & Banerjee, S. 2004. Development of a quick speech-in-noise test for measuring signal-to-noise ratio loss in normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America*, 116(4), pp.2395–2405.

Kim, S., Frisina, R. D., Mapes, F. M., Hickman, E. D., & Frisina, D. R. 2006. Effect of age on binaural speech intelligibility in normal-hearing adults. *Speech Communication*, 48(6), pp.591–597.

Kimura, D. 1961. Cerebral dominance and the perception of verba stimuli. *Canadian Journal of Psychology*, 15(3), pp. 166-171.

King, A., Hopkins, K., Plack, C. J., Pontoppidan, N. H., Bramsløw, L., Hietkamp, R. K., Vatti, M & Hafez, A. 2017. The effect of tone-vocoding on spatial release from masking for old, hearing-impaired listeners. *The Journal of the Acoustical Society of America*, 141(4), pp.2591–2603.

Kochkin, S. 2000. MarkeTrak V: 'Why my hearing aids are in the drawer': The consumers' perspective. *The Hearing Journal*, 53(2), pp.34–41.

Koo, T. K. & Li, M. Y. 2016. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractice Medicine*, 15, pp. 155-163.

Kramer, S. E., Kapteyn, T. S., & Festen, J. M. 1998. The self-reported handicapping effect of hearing disabilities. *Audiology*, 37(5), pp.302–12.

Kreisman, B. M., Mazevski, A. G., Schum, D. J., & Sockalingam, R. 2010. Improvements in Speech Understanding With Wireless Binaural Broadband Digital Hearing Instruments in Adults With Sensorineural Hearing Loss. *Trends in Amplification*, 14(1), pp.3–11.

Kwak, M. Y., Kang, Y. K., Kim, D. H., An, Y. H. & Shim, H. J. 2018. Further beneifical effect of hearing aids on speech recognition performance besides amplification: importance of restoration of symmetric hearing. *Otology & Neurotology*, 39(8), pp. e618-e626.

Lacher-Fougère, S., & Demany, L. 2005. Consequences of cochlear damage for the detection of interaural phase differences. *The Journal of the Acoustical Society of America*, *118*(4), pp.2519-2526.

Lavandier, M., & Culling, J.F. 2010. Prediction of binaural speech intelligibility against noise in rooms. *The Journal of the Acoustical Society of America*, 127(1), pp.387–399.

Lavandier, M., Jelfs, S., Culling, J.F., Watkins, A. J. A., Raimond, A. P. A., & Makin, S. S. J. 2012. Binaural prediction of speech intelligibility in reverberant rooms with

multiple noise sources. *The Journal of the Acoustical Society of America*, 131(1), pp.218–231.

Levitt, H., & Rabiner, L. 1967. Predicting binaural gain in intelligibility and release from masking for speech. *The Journal of the Acoustical Society of America*, 42(4), pp.820–829.

Licklider, J. C. R. 1948. The influence of interaural phase relations upon the masking of speech by white noise. *The Journal of the Acoustical Society of America*, 20(2), pp.150–159.

Litovsky, R. 2012. Spatial Release from Masking. *Acoustics Today*, 8(2), pp.18–25.

Lombard, E. 1911. Le signe de l'élévation de la voix. *Annals des Maladies des L'Orielle et du Larynx*, 37 101-119.

Loizou, P. C. P., Hu, Y., Litovsky, R., Yu, G., Peters, R., Lake, J., & Roland, P. 2009. Speech recognition by bilateral cochlear implant users in a cocktail-party setting. *The Journal of the Acoustical Society of America,* 125(1), pp.372–383.

Lorenzi, C., Gilbert, G., Carn, H., Garnier, S., & Moore, B. 2006. Speech perception problems of the hearing-impaired reflect inability to use temporal fine structure. *Proceedings of the National Academy of Sciences of the United States of America*, 103(49), pp.18866–18869.

MacCormack, A. & Fortnum, H. 2013. Why do people fitted with heairng aids not wear them? *International Journal of Audiology*, 52(5), pp. 360-368.

MacPherson, A & Akeroyd, M.A. 2014. Variations in the slope of the psychometric functions for speech intelligiblity: a systematic survey. *Trends in Amplification*, 18, pp.1-26.

Marrone, N., Mason, C.R, & Kidd Jr, G. 2008a. Evaluating the benefit of hearing aids in solving the cocktail party problem. *Trends in Amplification*, *12*(4), pp.300–15.

Marrone, N., Mason, C.R, & Kidd Jr, G. 2008b. The effects of hearing loss and age on the benefit of spatial separation between multiple talkers in reverberant rooms. *The Journal of the Acoustical Society of America*, 124(5), pp.3064–3075.

McShefferty, D., Whitmer, W.M. & Akeroyd, M.A. 2015. The Just-Noticeable-Difference in Speech-to-Noise Ratio. *Trends in Amplification*, 19, pp.1-9.

Miller, G. 1947. The masking of speech. *Psychological Bulletin*, 44(2), pp.105–129.

Miller, G., & Licklider, J. 1950. The intelligibility of interrupted speech. *The Journal of the Acoustical Society of America*, 22(2), pp.167–173.

Mills, J. H., Dubno, J., & He, N. 1996. Masking by ipsilateral and contralateral maskers. *The Journal of the Acoustical Society of America*, 100(5), pp.3336–44.

Moore, B. 2007. Physiological Aspects of Cochlear Hearing Loss. In *Cochlear Hearing Loss: Physiological, Psychological and Technical Issues.* pp. 1–37. John Wiley & Sons.

Moore, B., & Glasberg, B. R. 1983. Suggested formulae for calculating auditory-filter bandwidths and excitation patterns. *The Journal of the Acoustical Society of America*, 74(3), pp.750–753.

Moore, B., & Glasberg, B. R. 1986. Comparisons of frequency selectivity in simultaneous and forward masking for subjects with unilateral cochlear impairments. *The Journal of the Acoustical Society of America*, 80(1), pp.93–107.

Moore, B., Hopkins, K., & Cuthbertson, S. 2009. Discrimination of complex tones with unresolved components using temporal fine structure information. *The Journal of the Acoustical Society of America*, 125, pp.3214–3222.

Moore, B., Johnson, J. S., Clark, T. M., & Pluvinage, V. 1992. Evaluation of a dual-channel full dynamic range compression system for people with sensorineural hearing loss. *Ear and Hearing*, 13(5), pp.349–370.

Muller, S., & Massarani, P. 2001. Transfer function measurement with sweeps. *Journal of the Audio Engineering Society*, 49(6), pp.443–471.

Nilsson, M., Soli, S.D. & Sullivan, J.A. 1994. Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. *The Journal of the Acoustical Society of America*, 95(2), pp.1085–1099.

Noble, W., & Perrett, S. 2002. Hearing speech against spatially separate competing speech versus competing noise. *Perception & Psychophysics*, 64(8), pp.1325–36.

Noble, W., Sinclair, S., & Byrne, D. 1997. Extra-open ear moulds, localization, and speech hearing in spatially seperated noise.pdf. *The Australian Journal of Audiology*, 19(2), pp.99–107.

Nuesse, T., Steenken, R., Neher, T., Holube, I. 2018. Exploring the link between cognitive abilities and speech recognition in the elderly under different conditions. *Frontiers in Psychology*, 9, pp.1-17.

Oxenham, A., & Simonson, A. M. 2009. Masking release for low- and high-pass filtered speech in the presence of noise and single-talker interference. *The Journal of the Acoustical Society of America,* 125, pp.457-468.

Pallant, J. 2016. *SPSS Survival Manual*. 6th Edition. Open University Press.

Palmer, A. R., Shackleton, T. M., & McAlpine, D. 2002. Neural mechanisms of binaural hearing. *Acoustical Science and Technology*, 23(2), pp.61–68.

Patterson, R. D., Allerhand, M. H., & Giguère, C. 1995. Time-dommain modeling of peripheral auditory processing: A modular architecture and a software platform. *The Journal of the Acoustical Society of America*, 98(4), pp.1890–1894.

Peissig, J., & Kollmeier, B. 1997. Directivity of binaural noise reduction in spatial multiple noise-source arrangements for normal and impaired listeners. *The Journal of the Acoustical Society of America*, 101(3), pp.1660–1670.

Pichora-Fuller, M. K., & Schneider, B. A. 1991. Masking-level differences in the elderly: a comparison of antiphasic and time-delay dichotic conditions. *Journal of Speech and Hearing Research*, 34(6), pp.1410–1422.

Pichora-Fuller, M. K., & Schneider, B. A. (1992). The effect of interaural delay of the masker on masking-level differences in young and old adults. *The Journal of the Acoustical Society of America*, 91(4:1), pp.2129–35.

Picou, E. M., Ricketts, T. A. & Hornsby, B. W. 2013. How heairng aids, backgorund noise, and visual cues infuence objective listening effort. Ear and Hearing, 34(5): e52-e64.

Plomp, R. 1986. A signal-to-noise ratio model for the speech-reception threshold of the hearing-impaired. *Journal of Speech, Language and Hearing Research*, 29, pp.146–154.

Plomp, R., & Mimpen, A. 1979. Improving the reliability of testing the speech reception threshold for sentences. *Audiology*, 18, pp.43–52.

Plomp, R., & Mimpen, A. M. 1981. Effect of the Orientation of the Speaker's Head and the Azimuth of a Noise Source on the Speech Reception Threshold for Sentences. *Acustica*, 48, pp.325–328.

Quaranta, A., & Cervellera, G. 1974. Masking Level Difference in Normal and Pathological Ears. *Audiology*, 12, pp.428–431.

Rana, B. & Buchholz, J. M. 2016. Better-ear glimpsing at low frequencies in normal-

hearing and hearing impaired listeners. *The Journal of the Acoustical Society of America*, 140(2), 1192-1205.

Rana, B. & Buchholz, J. M. 2018. Effect of audibility on better-ear glimpsing as a function of frequency in normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America*, 143(4), 2195-2206.

Rayleigh, L., & Lodge, A. 1904. On the Acoustic Shadow of a Sphere. *Philosophical Transactions of the Royal Society A*, 203, pp.87–110.

Reisinger, T., Patel, A., Reingruber, H., Fladischer, K., Ernst, W., Bracco, G., Smith, H.I. & Holst, B. 2009. Poisson's spot with molecules. *Physical Review A*, 79, pp.0538231-4.

Rothauser, E. H., Chapman, W. D., Guttman, N., Hecker, M. H. L., Nordby, K. S., Silbiger, H. R., Urbanek, G.E. & Weinstock, M. 1969. IEEE recommended practice for speech quality measurements. *IEEE Transactions on Audio and Electroacoustics*, 17(3), pp.225–246.

Singh, G., Pichora-Fuller, M. K., & Schneider, B. A. 2008. The effect of age on auditory spatial attention in conditions of real and simulated spatial separation. *The Journal of the Acoustical Society of America*, 124(2), pp.1294–1305.

Smeds, K., Wolters, F., & Rung, M. (2015). Estimation of Signal-to-Noise Ratios in Realistic Sound Scenarios. *Journal of the American Academy of Audiology*, 26(2), pp.183–196.

Staffel, J. G., Hall, J., Grose, J. H., & Pillsbury, H. C. 1990. NoSo and NoSπ detection as a function of masker bandwidth in normal-hearing and cochlear-impaired listeners. *The Journal of the Acoustical Society of America*, 87(4), pp.1720–1727.

Strawbridge, W. J., Wallhagen, M. I., Shema, S. J., & Kaplan, G. A. 2000. Negative Consequences of Hearing Impairment in Old Age: A Longitudinal Analysis. *The Gerontologist*, 40(3), pp.320–326.

Strelcyk, O., & Dau, T. 2009. Relations between frequency selectivity, temporal fine-structure processing, and speech reception in impaired hearing. *The Journal of the Acoustical Society of America*, 125(5), pp.3328–45.

Strouse, A., Ashmead, D. H., Ohde, R. N., & Grantham, D. W. 1998. Temporal processing in the aging auditory system. *Journal of the Acoustical Society of America*, 104(4), pp.2385–2399.

Summers, V., & Leek, M. 1998. FO processing and the separation of competing speech signals by listeners with normal-hearing and with hearing loss. *Journal of Speech Language and Hearing Research*, 41, pp.1294–1306.

Surprenant, A. M. & Watson, C. S. 2001. Individual differences in the processing of speech and nonspeech sounds by normal-hearing listeners. *Journal of the Acoustical Society of America*, 110(4), pp.2085–2095.

Tabachnick, B., & Fidell, L. 2013. *Using multivariate statistics*. 6th Edition. Pearson Publishers.

Ter-Horst, K., Byrne, D., & Noble, W. 1993. Ability of hearing-impaired listeners to benefit from separation of speech and noise. *The Australian Journal of Audiology*, 15(2), pp.71–84.

Traunmüller, H., & Eriksson, A. 1994. The frequency range of the voice fundamental in the speech of male and female adults. *Department of Linguistics, University of Stockholm,* 97.

Tyler, R. S., Baker, L. J., & Armstrong-Bednall, G. 1983. Difficulties Experienced by Hearing-Aid Candidates and Hearing-Aid Users. *British Journal of Audiology*, 17, pp.191–201.

van de Par, S., & Kohlrausch, A. 1999. Dependence of binaural masking level differences on center frequency, masker bandwidth, and interaural parameters. *The Journal of the Acoustical Society of America*, 106(4), pp.1940–1947.

Vercammen, C., Goossens, T., Undurraga, J., Wouters, J., & van Wieringen, A. 2018. Electrophysiological and Behavioral Evidence of Reduced Binaural Temporal Processing in the Aging and Hearing-impaired Human Auditory System. *Trends in Hearing*, 22, pp.1-22.

Wack, D. S., Cox, J. L., Schirda, C. V., Magnano, C. R., Sussman, J. E., Henderson, D., & Burkard, R. F. 2012. Functional anatomy of the masking level difference, an fMRI study. *PLoS ONE*, 7(7), pp.1-11.

Westerhausen, R., & Kompus, K. 2018. How to get a left-ear advantage: A technical review of assessing brain asymmetry with dichotic listening. *Scandanavian Journal of Psychology*, 59, pp.66-73.

Westermann, A., & Buchholz, J. M. 2015a. The effect of spatial separation in distance on the intelligibility of speech in rooms. *The Journal of the Acoustical Society of*

America, 137(2), pp.757–767.

Westermann, A., & Buchholz, J. M. 2015b. The influence of informational masking in reverberant, multi-talker environments. *The Journal of the Acoustical Society of America*, 138(2), pp.584–593.

Westermann, A., & Buchholz, J. M. 2017. The effect of nearby maskers on speech intelligibility in reverberant, multi-talker environments. *The Journal of the Acoustical Society of America*, 141(3), pp.2214–2223.

Wiggins, I. I. M., & Seeber, B. U. B. 2013. Linking dynamic-range compression across the ears can improve speech intelligibility in spatially separated noise. *The Journal of the Acoustical Society of America*, 133(2), pp.1004–16.

Wilson, R.H. 2003. Development of a speech-in-multitalker-babble paradigm to assess word-recognition performance. *Journal of the American Academy of Audiology*, 14(9), pp.453-470.

Wright, B. A., & Fitzgerald, M. B. 2001. Different patterns of human discrimination learning for two interaural cues to sound-source location. *Proceedings of the National Academy of Sciences*, 98(21), pp.12307–12312.

Wu, Y-H. 2010. Effect of age on direcitonal microphone hearing aid benefit and preference. *Journal of the American Academy of Audiology*, 21(2), pp.78-89.

Wu, Y-H., Stangl, E., Chipara, O., Hasan, S. S., Welhaven, A., & Oleson, J. 2018. Characteristics of real-world signal to noise ratios of speech listening situations of older adults with mild to moderate hearing loss. *Ear and Hearing*, 39(2), 293-304.

Zeng, F.-G., Grant, G., Niparko, J., Galvin, J., Shannon, R., Opie, J., & Segel, P. 2002. Speech dynamic range and its effect on cochlear implant performance. *The Journal of the Acoustical Society of America*, 111(1), pp.377–386.

Zurek, P. 1996. Results of SRT reliability study. Unpublished manuscript.

Zwislocki, J. J. 1972. A theory of central auditory masking and its partial validation. *The Journal of the Acoustical Society of America*, 645(2:2), pp.644-659.

6. Publications related to this thesis

6.1.   Peer-reviewed publications:

Grange, J., Culling, J., Bardsley, B., Mackinney, L, Hughes, S., & Backhouse, S. 2018. Turn an ear to hear": How hearing-impaired listeners can exploit head orientation to enhance their speech intelligibility in noisy social settings. *Trends in Hearing*, 22, pp.1-13.

Grange, J., Culling, J., Bardsley, B., Mackinney, L, Hughes, S., & Backhouse, S. 2018. "Turn an ear to hear": How hearing-impaired listeners can exploit head orientation to enhance their speech intelligibility in noisy social settings. *Proceedings of the International Symposium of Auditory and Audiological Research*, 6, pp.9-16.

6.2.   Presentations to learned societies and professional organisations

6.2.1. Audiology Cymru

Bardsley & Culling. The effect of masker source characteristics on speech intelligibility in a virtual restaurant. Invited speaker in Cardiff on 20th July 2018.

6.2.2. British Society of Audiology

Bardsley, Culling & Shields. Spatial Release from Masking and binaural processing of Temporal Fine Structure in those with hearing impairment (preliminary data). Presented at the basic science conference in Cardiff on 3-4 September 2015.

Bardsley & Culling. The use of spatial cues in understanding speech in background noise: a forensic of those with hearing impairment. Presented at the annual conference in Coventry on 25-27th April 2016.

Bardsley & Culling. Speech intelligibility in noise in a virtual restaurant: the difficulties faced by those with hearing loss. Presented at the basic science conference in Cambridge on 5-6th September 2016.

6.2.3. Speech in Noise

Bardsley, Culling & Shields. Spatial Release from Masking and binaural processing of Temporal Fine Structure in those with hearing impairment (preliminary data). Presented at the conference in Groningen on 7-8 January 2016.

Bardsley & Culling. Speech intelligibility in noise in a virtual restaurant: the difficulties faced by those with hearing loss. Presented at the conference in Oldenburg on 5-6th January 2017.

6.2.4. International Hearing Aid Research Conference

Bardsley & Culling. The use of spatial cues in understanding speech in background noise: a forensic analysis of those with hearing impairment and the role of hearing aids. Presented at the conference in Tahoe City on 10-14 August 2016.

Appendix 1:

ID	Age	chapter	2	3	4	4	4	4	4
		title	character	HOR	SRM	BMLD	ITD	INDEP	CONTRA
		section	2.2.7	3.2.1	4.2.2	4.3.1	4.4.1	4.5.1	4.6.1
HI1	78			x	x	4	4	4	4
HI2	68		x	x	x	3	3	4	3
HI3	78		x	x	x	3	3	3	
HI4	86		x	x	x	3	3	3	3
HI5	79		x	x	x	4	4	4	4
HI6	64			x	x	4	4	4	4
HI7	65		x		x	3	3	3	
HI8	74				x	4	4		
HI9	79				x	4	4		
HI10	66				x	3	3	3	
HI11	56		x	x	x	4	4		4
HI12	77				x	4	4		
HI13	61			x	x	3	3	3	3
HI14	67		x	x	x	4	4	4	4
HI15	63		x	x	x	3	3	3	3
HI16	69		x		x	3	3	3	
HI17	87				x	4	4		
HI18	31				x	3	3		
HI19	58			x	x	3	3	3	3
HI20	74		x		x	4	4		
HI21	72			x	x	3	3	4	3
HI22	72		x	x	x	4	4	4	4
HI23	70			x	x	3	3	3	3
HI24	64				x		4	4	4
HI25	72			x					
HI26	69		x						