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Effects of Coordinated Bilateral Hearing Aids and Auditory Training on Sound Localization

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A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy

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EFFECTS OF COORDINATED BILATERAL HEARING AIDS AND AUDITORY
TRAINING ON SOUND LOCALIZATION AND SPEECH INTELLIGIBILITY IN NOISE

(Thesis format: Monograph)

by

Iman Ibrahim

Graduate Program in Health and Rehabilitation Sciences

A thesis submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
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Abstract

This thesis has three main objectives: 1) evaluating the benefits of the bilateral coordination of the hearing aid digital signal processing features by measuring and comparing the auditory performance with and without the activation of this coordination, and 2) evaluating the benefits of acclimatization and auditory training on such auditory performance, and 3) determining whether receiving training in one aspect of auditory performance (sound localization) would generalize to an improvement in another aspect of auditory performance (speech intelligibility in noise), and to what extent. Two studies were performed. The first study evaluated the speech intelligibility in noise and horizontal sound localization abilities in hearing impaired listeners using hearing aids that apply bilateral coordination of wide dynamic range compression. A significant improvement was noted in sound localization with bilateral coordination on when compared to off, while speech intelligibility in noise did not seem to be affected. The second study was an extension of the first study, with a suitable period for acclimatization provided and then the participants were divided into training and control groups. Only the training group received auditory training for sound localization. The training group performance was significantly better than the control group performance in some conditions, in both the speech intelligibility and the localization tasks. The bilateral coordination did not have significant effects on the results of the second study.

This work is among the early literature to investigate the impact of bilateral coordination in hearing aids on the users' auditory performance. Also, this work is the first to demonstrate the effect of auditory training in sound localization on the speech intelligibility performance.

Co-Authorship Statement

The study presented in Chapter 2 of this dissertation was accepted for peer-reviewed publication and was co-authored by Drs. Parsa, Macpherson, and Cheesman.

Drs. Parsa and Cheesman supervised the research, provided methodological guidance, and reviewed and revised draft of the manuscript and dissertation.

Dr. Macpherson contributed significantly to data analysis. Francis Richert, Dr. Laya Poost-Foroosh Bataghva and Dr. Paula Folkeard contributed significantly to participant recruitment and data collection.

I intend to submit the study presented in Chapter 4 for peer review and publication. Drs. Parsa, Macpherson, and Cheesman will be co-authors for this forthcoming publication. They have significantly contributed to the design and data analysis/discussion to ensure proper interpretation of the findings.

Keywords

speech intelligibility, speech in noise, horizontal sound localization, hearing aids, binaural, wireless synchrony, HINT, anechoic, auditory training, acclimatization.

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List of Abbreviations

AT: Auditory training

BBN: Broad-band noise

BILD: Binaural intelligibility level difference

BTE: Behind-the-ear

CASPERsent: Computer-Assisted Speech Intelligibility Testing and Training at the Sentence Level

CATS: Computer Assisted Tracking Simulation

CNS: Central nervous system

CR: Compression ratio

DI: Directivity index

DNR: Digital noise reduction

DSP: Digital signal processing

DSL: Desired sensation level

F/B: Front/Back

FM: Frequency modulation

HA: Hearing aid

HI: Hearing impaired

HINT: Hearing in Noise Test

HPN: High-pass noise

HRTF: Head-related transfer function

HSE: Head shadow effect

HTL: Hearing threshold level

ITD: Interaural time difference

ILD: Interaural level difference

IPD: Interaural phase difference

JND: Just-noticeable difference

KEMAR: Knowles Electronics Manikin for Acoustic Research

LACE: Listening and Communication Enhancement

LPN: Low-pass noise

L/R: Left/Right

MAA: Minimum audible angle

MCL: Most comfortable level

NBN: Narrow-band noise

NH: Normal hearing

PCP: particular communication partner

RECD: Real ear-to-coupler difference

RITE: Receiver in the ear

RMS: Root mean square

RT60: Reverberation time-60

SELA: Auditory Localization Evaluation System

SIN: Speech in noise

SNHL: Sensorineural hearing loss

SNR: Signal to Noise Ratio

SRT: Speech Reception Threshold

SSQ: Speech, spatial, and quality

T1: time 1 (after the acclimatization period)

T2: time 2 (after the training/control period)

W.on: Wireless synchrony enabled

W.off: Wireless synchrony disabled

VAD: Virtual auditory display

WDRC: Wide dynamic range compression

2-STDEV: 2 standard deviations

Preface

The objectives of this dissertation were: 1) to inspect the performance of hearing impaired listeners in some auditory tasks that reflect the processes of binaural hearing while evaluating the benefits of a hearing aid feature that enables two (right and left) hearing aids to communicate wirelessly with each other in order to synchronize the signal processing features, 2) to measure and evaluate the benefits of providing a period for acclimatization and auditory training together with the bilateral wireless coordination feature, and 3) to inspect and evaluate the possibility of improvement in one aspect of auditory performance (speech intelligibility in noise) after receiving auditory training in another aspect (horizontal sound localization).

Several studies pointed out that the independently-working digital signal processing (DSP) circuits in the right and left hearing aids could interfere with the naturally-occurring binaural cues (Bogaert et al. 2006; Keidser et al., 2006; Keidser et al., 2011). This interference could increase the localization errors and interfere with speech intelligibility especially in noisy backgrounds.

Recently, a new DSP feature has been incorporated into hearing aids - bilateral wireless coordination. It allows communication between a hearing aid pair, in order to apply the same signal processing algorithm in both aids. This feature is thought to improve the preservation of the interaural cues through coordinating the DSP and the volume settings of the two hearing aids.

Since this is a fairly new feature, there is a lack of studies that evaluate the benefits of applying wireless coordination in hearing aids and to what extent it preserves the naturally occurring binaural cues and improves the auditory functions that depend on these cues such as sound localization and speech understanding in noisy backgrounds.

The following dissertation aimed to: 1) evaluate the benefit of this new feature, either independently, while disabling all the other DSP features that could help improving localization and/or speech understanding in noise, or together with all the other features

in effect and 2) evaluate the effects of acclimatization and auditory training with this feature on localization and speech intelligibility in noise.

Chapter One reviews the relevant background literature that laid the foundation of the first study in this thesis work. First, the benefits of binaural hearing for both sound localization and speech intelligibility in noise were explained. Second, the effect of hearing loss on sound localization and speech intelligibility in noise were explored. Third, different digital signal processing features used in hearing aids were explained briefly and the studies investigating their effects on sound localization and speech intelligibility in noise were reviewed.

In Chapter Two, a study that evaluated the benefits of the binaural wireless synchrony for both sound localization and speech intelligibility in noise is presented. The research question addressed in Chapter Two is: Does bilateral coordination between the two hearing aids provide the listeners with improved binaural benefits, especially in terms of improving speech understanding in noise and sound localization?

Chapter Three reviewed the literature relevant to the auditory plasticity and auditory training, which is the basis for conducting the second study, to measure and evaluate the benefits of auditory training, and review the work done so far regarding auditory training for the HI listeners.

In Chapter Four, a study that evaluated the benefits of auditory training in combination with the bilateral wireless coordination feature is presented. The research questions addressed in Chapter Four are: 1) Would providing acclimatization and Auditory Training (AT), along with using the hearing aid that apply bilateral wireless coordination, significantly improve sound localization and speech understanding in noise? 2) Would training for localization only also result in improved speech intelligibility? 3) How would different acoustic environments (anechoic-reverberant) interact with and affect the results of AT?

Chapter Five is a general discussion, where the results of the two studies conducted in Chapters 2 and 4 are analyzed and compared, in order to extract conclusions,

implications, and recommendations regarding the preservation of the benefits of binaural hearing.

Chapter 1

1. Introduction

1.1 Background

Several anatomical factors and neural mechanisms make auditory performance with two ears (binaural hearing) clearly superior to listening with one ear (monaural hearing). This chapter will discuss the following points in detail: 1) the benefits of binaural hearing in horizontal sound localization and speech understanding in noise, 2) how sensorineural hearing loss (SNHL) affects horizontal sound localization and speech understanding in noise, and 3) how different hearing aid features affect horizontal sound localization and speech understanding in noise. Finally, a rationale for conducting the study in Chapter 2, as well as a summary and outline for the thesis is provided.

1.2 Benefits of binaural hearing

1.2.1 Benefits of binaural hearing in horizontal sound localization

Our ability to localize sounds helps us identify and separate sounds coming from different directions. Hence, it could be crucial for survival (such as the case of avoiding an approaching car by localizing the vehicle noise or a car horn) and it is also likely to contribute to our ability to follow conversations in noisy background or among multiple talkers (Devore et al., 2009; Keidser et al., 2006). The sensory receptors for vision and touch provide direct perceptual representation of space, as they are topographically oriented, while auditory space must be computed from the one-dimensional acoustic waveforms reaching each ear (Zahorik, 2006). Our auditory system depends on a number of cues to localize sounds in space:

i. Binaural processing of difference in arrival times between the two ears (or the Interaural Time Differences (ITDs)) provides one localization cue. These timing differences are very small, ranging between 10-700 μ s. Interaural phase differences (IPDs) occur coincidentally with the ITDs and vary systematically with source azimuth and wavelength. IPDs dominate in localizing the low frequency sounds (up to 1.5 kHz) (Blauert, 1983).

ii. The head diffracts sound waves, causing a difference in intensity between the two ears, known as Interaural Level Differences (ILDs). ILDs are the most prominent cue in localizing high frequency sounds (above 1.5 kHz) and can result in up to 20 dB difference between the two ears at 6 kHz (Blauert, 1983).

iii. The shape of the head and the folds and convolutions of the pinna result in a frequency dependent response, which varies with the sound position. This results in spectral shape cues that function mainly on broadband high frequency sounds (4-12 kHz) (Blauert, 1983).

Although the shape of the head, and the folds and convolutions of the pinna serve as monaural sound localization cues, comparing and processing the acoustic inputs at the two ears are important for sound localization. In 1907, Lord Rayleigh proposed the “Duplex theory” (Strutt, 1907), which explained the different roles of ITDs and ILDs in horizontal sound localization. Rayleigh found that the sound received at the ear far from the sound source would be effectively shadowed by the head, resulting in a difference in the level of the sound reaching the two ears. However, for low frequencies (below 1000 Hz), this intensity difference would be negligible, because the wavelength of the sound is similar to, or larger than, the distance between the two ears. Rayleigh also noted that human listeners can sense the difference in phase of low frequencies, and hence he concluded that the difference in arrival time can lead to phase difference between the two ears that could be used as a localization cue for low frequency sounds. Accuracy of horizontal localization is usually measured in terms of the minimum audible angle (MAA), which is the just noticeable difference (JND) in azimuth perceptible by a subject.

MAAs are usually smaller in the frontal midline, between 30° to -30° where they are about 1° - 2° , than at the sides where they are about 15° (Middlebrooks & Green, 1991).

1.2.2 Benefits of binaural hearing in speech intelligibility in noise

Our ability to detect and understand speech in a background of noise is of significant importance in our everyday communication, because we are confronted daily with complex acoustic environments. Our auditory system processes simultaneously occurring complex acoustic signals to extract relevant information. There is substantial evidence that speech intelligibility is enhanced with binaural presentation (Arsenault and Punch, 1999; Bronkhorst and Plomp, 1988; Bronkhorst and Plomp, 1989; MacKeith and Coles, 1971). The binaural advantage for speech intelligibility in noise is due to a combination of a physical phenomenon, *viz.* the head shadow effect, and a neurological process, *viz.* binaural squelch (Byrne, 1981).

Head shadow effect (HSE): Except when the sound sources lie directly in front (0° azimuth), or directly in the back (180° azimuth) of the listener, binaural listeners have one ear nearer to the source of the desired signal than the other. Therefore, they are in a better position compared to monaural listeners, regarding the relative levels of the signal and noise, because they will always have an ear closer to the sound source at any given position. A monaural listener may sometimes be positioned such that the head is interposed between the signal source and the functioning ear, leading to a considerable attenuation of frequencies above 1 kHz (Blauert, 1983).

Squelch effect (true binaural processing): Information provided from the ear further from the signal is integrated with information from the near ear. Information about the time of arrival and intensity differences at the two ears enable the listener to process the speech and noise signals separately, with an apparent unmasking of the speech (Arsenault and Punch, 1999; Byrne, 1981). Squelch effects can provide up to 15 dB of advantage in signal-to-noise ratio (SNR) for low-frequency sounds (Moore, 1989). The binaural

squelch effect acts mainly on low frequency, steady-state information (Bronkhorst & Plomp, 1988).

1.2.2.1 The relative contribution of ITD and ILD cues for binaural speech in noise (SIN):

Bronkhorst and Plomp (1988) tested the effect of ITDs and ILDs on binaural speech intelligibility in noise, using virtual auditory stimuli. They used three main noise types: FF (free field), dL (head shadow only), and dT (ITD only). The target speech material was recorded only from 0° (midline), while noise was recorded from seven azimuth angles, ranging from 0° to 180°. They found that when the benefits derived from ITDs and ILDs are separated, ILDs yield better speech reception thresholds (SRTs) than ITDs. Carhart et al. (1967) showed that ITD contributes only moderately to a gain in intelligibility, but yields a high gain for detection. Carhart also suggested that the presence of ILDs decreases the benefits derived from ITDs. In case of asymmetric hearing loss, deriving a benefit from ILDs depends on having the better ear closer to the sound source (presented with the higher SNR).

1.2.2.2 Other factors that affect speech intelligibility in noise

The number and nature of noise sources impact speech intelligibility in noise. The process of segregating and extracting information from a single target sound in a multi-source environment is known as the “Cocktail Party Effect” (Cherry, 1953; Pollack & Pickett, 1958), “sound source determination” (Yost, 1992, 1997), or “sound source segregation” (Bregman, 1990). Besides the binaural advantages, several other factors can either facilitate or complicate speech intelligibility in noise in multi-source environments. These factors depend on the nature of the target speech and the competing noises (such as the nature and the spatial separation between target and interfering noise). Some of these factors are discussed below:

a) Spatial location: This factor is directly related to the HSE. It is easier to identify and segregate sound sources that are spatially separated (Bregman, 1990). Speech is better understood when spatially separated from interfering noise source. This is known as

“spatial release from masking” (Bronkhorst and Plomp, 1992; Hawley et al, 1999). Determining the location of a sound source is a powerful tool for tracking it over time. Several studies such as Bronkhorst and Plomp (1990, 1992) and Arbogast et al. (2002) confirmed better speech recognition in noise when the target and the competing noise are separate in spatial location. Spatial location becomes the primary cue used to track a target signal when both target and interfering sources have the same frequency spectrum (Freyman et al., 1999). Spatial separation also provides a monaural advantage that results from the higher SNR at the ear closer to the target speech signal due to HSE. However, if multiple interferers are presented and spatially distributed to both sides of the head, the monaural advantage becomes insignificant (Hawley et al., 2004).

b) Temporal properties of interfering sound: It is easier to understand speech when the interfering sound has speech-like amplitude modulation. Speech has a fluctuating frequency spectrum and amplitude envelope, while noise generally lacks such modulation. These modulations cause dips in the temporal envelope and facilitates understanding of the target speech due to transient improvement in SNR (Hawley et al, 2004, Mackeith and Coles, 1971).

c) Differences in fundamental frequency (f_0): When two concurrent voices have different fundamental frequencies, listeners can easily separate and understand the target voice (Assmann and Summerfield, 1990). This explains why it is more difficult when target and background speakers are of the same sex and the fundamental frequencies of their voices are closer in frequency.

d) Informational masking: If the interfering sound is speech, its linguistic contents can be confused with the contents of the target speech. This form of interference cannot be caused by energetic masking (which results from the overlapping frequencies of the target and masker) and can be considered as “informational masking” (Hawley, 2004). Energetic masking results from an interfering sound which has its frequency components in the same auditory filters as the target signal, while informational masking can result from an interfering sound that has its frequency components in different auditory filters

than the target signal. Spatial release from masking is greater for informational compared to energetic masking (Arbogast et al., 2005).

From the above, it can be concluded that differences between the signal and the noise at both ears are essential for detecting and understanding speech in noisy background because the listener compares the input at both ears and accordingly attempts to extract the useful stimulus, which is usually speech, and ignore the unwanted stimulus, which is usually noise. ITDs are more important for speech detection; however, ILDs provide more benefit for speech intelligibility. Other stimulus-related factors, such as spatial location, temporal properties, and linguistic contents, also contribute to speech intelligibility in noise.

1.3 Effect of hearing loss on binaural benefits

1.3.1 Effect of hearing loss on horizontal sound localization

Several factors contribute to the disrupted localization abilities of listeners who have SNHL, such as elevated hearing thresholds, reduced frequency selectivity, and reduced intensity and temporal resolution (Moore, 1996). Several studies demonstrated deteriorating localization performance in hearing impaired (HI) participants. In order to investigate the predictability of localization performance from the type, degree, and configuration of hearing loss, Noble et al. (1994) evaluated and compared the horizontal and vertical localization performance of the hearing impaired (HI) listeners, who had either bilateral SNHL, mixed, or conductive hearing losses, as well as normal hearing (NH) listeners. Stimuli were pink noise bursts, presented at each listener's most comfortable level (MCL), and $\frac{1}{2}$ MCL (the average of hearing threshold and MCL) in separate blocks. The authors reported the correlations between the hearing thresholds (HTL) and localization accuracy, and performed a hierarchical regression procedure to examine the contribution of audiometric thresholds and localization performance in both the horizontal and vertical planes. Only the horizontal localization performance will be discussed here.

For the individuals with SNHL, in general, a fair correlation of 0.3 to 0.4 (Portney & Watkins, 2000) was found between the localization performance in the horizontal plane and HTL. A slight predominance of low frequency hearing sensitivity was present in the frontal horizontal plane localization, while low and mid-to-high frequencies predominated localization in the lateral horizontal plane. A similar but weaker correlation was found at $\frac{1}{2}$ MCL. The correlation was rather between HTL at 1, 2, and 4 kHz than HTL at low frequencies with performance in frontal horizontal localization.

The results of Noble et al. (1994) revealed that hearing thresholds have only a mild predictive power on localization performance. Other possible factors that could affect localization are reduced frequency selectivity, intensity and temporal resolution, measurement errors, or differences in pinna tuning properties. Reduced frequency selectivity could alter sound localization especially in multisource environments, where interfering sounds other than the target sound and similar or very close to the target sound in frequency spectrum exist. Noble et al. suggested that reduced intensity and temporal resolution could alter intensity and temporal localization cues. Smoski and Trahiotis (1986) reported that ITD thresholds for low frequency stimuli are slightly greater compared to normal hearing individuals.

From the above, it could be concluded that the degradation in horizontal sound localization abilities in hearing impaired individuals is not completely attributable to decreased audibility. Other factors must contribute to this degradation, such as reduced frequency selectivity.

1.3.2 Effect of hearing loss on speech intelligibility in noise

Speech is a highly redundant signal. That is why even in a moderately noisy environment, speech can still be fairly intelligible (Tawfik et al, 2010). Individuals with SNHL usually report difficulties in understanding speech in the presence of background noise. Several studies (Plomp, 1978; Plomp and Duquesnoy, 1982; Plomp and Mimpen, 1979) reported that individuals with even mild SNHL may have greater difficulty when listening in noisy environments than do NH listeners.

Plomp and Duquesnoy (1982) developed a quantitative model that describes hearing loss for speech as the sum of two factors: i) an attenuation factor, caused by the reduction of the levels of both speech and noise signals, and ii) a distortion factor, which reduces the “functional” signal-to-noise ratio, as it affects frequency and temporal resolution, and hence, affects speech intelligibility. It is important here to note that it is not possible to separate the attenuation from the distortion factor in a hearing impaired listener. It is possible that the relative contribution of each of these factors to the hearing impairment leads to the wide variations in performance of different auditory tasks demonstrated by the HI listeners compared to the normal hearing listeners. Different aetiologies of hearing loss could result in different combinations of attenuation and distortion.

To test the effect of hearing impairment on binaural cues (ITDs and ILDs), Bronkhorst and Plomp (1988) tested the performance of NH and HI listeners. To simulate unilateral hearing loss, a condition with 20-dB attenuation was applied to the speech presented to the NH listeners. The results showed that the hearing-impaired listeners had significantly higher SRT in noise than the NH group. When considering the relative gain due to the ITD, there was hardly any difference in performance between the two groups. The hearing-impaired participants had mean Binaural Intelligibility Level Difference (BILD) of 4.2 dB, which was not significantly different from the 4.7 dB obtained by the NH group. BILD is defined as the difference in signal level in decibels between two binaural conditions for a given percent intelligibility (Levitt & Rabiner, 1966). Reducing the presentation level on either side had a limited effect on SRT. The ability to benefit from ITD varied within the hearing-impaired group, which suggests that it is related to the degree or configuration of hearing impairment.

Comparing the relative gain due to ILD, participants with hearing impairment were found to benefit less from ILD than the NH group. For the asymmetrical HI listeners, the BILDs for the ITD-only noise did not significantly differ from symmetrical condition. Asymmetrical HI listeners benefit less from head shadow when they have to depend on the poor ear. Spatial separation resulted in 9.8 dB of BILD for the NH listeners, 7.1 dB for the symmetrical hearing loss, and 4.7 or 7.2 dB for the asymmetrical, when the noise source was moved to the good or bad ear, respectively. The authors concluded that HI

listeners perform worse in speech in noise (SIN) during binaural listening mainly due to their inability to take full advantage of the ILD cue. Since the head shadow that results in the ILD at 90° azimuth is most prominent between 3-5 kHz, their binaural gain is affected by hearing loss in this frequency region. Listeners with bilaterally symmetric hearing loss benefit almost equally from the ITD when compared with normal hearing listeners. However, listeners with asymmetrical impairment benefit significantly less from ITD when it is the only cue available. HI listeners benefit less from ILD mainly due to elevated hearing thresholds, especially in the high frequency region. The following section will discuss how listeners' hearing impairment might disrupt the binaural benefits for SIN. This section will focus on individuals with mild-to-moderate SNHL that affects mainly the high frequency region, because this is the frequency region most commonly affected by mild-to moderate SNHL (Schmiedt, 2010).

1.3.3 Effect of bilateral mild-to-moderate SNHL on the benefits from head-shadow effect and binaural squelch

Because some studies address more than one aspect of binaural benefits, only the relevant result(s) of each study will be discussed under the corresponding subsection.

a) Head shadow

Bronkhorst and Plomp (1989) reported that bilaterally HI individuals benefit less from the head shadow effect, compared to NH listeners. They found that spatial separation resulted in 9.8 dB of BILD for the NH participants and 7.1 dB for those with symmetrical hearing loss.

Arsenault and Punch (1999) found that comparing the dichotic head shadow (in which the stereo presentation was similar to the original stimulus recording) to the diotic binaural favorable condition (in which the noise-shadowed ear recording was presented to both ears) revealed a 2.3 dB and 0.3 dB advantages, for the NH and HI groups, respectively. This result demonstrates that the NH individuals benefit from the full array of the available binaural cues, while the HI individuals cannot.

b) Binaural squelch

As mentioned above, binaural squelch refers to the ability of the auditory system to take advantage of the different inputs from the right and left ears in order to improve speech intelligibility in noise (Byrne, 1981). Arsenault and Punch (1999) measured and compared the benefit derived from binaural squelch between NH and HI listeners. They found that the HI listeners had less advantage of binaural squelch effects compared to NH listeners. A difference of 3.2 dB SNR (4.9 dB SNR benefit for NH listeners compared to 1.7 dB SNR benefit for HI listeners) was reported by Arsenault and Punch (1999). A similar difference of 2.7 dB in BILD benefit between NH and HI listeners was reported by Bronkhorst and Plomp (1989).

c) Other factors

Hawley et al. (2004) examined the effect of the type and number of interfering sounds. Interfering sources can be noise (energetic masking) or speech (informational masking) sources. When several interfering sources are present the binaural system can suppress the interference more effectively from speech than noise sources, particularly when these sources are spatially separated. SRTs are better with speech than with noise when one interferer is presented, but this changes in the presence of multiple interferers either because the auditory system is no longer able to utilize f_0 differences or informational masking is occurring. When the interferers are speech, spatial separation is more beneficial than for noise interferers (i.e. spatial release from masking is greater for informational compared to energetic masking).

Arbogast et al. (2005) found that the HI listeners benefit less from spatial separation between the target speech and interfering informational masker, while the benefit was the same for both NH and HI groups when the masker was mainly energetic.

Hearing loss decreases speech intelligibility due to two main factors: an attenuation factor, and a distortion factor (Plomp & Duquesnoy, 1982). It is not possible to separate the relative contribution of each factor. As mentioned in section 1.3.2, ITDs are more important for speech detection and ILDs are more important for speech intelligibility. A

person with mild-to-moderate bilateral hearing loss will still benefit from ITD cues than a NH person. However, he/she will benefit considerably less from ILD cues due to both attenuation and distortion factors stemming from hearing loss.

1.4 Effect of hearing aid fitting on binaural hearing

1.4.1 Effect of hearing aids fitting on horizontal sound localization

When hearing aids are worn for the first time, localization is likely to be disrupted because different signal processing features in the hearing aids distort the familiar localization cues. There is substantial evidence that users adapt to these altered ITDs and ILDs. Within a few hours significant adaptation commences and continues for a few days and, to a lesser extent, for a few weeks (Bauer, Matusza & Blackmer, 1966; Byrne & Dirks, 1996). In mild to moderate SNHL, the decreased localization ability is most likely due to a decreased audibility of the signal rather than an inability to utilize the localization cues that are well above hearing threshold. Thus, a bilateral hearing aid fitting will provide better localization abilities than a unilateral hearing aid fitting whenever the signal is inaudible in the unaided ear. Because audibility is the main factor affecting localization, the bilateral fitting advantage in localization is more obvious in cases with moderate-to-severe hearing loss (Dillon, 2001). A signal is considered of adequate sensation level (adequately audible) if it is 10 dB above threshold (Markides, 1977). However, decreased frequency and temporal resolution also affect localization. Macpherson and Cumming (2012) reported that even when audibility is compensated for, individuals with low-frequency hearing impairment performed poorly in dynamic localization task.

In a survey of 1,511 hearing aid users by Kochkin (2005), 66% reported being satisfied with their aided localization and only 12% reported that they were very satisfied. Unfortunately, bilateral hearing aid fitting does not completely solve localization problems, due to several factors, such as long-standing hearing deprivation, poor audibility in the high frequencies as a result of the limited bandwidth of the hearing aids,

the competition between both the direct and amplified sound paths in case of open ear fittings, hearing aid microphone location, and hearing aid processing delays resulting from implementing several signal processing algorithms, such as compression, directional microphones, and noise reduction (Chalupper et al., 2009). The effects of Wide Dynamic Range Compression (WDRC), microphone configuration (directional microphones, multiband adaptive directionality, and mismatched microphone mode), and Digital Noise Reduction (DNR), on horizontal sound localization will be discussed here.

1.4.1.1 Effect of Wide Dynamic Range Compression (WDRC) on horizontal sound localization

Compression is used in hearing aids mainly to decrease the dynamic range of input signals to match the restricted dynamic range of the HI user. Compression is also used to avoid discomfort, distortion and damage, maximize speech intelligibility, increase sound comfort, reduce noise, and normalize loudness (Dillon, 2001). Although several compression strategies, such as high level, low level, and WDRC exist in hearing aids, for the purpose of this paper, discussion will be restricted to WDRC, because it is the compression system used in the studies performed for this thesis.

In WDRC, a gradual reduction is applied over a wide range of input levels, so that the corresponding output levels are not compressed closely together. In most cases, hearing loss varies with frequency. If gain reduction is applied to the whole frequency range of the hearing aid, target signals might be attenuated just because noise signals have high level, although they have different frequency ranges. To avoid this problem, multichannel compression is applied, where every frequency band has its own compressor (Dillon, 2001).

Compression has the dynamic characteristics of attack and release times and the static characteristics of compression threshold and compression ratio. Since the attack and release times are measured in milliseconds, which are much greater than the microsecond range of ITDs, these time constants are not expected to affect the ITDs. However, it is anticipated that applying WDRC independently in the two ears could result in an

asymmetric change in output level, thus, a distortion in ILD cues with WDRC in comparison with linear amplification.

Keidser et al. (2006) tested the effect of applying multi-band WDRC on the localization abilities of hearing aid users who had symmetrical hearing loss. Results revealed an insignificant effect of scheme (linear or multi-channel WDRC), and time provided for acclimatization. The interaction between scheme and time was insignificant as well. By comparing the ILDs measured in the reference (linear) and WDRC conditions, it was found that the ILDs were almost halved, corresponding to the 2:1 compression ratio applied. However, the authors concluded that the distortion of ILDs and spectral cues caused by the multi-channel WDRC did not significantly affect the localization performance. The reason for this could be that the unaffected ITD cues that helped preserve the localization performance.

Another study, by Musa-Shufani et al. (2006) investigated the effect of WDRC on horizontal localization in general, and on isolated ILD and ITD cues. Participants were NH and HI listeners. Different compression schemes with various compression ratios (CR) and attack times were created. In general, and as expected, the HI listeners performed worse than the NH individuals. Results revealed a significant effect of CR, interaction between CR and attack time (attack time reveals larger effect with higher CR), and of hearing loss. Neither CR nor attack time had a systematic impact on ITD discrimination. The performance was worse with higher CR and shorter attack time. Thus, the attack time had an impact on ILD and the shorter the attack time, the more the negative impact on the ILD. The authors explained this fact by the extra time available for the subject to analyze the original ILD before compression commences. At the highest CR used (8:1), the JND at an attack time of 200 ms for the NH listeners was doubled with WDRC when compared with linear scheme, and the same but less pronounced effect was noticed with the HI listeners. The authors assumed that when using very long attack times (200 ms in the study), compression will not affect ILD.

1.4.1.2 Effect of microphone configuration (multi-band adaptive directionality) on horizontal sound localization

Directional microphones are constructed either from a single microphone with two entry ports, or by combining the electrical outputs from two or more microphones (Dillon, 2001). Sixty years ago, directional microphones were first used in public address systems to reduce acoustic feedback. In the early 1970s, hearing aids with directional microphones became available in the United States (Preves, 1997). Hawkins and Yacullo (1984) and Dillon and Macrae (1984) reported a 3-4 dB signal-to-noise ratio (SNR) advantage with directional microphone hearing aids compared to omnidirectional microphones in listeners with hearing loss.

Directional microphone systems can be activated manually, via remote control or program button, or automatically, via the signal processing decisions made for a given listening environment. Directional microphones have polar patterns (directionality) that show how sensitive the microphone is to sounds arriving at different angles about its central axis. The polar pattern can be cardioid, supercardioid, hypercardioid, or bi-directional (also known as figure 8 microphone) in nature. Polar patterns are typically less sensitive to signals at the sides or the back of the listener's head.

Directional microphone systems can be fixed (where the pattern does not change in different listening environments) or adaptive. Adaptive systems may be either broadband or multi-band. In multiband adaptive systems, different polar patterns in independent frequency bands are automatically activated in response to spatially dynamic noise sources (Fabry, 2005). This provides further benefits in situations where different noise sources that have different spatial locations and spectral patterns are present. In broadband systems, only the most intense noise source is suppressed, but for multiband adaptive directional systems (in which up to 20-bands are available), the most intense noise on each channel is reduced. For example, given a situation where two different noise sources exist: a human voice, located at 135° azimuth, and a microwave oven located at 180° azimuth, different polar patterns for the different frequency regions that correspond to the primary energy peak at each azimuth will be applied. If signals overlap on one channel, only the most intense source will be suppressed. As a result, better

resolution for isolating and suppressing noise sources that differ spectrally and spatially is provided by multiband directional systems (Fabry, 2005).

Hearing aids may mimic the pinna effect on signals by altering the spectral shape of the sound as a function of arrival direction (Keidser et al., 2009). A sound arriving from the front will have a greater high-frequency emphasis than the same sound arriving from the back, to approximate the frequency response alterations produced by the pinna shadow. This is expected to help to resolve the front/back (F/B) confusion that occurs when a microphone has constant directivity across frequencies, including the omnidirectional microphone. Limiting directivity to the high frequency is also expected to result in lower internal noise and higher available gain and output across the low frequencies (Keidser et al., 2009).

In the case of bilateral hearing aid fitting, where each hearing aid operates independently, applying adaptive directional microphones may cause more disruption to the interaural cues than would a pair of omnidirectional microphones. This is because different polar patterns will be generated in response to the acoustically varying environment. ITDs will be distorted because there will be different internal time delays used to implement each specific polar pattern. ILDs are distorted as well because: a) the polar pattern response shapes are affected by both the head and the free-space directivity patterns, and b) different gain-frequency responses will be applied on each side depending on the direction of the sound source. Spectral cues will be affected also with a microphone mode mismatch between the two ears, as polar patterns tend to vary with frequency. In multi-memory devices, unintentional use of different programs on the left and right ear will result in different microphone characteristics. Microphone drift (changes in output related to aging, averaging 0.25 dB/year) can also cause a mismatch in polar patterns across devices (Keidser et al., 2006; Tchorz, 2001).

Keidser et al. (2006) tested the localization performance of 12 participants with different microphone configurations: a) two cardioids in both ears; b) one cardioid and one omnidirectional, and c) one cardioid and one figure eight (bidirectional). These three conditions were compared to a reference condition with two omnidirectional

microphones. In the left/right (L/R) localization dimension, there was a significant effect of microphone mode and significant interaction between the period of hearing aid use and microphone mode. The performance with the cardioids/figure-eight mode degraded significantly over time. At both two weeks and two months post-fitting, performance was significantly worse with the two microphone mode mismatch conditions than with the two matched microphone mode conditions (cardioid/cardioid, and omnidirectional/omnidirectional). In the microphone mismatch conditions, a significant bias occurs away from the ear wearing the cardioid microphone, almost exclusively in the rear hemisphere (where cardioid configuration is least sensitive).

In the F/B dimension, the two factors (microphone mode and time) and the interaction between them were significant. Localization performance improved over time with the cardioid/cardioid condition. At two weeks, the cardioid/omnidirectional condition yielded the best performance and, together with the cardioid/cardioid condition, both provided a significantly better performance than the other two conditions. So, a cardioid microphone on its own or in combination with an omnidirectional microphone reduced F/B confusions when listeners were given time to adjust to the signal processing.

Keidser et al. (2009) tested the effect of multiband (frequency-dependent) microphone directionality on horizontal localization performance in hearing aid users. Four directional test schemes were implemented: 1) omnidirectional on all 4 channels; 2) omnidirectional on the lowest two channels and hyper-cardioid on the highest two channels (partial-1); 3) omnidirectional on the three lowest frequency channels and hypercardioid in the highest channel above ~2 kHz (partial-2); and 4) hypercardioid on all four channels (full directional). These schemes were synchronized between the two ears through the wireless bilateral coordination option. For the L/R dimension, there was a significant effect of microphone mode scheme, stimulus, and of the interaction between the two. The omnidirectional mode provided a significant improvement for a pink noise stimulus. The full directional scheme produced high L/R root mean square (RMS) errors for the pink noise stimulus. For the F/B dimension, there was a significant effect of microphone mode scheme, stimulus, and of the interaction between scheme and both stimulus and time.

After three weeks, participants made fewer F/B RMS errors with the partial-1 scheme than with other schemes. They also performed significantly better with the partial-2 than with the omni scheme. The partial-1 scheme significantly improved the F/B performance relative to omni scheme in the pink noise and cockatoo noise, and significantly improved the F/B localization relative to the full-directional scheme for the 3-kHz pulsed pink noise. The Speech, spatial, and quality questionnaire (SSQ) results revealed no strong preference for one scheme over the others.

Additionally, the two partial schemes had the best performances in the F/B dimension, while the omni and full directionality schemes performed the worst. The improvement in performance after three weeks in the partial-1 scheme suggested that HI listeners utilize alterations in the spectral shape cues rather than overall level change for F/B localization. The main effect of microphone configuration in this experiment was the relatively poor L/R localization with the full directional microphone with high-frequency weighted stimuli. This did not occur with partial directionality. These findings differ from that of Keidser et al. (2006), in which microphone mismatch increased the L/R errors; however, the Keidser et al. (2009) results could be attributed to the difference in settings. The full directional scheme was bilateral hypercardioid directionality in all frequency channels, a scheme that was not tested in Keidser et al (2006) and the hypercardioid microphone reduces some sounds from the sides. Also, the stimuli used in both studies are different. Keidser et al. (2006) used only pink noise and Keidser et al. (2009) used five different stimuli. The L/R errors were more prominent with the pink noise and cockatoo noise, which are high frequency stimuli not used in the earlier Keidser et al. study.

1.4.1.3 Effect of mismatched microphone mode on horizontal sound localization

Keidser et al. (2006) also showed that the two mismatched microphone conditions caused a substantial shift of the ILDs across the rear hemifield. More negative than positive ILDs were measured, meaning that higher input levels were arriving at the right ear (the one with the omnidirectional or figure-eight polar plot).

The two mismatched microphone conditions also caused a shift in ITDs in the rear hemisphere. The sound arrived later to the ear wearing the omnidirectional microphone,

and sooner to the ear wearing figure-eight microphone. So, for the cardioid/figure-eight condition, both the ILD and ITD distortion causes a bias in response towards the ear fitted with a figure-eight microphone, while for the cardioid/omnidirectional condition, the ITD and ILD distortions pulled the bias in opposite directions. For the cardioid/omnidirectional mode, the shift in the mean L/R error correlated with both shifts in ILD and ITD, while for the cardioid/figure-eight, L/R error correlated only with the shift in ILD. Based on these results, the authors suggested that ILD is the dominant cue for L/R discrimination.

Keidser et al. (2006) concluded that the microphone mode mismatch significantly affected L/R discrimination. The sound direction was shifted toward the ear wearing either the omnidirectional or figure-eight microphone when each was paired with a cardioid microphone, mainly in the rear azimuth (where the cardioid microphone is least sensitive). The correlation analysis suggests that ILD is the main cue. This contradicts previous findings suggesting that ITD is the main cue for broadband stimuli that have low frequency components (Wightman & Kistler, 1992; Zurek, 1993). Macpherson and Middlebrooks (2002) quantified the relative weight of ITDs and ILDs for lateral angle localization using different stimuli, and found that listeners weighted the ITD cue strongly as a cue for lateral angle, while generally ignore ILDs at low frequencies. However, both cues were given substantial weight for wideband stimuli, with ITDs being the dominant cue for most listeners.

Van den Bogaert et al. (2006) tested the frontal horizontal localization ability of NH participants and participants with bilateral symmetrical mild-to-moderate hearing loss who were experienced bilateral hearing aid users. HI listeners were tested unaided, with hearing aids using the omnidirectional microphone mode, and with hearing aids using the adaptive microphone mode. The broadband stimulus was tested both in quiet and in noise (multi-talker babble). Results in general were consistent with the literature, in that the average performance was better with the low frequency (200 ms, 500 Hz) narrow-band noise (NBN) stimulus (mainly ITD cues) than with the high frequency (200 ms, 3150 Hz) NBN stimulus (ILD cues). Performance improved with the broadband stimulus (telephone ring), possibly because of combining ITD and ILD cues, as well as the length

of the stimulus (1 s), which gives a chance for a slight head movement. Data analysis for the HI listeners revealed that, in general, performance was better in the unaided conditions than in all aided conditions. The omnidirectional and adaptive modes were not significantly different; however, the difference between them was close to significance (for a significance level of $p=0.05$, p was found to be 0.053).

The only condition in which the omnidirectional mode was significantly better than the adaptive directional mode was with the broadband (telephone ringing) in multi-talker babble. L/R confusions for the extreme left and right angles ($\pm 90^\circ$) were prominent with the adaptive directional mode. In general, only small differences in the number of lateralization errors occurred in adaptive and omnidirectional modes for the 500 Hz stimulus condition, but large differences were evident for the 3150 Hz stimulus in 5 out of the 10 listeners. This suggests that for those listeners, the extra distortion caused by the adaptive directionality is mainly ILD distortion. The authors stated that their results should be taken with caution, because hearing aids are multiband processing devices. Different frequency bands may be processed in different ways, producing not only distorted interaural cues, but also interfering interaural cues in these different frequency bands, a factor that adds extra confusion and hence increases the localization errors. Another contributing factor may be the unique reaction of each participant's auditory system to these interfering cues.

1.4.1.4 Effect of digital noise reduction algorithms on horizontal sound localization

One of the biggest problems that hearing aid users face is the interference produced by background noise, especially when listening to speech (Dillon, 2001). Source characteristics, distance, reverberation, and diffraction around objects contribute to noise usually having more intense low-frequency components than speech, which can significantly degrade speech because it masks the first formant of vowels and the upward spread of masking can also affect consonants. One of the solutions to this problem is to decrease the gain in low-frequency regions. One method of altering the gain in different frequency regions is through "Wiener filtering" (Dillon, 2001). A Wiener filter functions

by calculating the spectral power of the target (speech) plus noise signal, calculating the spectral power of the noise alone (when speech is absent), and then subtracting the noise alone from speech plus noise signal across frequency channels in order to reduce the gain in channels that have low SNR (Bentler & Chiou, 2006; Dillon, 2001).

Another approach to noise reduction is spectral subtraction, in which the noise spectrum is estimated during the pauses in the speech signal or before the speech signal begins. This is then subtracted from the speech plus noise spectrum (Bentler & Chiou, 2006; Dillon, 2001). Still other noise-reduction schemes rely on co-modulation. They depend on harmonic structure as the main factor for determining the target signal (Bentler & Chiou, 2006).

DNR algorithms can be described by three parameters: degree of gain reduction provided, time constants of the algorithm, and threshold of activation (Bentler & Chiou, 2006). Activating the noise reduction algorithm in a hearing aid can cause distortion in the ILD cues (Keidser et al., 2006). If a noise source is positioned close to one ear, and the target source is on the other side of the head, gain will be reduced on the side closer to the noise, increasing the ILD. As the DNR is activated independently in different frequency bands, a different amount of gain may be applied across frequencies. Distortion is expected to occur in spectral cues as well.

Keidser et al. (2006) tested the effect of digital noise reduction on localization performance. Two fitting schemes were compared, both using linear amplification with omnidirectional microphone, one with noise reduction off and one with maximum noise reduction. A loudspeaker at 80° azimuth was used to generate 65 dB SPL of constant noise. The stimulus level was 72 dB SPL. A significant effect of noise reduction in both the F/B and the L/R dimensions was observed, but the effect of time was insignificant. The effect was not the same for both dimensions; while the L/R performance was significantly worsened by the activation of noise reduction, the F/B performance was significantly improved. However, due to the small difference in RMS errors compared to the total errors in both dimensions, the authors concluded that the effect of noise reduction even when it is on the maximum is clinically unimportant. A significantly

greater shift of response to the left side occurred when maximum noise reduction was applied. The authors explained this shift by the higher ILD values measured at the Knowles Electronics Manikin for Acoustic Research (KEMAR)'s left ear during stimulus recording.

From the above, we can summarize the effects of the different digital signal processing features discussed here on horizontal sound localization. WDRC tends to negatively affect localization only when applying short attack time and large CR. When inspecting the different microphone configurations in the studies reviewed here, we found a general trend that for the L/R localization, the matched microphone mode resulted in a better performance when compared to mismatched microphone modes. However, the presence of a directional microphone in one or both hearing aids would significantly improve the F/B localization performance. Digital noise reduction was found to worsen the L/R performance, and improve the F/B performance, however the differences in RMS errors were small, and the clinical effect of noise reduction on horizontal localization was clinically unimportant.

1.4.2 Effect of hearing aid fitting on speech intelligibility in noise

As discussed earlier in section 1.5.1, difficulty understanding speech in a background of noise is the most common complaint of the HI participants (Dillon, 2001). Hearing aids amplify both the speech signal and the background noise; hence the SNR is not increased, on the contrary, speech intelligibility decreases because of the upward spread of masking at high listening levels and the distortion caused by hearing aids (Launer & Moore, 2003). Earlier research reported either a detrimental effect of hearing aids on speech understanding in noise, (Plomp & Mimpen, 1979; 1986), or no effect of hearing aids on speech understanding in noise, (Verschuure & van Benthem, 1992; Welz-Müller & Sattler, 1984). However, recently with the technological advancements, DSP features in hearing aids can improve speech intelligibility. Among the digital signal processing features, directional microphone is the feature that has been shown to improve speech intelligibility in noisy backgrounds. The following section will review the effects of different DSP features on speech intelligibility in noise. The effects of WDRC,

microphone configuration (directional microphones, multiband adaptive directionality, and mismatched microphone mode), and DNR, on speech intelligibility in noise will be discussed here.

1.4.2.1 Effect of WDRC on speech intelligibility in noise

Although WDRC is expected to enhance speech audibility, and hence improve speech intelligibility, research has failed to prove such an effect. The majority of studies revealed either no effect or even reduced speech intelligibility with WDRC (e.g., Souza et al., 2006). The different parameters of WDRC, such as fast attack time and high compression ratio, can result in degraded speech intelligibility in background noise (Dillon, 1996; Moore et al., 1999; Souza et al., 2000).

Souza et al. (2006) attempted to measure the acoustic effects of WDRC on speech intelligibility in noise. They used a phase inversion technique that allowed for separation of speech and noise. A comparison of the SNR after linear amplification, single channel WDRC, and multichannel WDRC revealed that while linear amplification did not change the output SNRs relative to the input SNRs, WDRC resulted in degradation in the output SNRs. Degradation was more prominent in less favorable SNRs than in more favorable SNRs and was also larger for the single channel WDRC than for the multichannel WDRC. The authors suggested that noise amplification during speech pauses could be the reason for the degraded SNRs with WDRC. Along with degradation in SNRs, the authors suggested that when WDRC is applied to speech in noise, the effective compression ratio is less than for speech in quiet, i.e., the amplitude envelope of speech is less affected by compression in noise when compared to speech in quiet, thus, the difference in amplitude of low-intensity sounds to high-intensity sounds in the speech signal remains high.

1.4.2.2 Effect of Directional microphones on speech intelligibility in noise

Directional microphones were first incorporated into hearing aids in 1971 in the U.S. markets. Some obstacles hindered the use of directional hearing aids and led to a decline in their use in the 1980's, including the relatively large size of directional microphones

when the HA market was moving towards smaller-sized hearing aids, the paucity of instruments providing both omnidirectional and directional microphones, and the position of the hearing aid on the head which limited the directivity of the microphone (Ricketts, 2005).

Directional microphones in hearing aids can improve speech intelligibility in noise by attenuating sounds arriving from directions other than the front of the user, and the effectiveness of this attenuation is measured by the directivity index (DI). However, because everyday life situations vary greatly, it is not always the case that the signal of interest is at the front of the listeners and the unwanted signals are in the other directions. With this fact in mind, the use of hearing aids that have directional microphones (directional hearing aids) could be detrimental in certain situations. However, only directional microphones and frequency modulation (FM) technology have been proven to improve the SNR (Kim & Bryan, 2011). Valente and Mispagel (2008) reported a significant improvement in reception thresholds for sentences with the use of directional microphones compared to both unaided and omnidirectional performances, while there was no significant differences between the unaided and omnidirectional performances.

Several studies demonstrated the effectiveness of directional hearing aids in improving speech understanding in noise, including Ricketts and Hornsby (2003), Boymans and Dreschler (2000), Quintino et al. (2010), and Tawfik et al. (2010).

1.4.2.3 Effect of microphone mode mismatch on speech intelligibility in noise

Typically, directional microphones are enabled in the “noise program” in the hearing aids, while the omnidirectional microphones are usually enabled in the “quiet program”. Usually, the default setting is “omnidirectional” and the hearing aid user must manually change the program to enable the directional microphone in noisy environments. Palmers et al. (2006) tested individuals with manually switchable hearing aids, and found that the noise program was used only 25% of time. Desjardins and Doherty (2009) showed that approximately half listeners are unable to effectively use their noise program which enables the directional microphone when needed. Addressing these issues, and in order to get the most benefit from the directional microphone in everyday use of the hearing aid,

Kim and Bryan (2011) tested the difference in performance between four microphone settings: binaural omnidirectional, left asymmetric directional (left directional microphone and right omnidirectional microphone), right asymmetric directional, and binaural directional settings. They found that both the asymmetric directional and the binaural directional modes resulted in significantly better speech intelligibility in noise compared to the binaural omnidirectional mode, and the difference between the two asymmetric directional and the binaural directional modes was not statistically significant. These results confirm the benefits of directional microphones in improving speech understanding in noise and also suggest the use of the asymmetric directional microphone as a practical solution to improve speech understanding both in quiet and noisy environments without the need to manually switch between the two modes, and hence increase the gained benefits from the directional microphone.

1.4.2.4 Effect of noise reduction on speech intelligibility in noise

Different noise reduction algorithms have been discussed in section 1.5.1. Noise reduction algorithms in hearing aids function by detecting the different acoustic characteristics of speech signals and noise and then alter the gain in the frequencies where noise level is high. The studies that evaluated the benefits of noise reduction algorithms did not reveal consistent results. Some studies revealed no improvement in speech understanding in noise with the noise reduction algorithms, such as Alcántara et al. (2003), and other studies, such as Valente et al. (1998), and Berninger and Karlsson (1999), found that the improvement was limited only to self-assessment questionnaires and not measured speech intelligibility. However, Oliveira et al. (2010) found a significant improvement in speech perception with activation of the noise reduction algorithm. Zakis et al. (2009) also found a clinically significant improvement of 2 dB with activation of noise reduction algorithm.

Tawfik et al. (2010) found a statistically significant benefit with the use of noise reduction algorithms when compared to unaided outcome in speech understanding in noise. When compared with the benefits provided by the directional microphone, the benefit provided by noise reduction algorithms was found to be much smaller than that

provided by the directional microphone and not statistically significant (Boymans & Dreschler, 2000).

A few studies evaluated the effect of combining noise reduction algorithms with other digital signal processing features. Tawfik et al. (2010) found that combining directional microphones with noise reduction was significantly better with noise reduction algorithm only, while Boymans and Dreschler (2000) found adding the noise reduction to the directional microphone did not result in a noticeable difference in speech-in-noise performance. Peeters et al. (2009) found that both the directional microphone and noise reduction algorithms improved subjective and objective speech in noise performance measures (HINT scores and acceptable noise levels), however, combining noise reduction to directional microphone was most effective in improving SNR in noise. Similar results were reported by Prosser et al. (2009), where combining directional microphone and noise reduction algorithms improved SRT by 2-3 dB in the presence of diffuse noise sources.

From the above, we can conclude that the effect of the different digital signal processing features discussed here on speech intelligibility in noise is variable. WDRC had been shown to either degrade or have no effect on it. Reasons for this could be noise amplification during speech pauses, or decreased effective compression ratio when applied to speech in noise versus speech in quiet. Directional microphones are the only signal processing feature that can significantly improve speech in noise. Even when applied asymmetrically, they provide a significant benefit when compared to omnidirectional microphones. As for digital noise reduction, there were no consistent findings regarding its effect, however, it was found to be either of no effect or of minimal positive effect on speech understanding in noise.

Recently, communication between a hearing aid pair, in order to apply the same signal processing algorithm in both aids is presented in order to preserve the binaural cues that listeners depend on for sound localization and speech intelligibility in noise.

The study presented in Chapter Two investigated the effect of coordinated WDRC on sound localization and speech intelligibility in noise.

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Chapter 2

2. Evaluation of speech intelligibility and sound localization abilities with hearing aids using bilateral wireless coordination

2.1 Introduction

The purpose of the current study was to measure and evaluate the benefits of technology that enables wireless signal processing coordination between a pair of hearing aids. The goal was to generate evidence on the benefits of this relatively new feature in hearing aids. Two aspects of binaural hearing, speech intelligibility in noise and horizontal sound localization, were investigated in evaluating the benefits of the synchronized signal processing.

2.2 Background

In Chapter one, the performance of various digital signal processing features was reviewed. It was clear that most of these features, although meant to improve speech intelligibility in noise, either degrade or have no effect on the HI listeners' speech performance. Only one feature, namely the directional microphone, was proved to result in a significant improvement in speech intelligibility in noise. Directional microphones were also the only feature that resulted in an improvement in the F/B aspect of horizontal localization.

As discussed in Chapter one, binaural hearing enhances speech understanding in noise because of binaural redundancy, which refers to the role of the central auditory system in taking advantage of amplitude and timing differences of speech and noise arriving at each ear; and binaural squelch, which refers to the ability of the central auditory system to combine the signals arriving at the two ears (Dillon, 2001). There is evidence, at least in a

laboratory setting, that bilateral hearing aid users extract benefit from binaural hearing as well (Byrne, Noble, & LePage, 1992, Boymans et al., 2009), with listeners with more severe hearing losses extracting more benefit (Day et al., 1988). This documented binaural benefit accounts for the increasing rate of bilateral hearing aid fitting (Kochkin, 2009). Together with advances in digital signal processing (DSP) features, such as adaptive directionality and digital noise reduction, bilateral amplification is expected to continue to contribute to hearing aid fitting success (Bretoli, Bodmer, & Probst, 2010).

However, when two hearing aids each with its independently working circuits and DSP features are fitted, they may disrupt the naturally occurring cues for sound localization (Van den Bogaert et al., 2006). The disturbed localization abilities due to hearing loss might contribute to the problem of decreased speech intelligibility especially in noisy backgrounds because locating the person who is talking becomes more difficult (Byrne & Noble, 1998; Dillon, 2001). Furthermore the distortion of ITD and ILD features may negate any potential benefit arising from binaural hearing.

To give an example, In the case of non-synchronized processing, assuming that there is a sound source close to the right ear; sound will arrive earlier and at a higher intensity to the right ear when compared to the left. Compression will commence in the right hearing aid (because it is closer, and the sound signal is loud), but it will not commence in the left ear, because sound reaching it will be lower. The result would be a distortion of the ILDs.

A review of the studies that have investigated the effect of hearing aid DSP features on sound localization and speech understanding in noise is available in Chapter one, and a summary of these effects is presented here.

WDRC did not significantly degrade sound localization. However, applying short attack time and large CR tends to negatively affect horizontal localization abilities. When inspecting the different microphone configurations in the studies reviewed here, we found a general trend that for the L/R localization, the matched microphone mode resulted in a better performance when compared to mismatched microphone modes. However, the presence of a directional microphone in one or both hearing aids significantly improved the F/B localization performance, obviously due to amplifying sounds from the front

more. Digital noise reduction was found to worsen the L/R performance, and improve the F/B performance. However, the differences in RMS errors were small, and the effect of noise reduction on horizontal localization was found to be clinically unimportant.

The effect of the different digital signal processing features on speech intelligibility in noise was variable (see Chapter One for a detailed review). WDRC, although expected to improve speech intelligibility in noise, either degraded or had no effect on it. Reasons for this could be noise amplification during speech pauses or decreased effective compression ratio when applied to speech in noise versus speech in quiet. Directional microphones were the only signal processing feature that significantly improved speech in noise. Even when applied asymmetrically, directional microphones provided a significant benefit when compared to omnidirectional microphones. As for digital noise reduction, there were no consistent findings regarding its benefits to speech intelligibility in noise. It was found to be either of no effect or of minimal positive effect at best.

The factors that affect speech intelligibility in noise, in particular the spatial separation between the target and the number of competing noise sources have been discussed in detail in Chapter one. Because spatial separation between the signal of interest and the interfering signal(s) is important for speech understanding in noise (Hawley et. al, 1999; Rychtarikova et al, 2011), restoring the binaural cues (mainly ILDs) through wireless synchrony of WDRC and volume control, as well as synchronized noise reduction algorithms, are expected to improve speech understanding in noise because the binaural cues that are maintained will facilitate locating the speaker (or source of interest) and decrease noise.

With the aim of preserving naturally occurring binaural cues, bilateral HAs that coordinate and synchronize their processing through wireless communication were introduced to the market in 2004. They provide communication between the right and left hearing aids by means of electromagnetic transmission. The two hearing aids are continually sharing information about the environment and control settings. When this feature is enabled, acoustical information from both hearing aids is analyzed. Based on this analysis the signal is classified and decisions are made. Because inputs from both

hearing aids are used in the decision-making process, the probability that the correct decision is taken is increased. This technology assures that both hearing aids apply the same digital signal processing features at the same time (Powers & Burton, 2005).

Wireless synchrony feature is expected to improve sound localization, because the signal processing features that affect localization cues will be adjusted in both aids simultaneously (Ricketts & Hornsby 2003). As discussed earlier, improved sound localization is assumed to improve speech understanding in noise, because it facilitates locating the speaker in a noisy atmosphere and facilitates perceived spatial separation between the source and the interfering noise(s).

Kreisman et al. (2010) reported a significant improvement in the scores of two speech in noise tests (QuickSIN and HINT) with the use of bilateral hearing aids that apply the binaural wireless synchrony (when all the adaptive features were activated), when compared to a pair of hearing aids that did not apply this technology. The participants were provided with a hearing aid acclimatization period before testing. Sockalingam et al. (2009), which is a white paper by Oticon, found that the listeners performed significantly better when they activated the bilateral coordination compared to the deactivated bilateral coordination. The activated coordination was also rated better than the deactivated coordination for certain listening conditions. Smith et al. (2008) compared the performance of synchronized and non-synchronized bilateral Siemens HAs using the Speech, Spatial, and Qualities of Hearing scale. Results revealed a general trend in the preference for the synchronized HA condition on many survey items in the speech and spatial domain.

In summary, there is a potential for the hearing aid's adaptive signal processing algorithms in the left and right hearing aids to distort cues necessary for sound localization and speech understanding in noise, if they are allowed to operate independently. Hearing aid manufacturers have now developed "binaural" hearing aids that co-ordinate their signal processing through wireless communication. There is very little independent evidence on how well this strategy works, and if there is any performance difference among the binaural wireless hearing aids offered by different

manufactures. The current study aimed to address this gap by examining the effect of wireless synchronization in bilateral HAs on two aspects of binaural hearing: sound localization and speech intelligibility in noise when multichannel WDRC is the only DSP feature active. The working hypothesis was that synchronized multi-channel WDRC will better preserve ILDs and therefore, enhance horizontal sound localization abilities.

2.3 Materials & Method

2.3.1 Participants

Eight participants with normal hearing (NH), with a mean age 26 years (± 3 years standard deviation) with hearing thresholds ≤ 25 dB HL at 0.25-8 kHz participated in the study as a control group. Twelve participants, with a mean age 69 years (± 5 years standard deviation), with bilaterally symmetrical (difference between right and left ear thresholds is ≤ 10 dB at all measured frequencies) moderate-to-severe hearing loss participated in the hearing-impaired group. All had a minimum of one year experience with hearing aid use. Figure 2-1 shows the mean audiograms for the HI participants with details given in Appendix B.

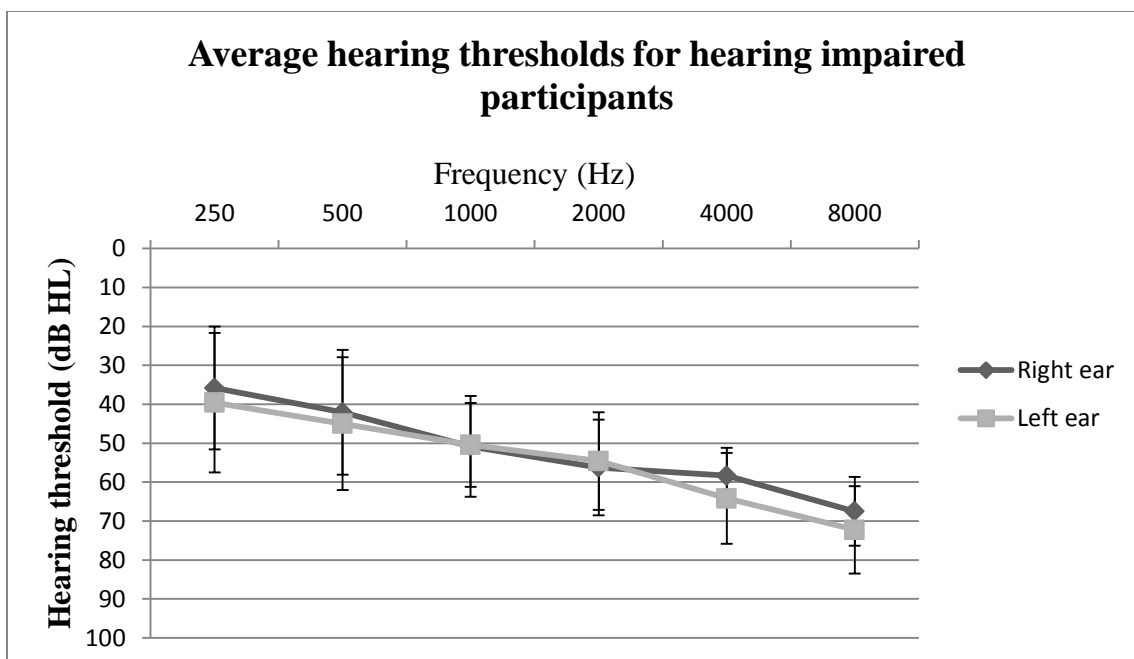


Figure 2-1. Means and standard deviations of hearing thresholds of HI participants.

2.3.2 Hearing aids

Two pairs of hearing aids were used: Oticon Epoq XW and Siemens Motion 700. Both these hearing aids were programmed to fit the targets specified by the Desired Sensation Level (DSL v5.0) formula (Scollie et al., 2005) for each HI participant and verified using AudioScan Verifit. For the NH participants, the hearing aids were programmed to fit the DSL v 5.0 targets for a flat audiogram of 25 dB HL across all audiometric frequencies. The directional microphone, noise reduction, and feedback management features were disabled and the binaural wireless connection was used to synchronize the volume and the WDRC settings between the two HAs (Oticon 2007). Synchronizing the volume enables the user to adjust the volume in both hearing aids by pressing the volume button in one hearing aid. As discussed in Chapter one, directional microphones result in significantly better speech understanding in noise (Boymans & Dreschler 2000; Quintino et al. 2010; Ricketts & Hornsby, 2003; Tawfik et al. 2010), and also will improve F/B localization (Keidser et al., 2006). Also, some studies revealed no improvement in speech

understanding in noise with the noise reduction algorithms, such as Alcántara et al. (2003), and other studies, such as Valente et al. (1998), and Berninger et al. (1999), found that the improvement was limited only to the self-assessment questionnaires. It was planned, therefore, to test wireless synchrony between WDRC in isolation without contamination from other features that are known to improve auditory performance.

The way each HA applies WDRC is different. Oticon Epoq XW (ha#1) applies a mixture of two parallel compression systems: a slow 15-channel and a fast 4-channel system. The relative contribution of each is determined depending on the acoustic environment in order to provide both speech intelligibility (fast compression) and a high quality speech that minimizes listening fatigue (slow compression). Siemens Motion 700 (ha#2) applies a 16-channel dynamic range compression that aims at providing comfortable listening to various loudness levels. Microphone mode was set to “omnidirectional”, digital noise reduction and feedback cancellation were both disabled as well. Directional microphones result in significantly better speech understanding in noise (Boymans & Dreschler 2000; Quintino et al. 2010; Ricketts & Hornsby, 2003; Tawfik et al. 2010) and also will improve F/B localization.

Among the twelve HI participants, five also performed the localization test using their own hearing aids. Their own hearing aid performance compared to their new hearing aids performance is presented in section 2.4.2.

2.3.3 Method

The study was divided into 3 sessions. During the first session, participants signed the information letter and had their hearing assessed by otoscopy, immittance, and pure tone audiometry if their most recent assessment was more than six months old. Ear impressions were taken to produce hard, unvented full-shell molds with regular #13 tubing. Sessions two and three were performed in a hemi-anechoic chamber, where a

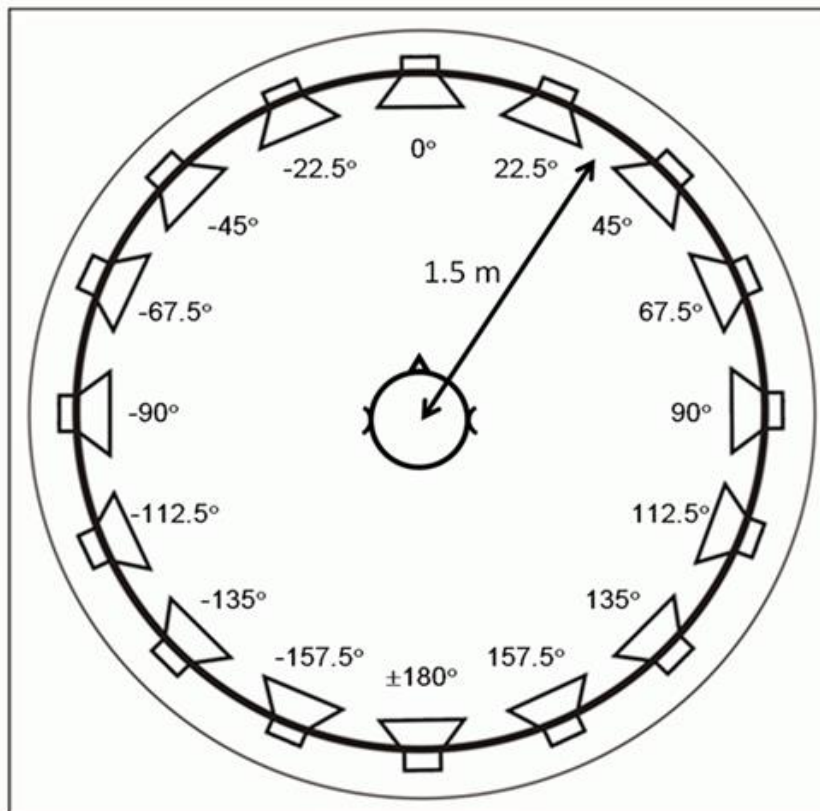


Figure 2-2 Speaker arrangement in the hemi-anechoic chamber used for testing speech intelligibility and localization.

circular array of 16 Tannoy i5 AW speakers was used, as shown in Figure 2-2. The speakers received signals from the computer through an Echo AudioFire 12 sound card (for digital to analog conversion), Soundweb 9008 networked signal processor (for speaker equalization and level control), and QSC CX168 power amplifiers (for power amplification and impedance matching). Participants stood in the middle of the speaker array on an adjustable stand. This setup was utilized for both intelligibility and localization experiments, details of which are given below. To correct for individual loudspeaker characteristics, each target sound was equalized in the frequency domain by dividing by the appropriate loudspeaker transfer function measured with a reference microphone (Bruel & Kjaer 4189) placed at the center of the array in the absence of the listener's head. The transfer functions were derived from measurements of the impulse response from each loudspeaker to the microphone using a 2047-point maximum-length sequence signal (Rife & Vanderkooy, 1989) presented at a sampling rate of 48828 Hz via

the Tucker Davis Technologies RX6 real time processor and QSC CX168 power amplifiers. Prior to computing the transfer functions, the impulse responses were windowed in post-processing to remove any residual reflections.

2.3.3.1 Speech Intelligibility

Speech intelligibility was assessed using the Hearing In Noise Test (HINT) (Nilsson et al. 1994) procedure under three test conditions: (1) noise presented to the right of the participant (90° azimuth), (2) noise presented to the left of the participant (270° azimuth), and (3) noise presented simultaneously from 90° and 270° azimuths. Under all test conditions, the speech was presented from directly in front of the participant (0° azimuth). Twenty sentences were presented in each condition, and the participants were asked to repeat the sentences they heard. In the HINT procedure, the noise level remained stable (65 dBA), and the speech level changed according to the participant's response. At the beginning of the test, speech level was varied in 4-dB steps until a correct response was obtained, then the speech level was varied in 2-dB steps in order to provide the Signal-to-Noise Ratio (SNR) at which 50% of the speech was intelligible. HINT was administered 5 times for each subject: unaided, plus four combinations of the hearing aid make and wireless synchrony mode. The order of these device settings was randomized for each participant. Custom software developed at the National Centre for Audiology was used to automate the HINT process, to visually monitor the test progress, and to store the test results. The target (speech sentences) and the noise were played through an Echo AudioFire 12 sound card. The noise used was a broadband stationary noise, and the noise presentation level was stable at 65 dBA. The speech level was varied according to the response of the participant, in order to provide the Signal-to-Noise Ratio (SNR) at which 50% of the speech is intelligible.

2.3.3.2 Localization test

Localization abilities were tested using two different stimuli: a car horn of 450-ms duration in stereo traffic noise with +13 dB SNR and a 1/3-octave narrow-band noise centered around 3150 Hz with 200-ms duration and 76 dB SPL.

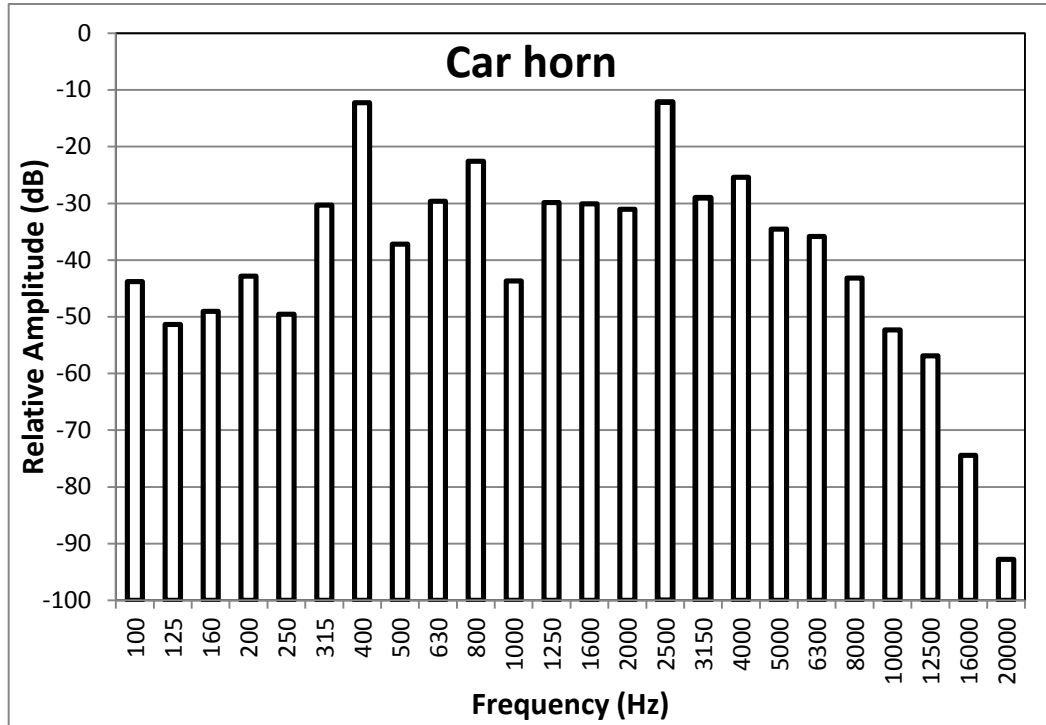


Figure 2-3. 1/3-octave spectrum of the car horn stimulus used in sound localization.

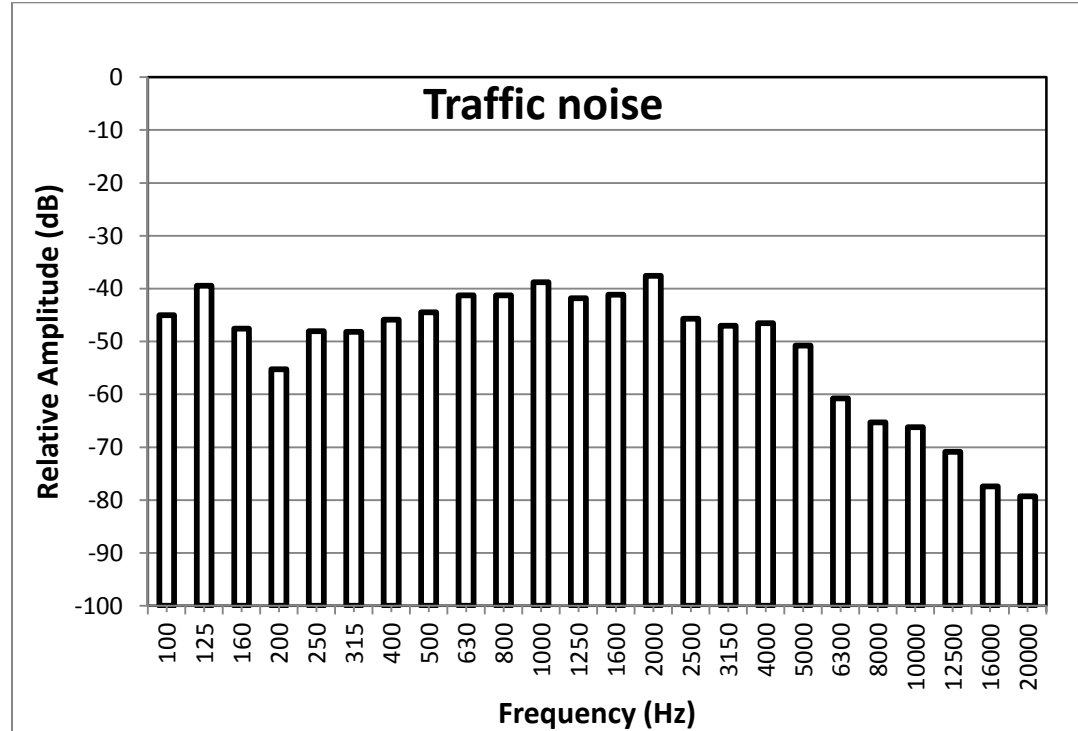


Figure 2-4. 1/3-octave spectrum of the traffic noise used in sound localization.

The car horn in traffic noise was chosen to simulate common everyday situations where localization abilities play an important safety role. For this test condition, the stereo traffic noise was played from two fixed speaker locations at 90° and 270° azimuths, which were placed slightly below the speakers used for localization testing. The car horn signal was a Datson 180B car horn, downloaded from the website: <http://www.freesound.org/people/conny/sounds/2937/>. Figure 2-3 displays the 1/3-octave spectrum for the car horn, which shows most energy in the 400 and 2500 Hz bands. The traffic noise was a 3:06 minute stereo recording of traffic noise, with a minimum intensity of 53.73 dB SPL, downloaded from the website: <http://www.freesound.org/people/inchadney/sounds/21245/>. Figure 2-4 displays the spectrum of the traffic noise used in the localization experiment. A 1/3-octave narrow band noise with a center frequency of 3150 Hz was chosen as a second stimulus to replicate the previous study by Van den Bogaert et al. (2006). Each stimulus was presented 48 times (3 times from each speaker, in a randomized order) at a presentation level of 76 dB SPL for the NBN stimulus, and 73 dB SPL for the car horn stimulus. Participants stood in the middle of the speaker array wearing a head tracker (Polhemus Fastrak) helmet with a light emitting diode (LED) and a response button box in hand. Upon hearing the stimulus, the participants turned their head to the perceived source speaker. A red light emitted from the LED on the helmet provided visual feedback as to the participant's head position relative to the speaker. Participants then registered their response with a button press. Although stimuli were too brief to allow head movement while they were played, participants were free to move their heads and/or body to locate the stimulus. The next stimulus was presented 600 ms after a button press following the return of the head orientation towards the centre of the speaker array (0° azimuth). Similar to the intelligibility test, localization experiments were performed under 5 conditions: with each hearing aid pair and the wireless feature on, with each hearing aid pair while wireless feature was off, and in the unaided condition.

Prior to the actual testing, the localization task started with a practice session to familiarize the participant with the task. Participants were asked to orient toward 0° azimuth at trial initiation and after stimulus onset they were free to move their heads to localize. Participants were not given instructions regarding head movements because it

was meant to measure the natural response as it would be in real life. Audibility of the stimuli, and the ability to understand and perform the localization task were assessed by 3 practice stimuli; each played 10 times from a randomly-chosen different speaker. Practice stimuli were broad band noise bursts, gradually decreasing in duration: 3x500 ms, 5x300 ms, and finally 3x300 ms. The traffic noise was played through an Echo AudioFire 12 sound card, and the target (car horn) was played through the Tucker Davis Technologies RX6 real time processor.

2.4 Results

The data collected for both speech intelligibility and localization were averaged and the means were compared for statistical significance. Statistical significance was assessed using the repeated measures analysis of variance (ANOVA) procedure implemented in SPSS v16.0. The localization data were analyzed to obtain F/B error rates, lateral angle gain, bias, and scatter.

2.4.1 Speech Intelligibility

Due to technical difficulties, and difficulties in rescheduling, two participants did not perform the HINT. Figure 2-5 displays the averaged HINT data for 6 out of the 8 participants in the NH group. Scores from each experimental condition (hearing aid make + wireless condition) depicted as a separated bar. The error bars denote one standard deviation. A 5x3 repeated measures ANOVA was performed, with 5 aided conditions: (unaided, ha#1 wireless/on, ha#1 wireless/off, ha#2 wireless/on, ha#2 wireless/off), and 3 noise presentation angles (90° , 270° , both) as the independent variables. Results revealed a significant main effect of the angle of presentation ($F(2, 4) = 19.53$, $p = 0.009$). As expected, HINT scores were worse for the condition in which noise was presented from both 90° and 270° azimuths. No other main effects or interactions were found to be significant. When comparing the average aided performance with the unaided performance using a paired-samples t-test, the difference was not significant: $t(5) = -0.538$, $p = 0.613$.

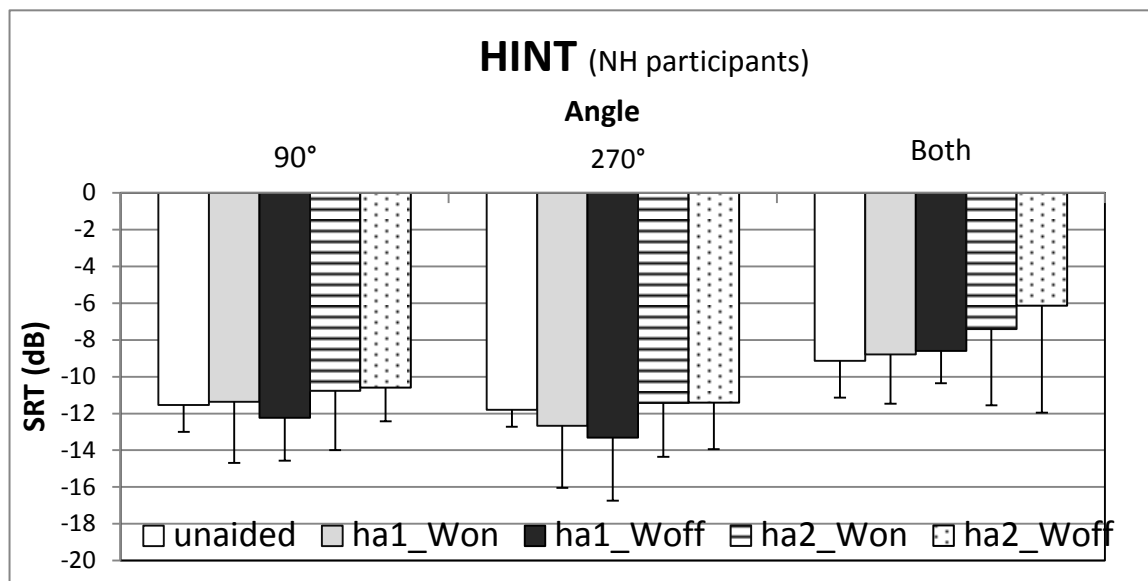


Figure 2-5: HINT results for six of the NH participants. Here, ha1=hearing aid #1, ha2=hearing aid #2, Won = wireless connectivity activated, and Woff = wireless connectivity disabled.

Figure 2-6 depicts the averaged HINT data collected from twelve HI participants, with the data displayed in a manner similar to Figure 2-5. The HI HINT data were analyzed in two different ways using ANOVA: (a) Similar to the NH HINT data, the HI HINT data were analyzed using a 5 x 3 repeated measures ANOVA: 5 aided conditions (unaided, ha#1 wireless/on, ha#1 wireless/off, ha#2 wireless/on, ha#2 wireless/off) X 3 angles (90⁰-270⁰-both). (b) Excluding the unaided condition, another 2 x 2 x 3 repeated measures ANOVA: 2 hearing aids X 2 wireless conditions X 3 angles. In both analyses, only the “angle” was statistically significant. ($F(2, 9) = 18.56, p = 0.001$), and ($F(2, 9) = 43.4, p < 0.001$), where the performance was significantly better with one noise source (90⁰ or 270⁰), compared to noise from both sides. The 2x2x3 ANOVA revealed also a significant interaction between the hearing aid and the noise presentation angle ($F(2, 9) = 4.81, p = 0.38$); the performance with ha#1 was better than the performance with ha#2 at either 90⁰ and 270⁰ noise presentation angles, and the performance with ha#2 was better when the noise was presented from both 90⁰ and 270⁰ simultaneously. A significant interaction between the hearing aid, the wireless condition, and the noise presentation

angle was also noted ($F(2, 9) = 4.78, p = 0.038$), where performance with ha#1 in the wireless off condition was significantly better than all the other conditions when the noise was presented from 90° . No other main effects or interactions were found to be significant.

A comparison of the average aided performance with the unaided performance using paired-samples t-test revealed that the aided performance was significantly better than the unaided performance: $t(10) = -2.92, p = 0.015$.

Means and standard deviations of HINT scores for both NH and HI listeners are provided in Appendix C.

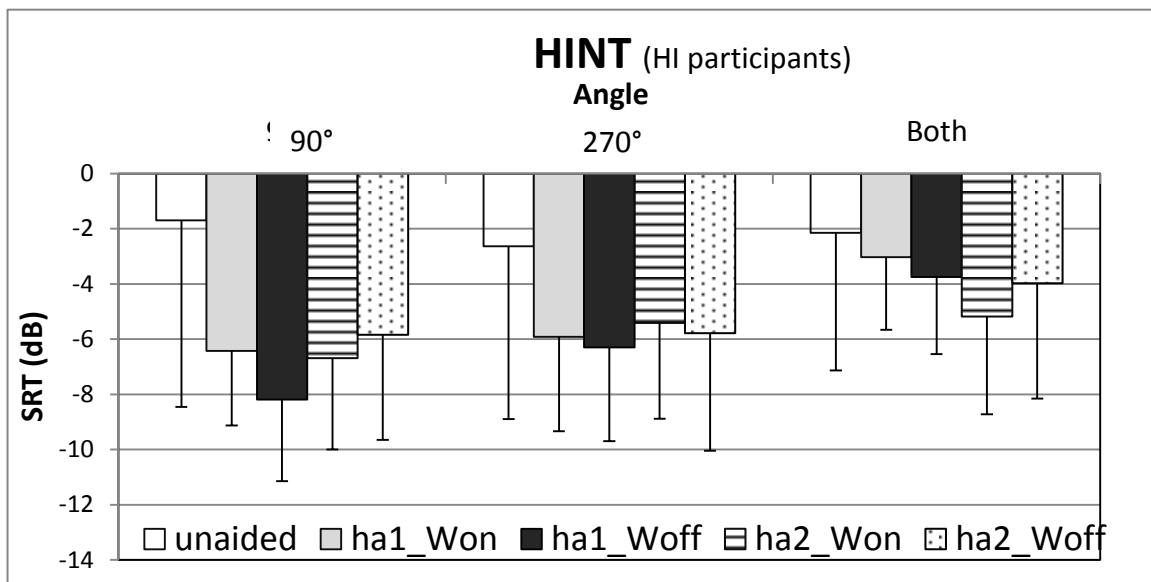


Figure 2-6: HINT results for the HI participants. Here, ha1=hearing aid #1, ha2=hearing aid #2, Won = wireless connectivity activated, and Woff = wireless connectivity disabled.

2.4.2 Sound Localization

Figure 2-7 displays a sample output of one sound localization experiment for one of the HI participants. In Figure 2-7a, the x-axis represents the target azimuth, which is the angle of the speaker that emitted the car horn sound and the y-axis represents the response azimuth, which is the angle the listener reported that the sound came from. In

this plot, the grey boxes at the horizontal axis as well as the black boxes at the vertical axis contain the trials that represent F/B and B/F errors, respectively.

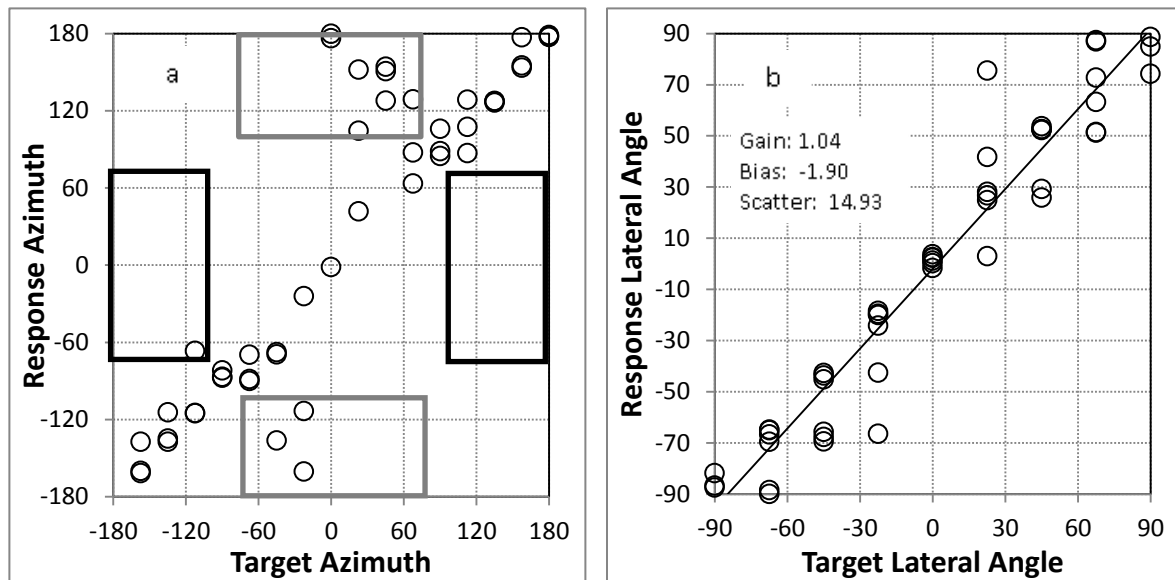


Figure 2-7: Sample localization data from one of the HI participants for an experimental condition. (a) Localization data illustrating F/B confusions. (b) Lateralization data from which lateral angle gain, bias, and scatter parameters are calculated. The grey boxes at the horizontal axis as well as the black boxes at the vertical axis contain the trials that represent F/B and B/F errors, respectively

To calculate the rate of F/B errors, the data set was reduced to those trials on which both target and response were within the ± 67.5 and/or ± 112.5 degree ranges. The number of target/response hemisphere mismatches was computed within this range and then divided by the total number of trials. Figure 2-7b displays the lateralization response of the subject, where the F/B data within left and right hemispheres were collapsed. A linear fit to the lateralization data was used to compute three metrics: lateral angle gain – which is the slope of the linear fitting function; lateral angle bias – which represents the shift in lateral response either towards the left or right hemisphere; and lateral angle scatter – which represents the root-mean-square deviation of the response lateral angles from the values predicted by the regression. Figure 2-8 displays the F/B error rate for the NH participants. A 2 x 2 x 2 repeated measures ANOVA with stimulus, HA, and the wireless condition was performed, and revealed no statistically significant main effect or

interaction. Comparing the average unaided to the averaged aided performance using paired-samples t-test revealed a significantly better unaided performance: $t(7) = -3.14$, $p=0.016$.

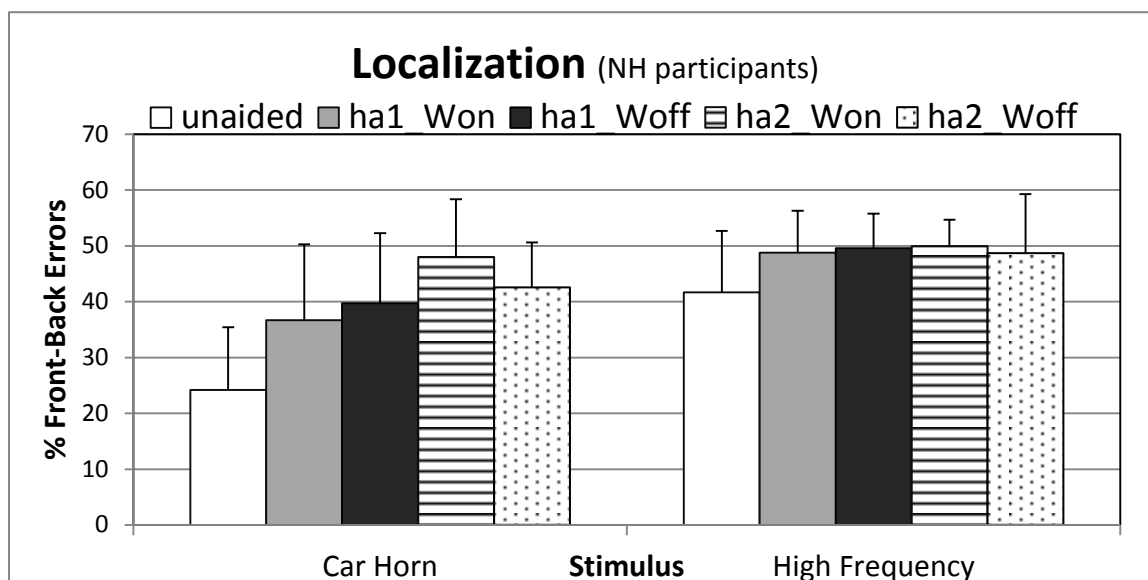


Figure 2-8: F/B error rate for the NH participants for the two test stimuli is shown here. Note that ha1=hearing aid #1, ha2=hearing aid #2, Won = wireless connectivity activated, and Woff = wireless connectivity disabled.

Figure 2-9 displays the F/B error rate for the HI group. Statistical analysis using repeated measures 2 x 2 x 2 ANOVA (HA, the wireless condition, and stimulus) revealed a significant main effect of the wireless condition ($F(1, 11)=6.33$, $p=0.029$) indicating that activating the wireless feature allowed for better discrimination in the F/B dimension. No other significant main effects or interactions were noted.

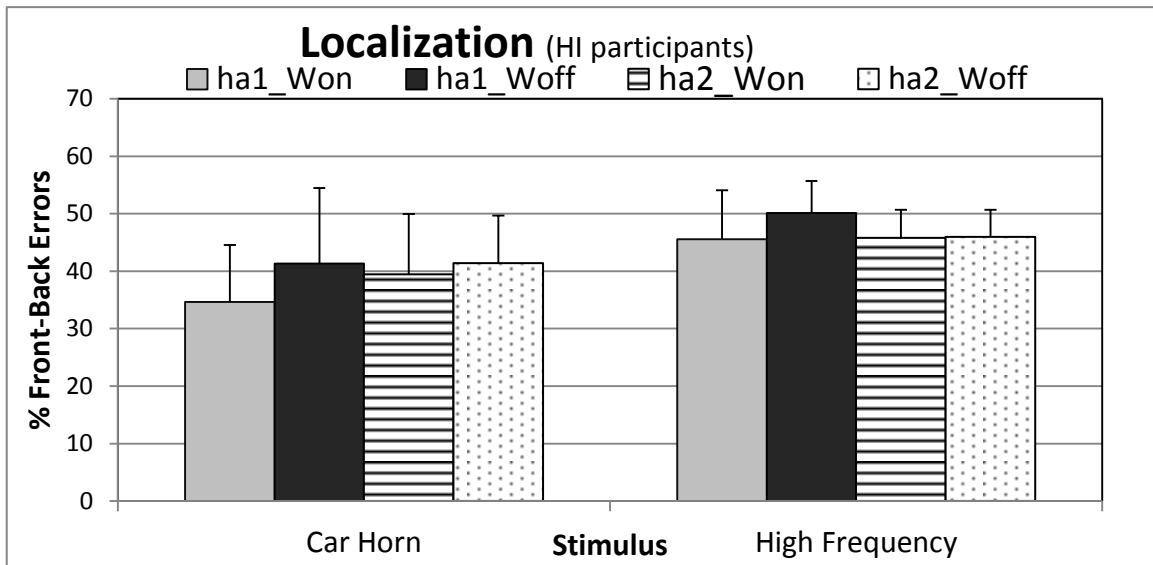


Figure 2-9: F/B error rate by HI participants for the two test stimuli. Note that ha1=hearing aid #1, ha2=hearing aid #2, Won = wireless connectivity activated, and Woff = wireless connectivity disabled.

Among the twelve HI listeners, five performed the localization task with their own hearing aids. Their performance compared to the wireless on and wireless off collapsed across the two hearing aids under investigation is displayed in figure 2-10. No statistically significant effect of the stimulus nor the hearing aid type or wireless synchrony was observed. However, when investigating the performance in the car horn in traffic condition, the wireless on performance resulted in lower errors (20.61%) when compared to the wireless off (26.43%), but quite similar to the listeners' own hearing aid (20.81%) performances.

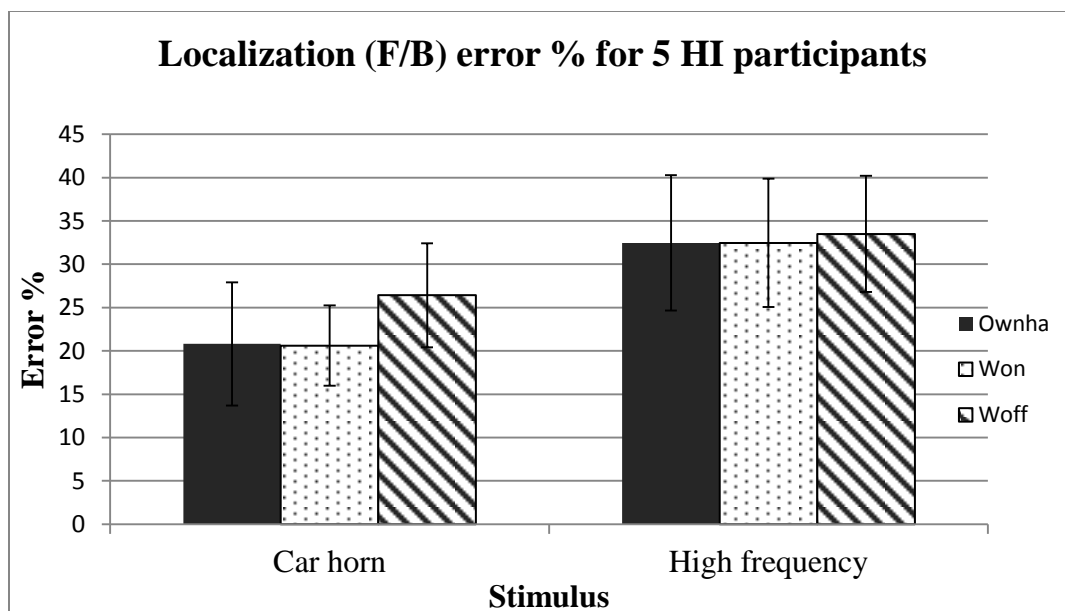


Figure 2-10: F/B error rate for five HI participants comparing the localization performance in the two stimuli condition, with their own hearing aid “ownha”, with the wireless synchrony feature on collapsed across the two hearing aids “Won”, and with the wireless synchrony feature off collapsed across the two hearing aids “Woff”.

Figure 2-11 shows the lateral angle gain for the NH participants’ localization data. A value of 1 for the lateral gain parameter indicates no bias in response either to the left or right hemisphere, while a value of 0 indicates a bias towards the midline (undershoot). Repeated measures ANOVA on the NH data did not reveal any significant main effect or interaction, except for the interaction between the HA and wireless ($F(1,7) = 6.867, p < 0.05$) which results from the greater difference between the wireless enabled and disabled conditions for ha#2. Figure 2-12 displays the lateral angle gain for the HI listeners. There was a significant main effect of the stimulus ($F(1,11) = 12.189, p < 0.05$), with the high frequency NBN resulting in a lateral gain of significantly less than 1. No other main effect or interaction was observed.

Figure 2-13 displays the lateral angle bias calculated from the data of the NH participants. Figure 2-14 displays the lateral angle bias for the HI listeners. There was a significant difference achieved by the wireless mode for the HI participants ($F(1,11) = 4.95, p < 0.05$). Lower bias was achieved when the wireless synchrony was activated.

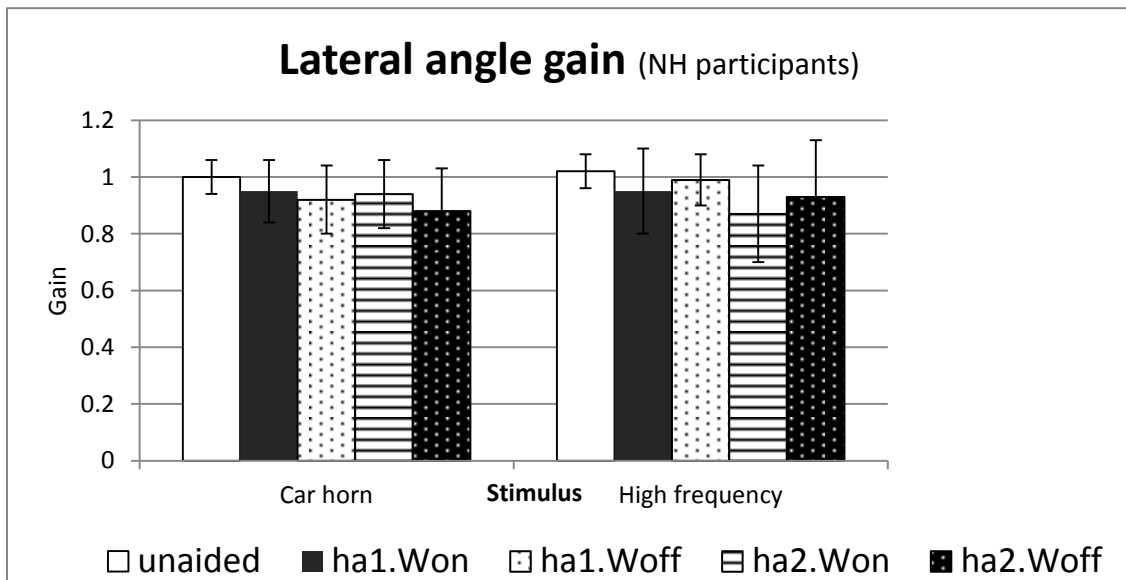


Figure 2-11: Lateral angle gain computed from the localization data obtained from NH participants for the two test stimuli. Note that ha1=hearing aid #1, ha2=hearing aid #2, Won = wireless connectivity activated, and Woff = wireless connectivity disabled.

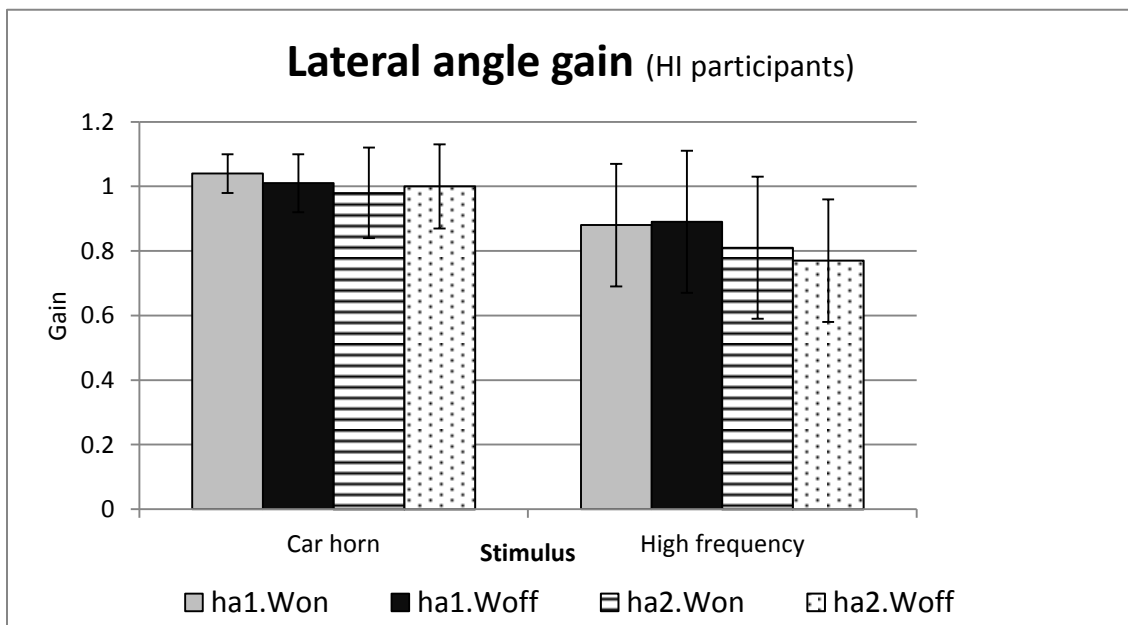


Figure 2-12: Lateral angle gain computed from the localization data obtained from HI participants for the two test stimuli. Note that ha1=hearing aid #1, ha2=hearing aid #2, Won = wireless connectivity activated, and Woff = wireless connectivity disabled.

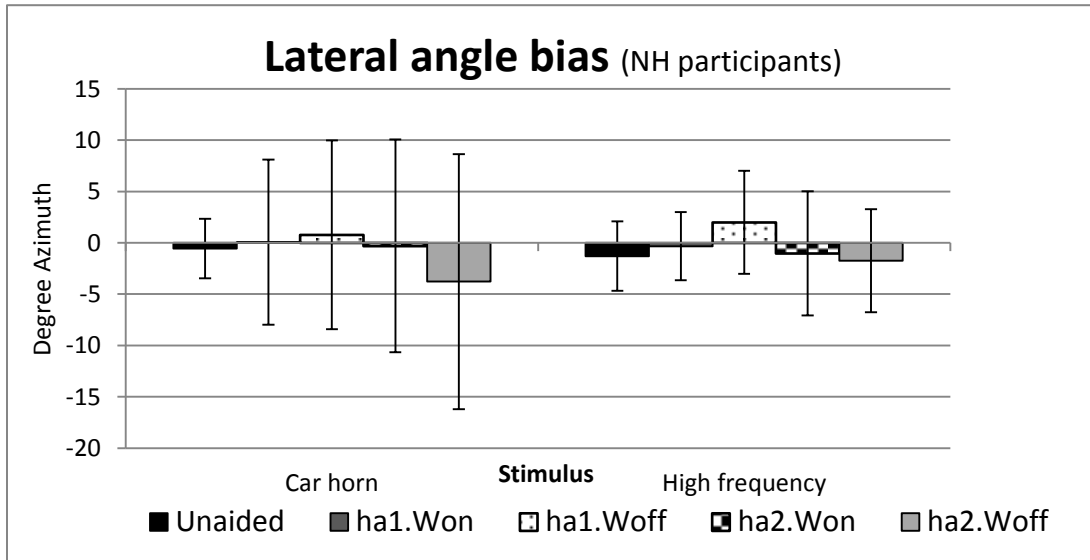


Figure 2-13: Lateral angle bias computed from the localization data obtained from NH participants for the two test stimuli. ha1=hearing aid #1, ha2=hearing aid #2, Won = wireless connectivity activated, and Woff = wireless connectivity disabled.

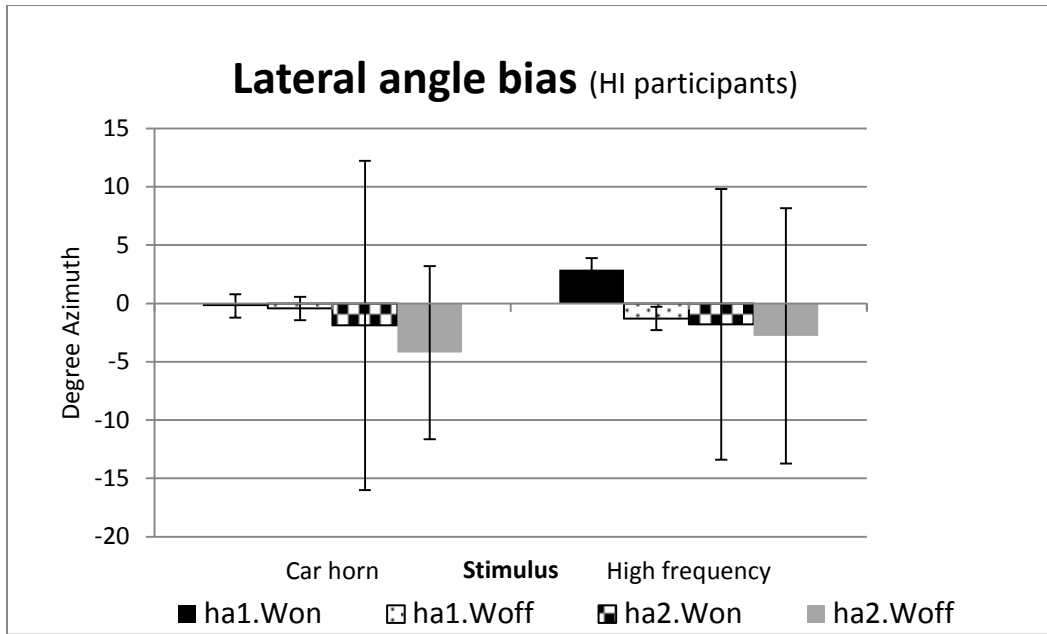


Figure 2-14: Lateral angle bias computed from the localization data obtained from HI participants for the two test stimuli. ha1=hearing aid #1, ha2=hearing aid #2, Won = wireless connectivity activated, and Woff = wireless connectivity disabled.

Figures 2-15 and 2-16 display the lateral angle scatter calculated from the data of the NH and HI listeners, respectively. Statistical analysis of the lateral angle scatter did not reveal statistically significant differences. Means and standard deviations for all the localization data for both the NH and the HI participants are provided in Appendix D.

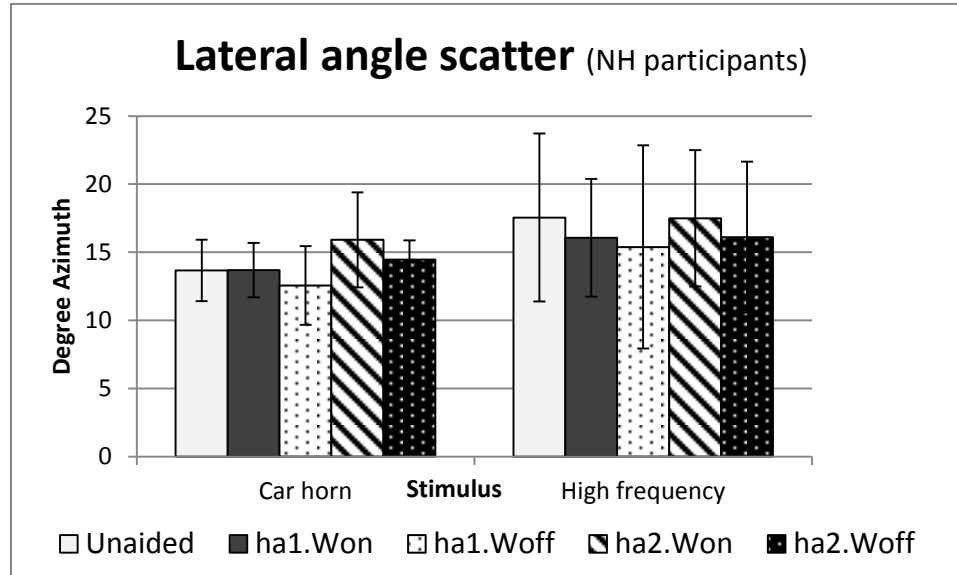


Figure 2-15: Lateral angle scatter computed from the localization data obtained from NH participants for the two test stimuli. ha1=hearing aid #1, ha2=hearing aid #2, Won = wireless connectivity activated, and Woff = wireless connectivity disabled.

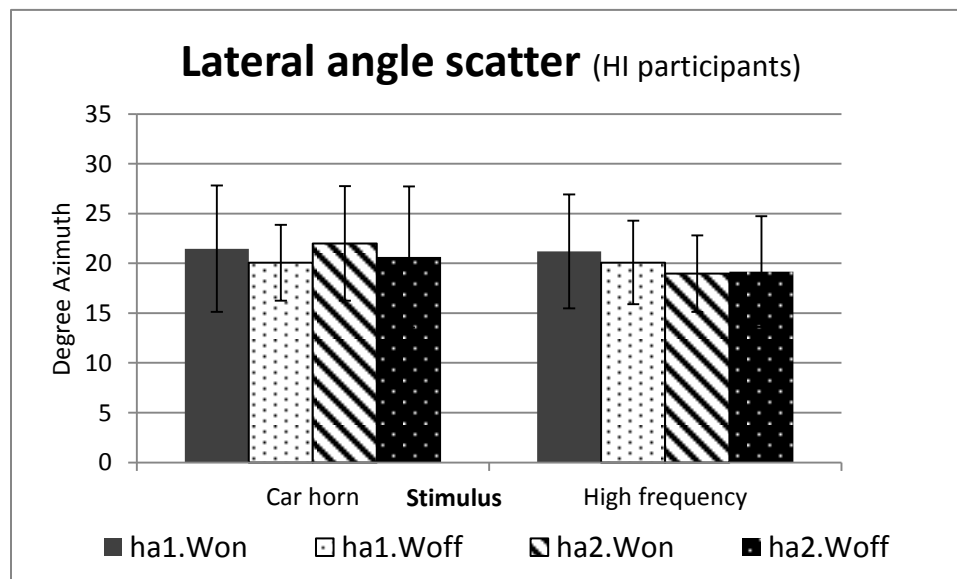


Figure 2-16: Lateral angle scatter computed from the localization data obtained from HI participants for the two test stimuli. ha1=hearing aid #1, ha2=hearing aid #2, Won = wireless connectivity activated, and Woff = wireless connectivity disabled.

2.5 Discussion

The study presented in this chapter was designed to evaluate the benefits gained by the hearing impaired listeners when both hearing aids are wirelessly communicating and coordinating the WDRC in order to restore the benefits of binaural hearing. Participants' performances in horizontal sound localization and speech intelligibility in noise were evaluated. Two modern HAs with the wireless synchrony feature were tested with a group of eight normal and 12 HI listeners. The HINT in its standard format was used to evaluate the speech intelligibility in noise. For testing the localization abilities, two stimuli were used: a car horn in stereo traffic noise and a 1/3-octave narrowband noise centered around 3150 Hz. Results showed that activating the wireless feature did not result in a significant effect on the HINT scores, but did lower the localization error rate for the HI listeners in the F/B dimension for a broadband stimulus. These results are discussed in detail below.

Results from sound localization experiments agree with previously published data on several fronts: (a) broadband stimuli are more accurately localized than high frequency narrowband stimuli (e.g., Keidser et al. 2009, 2011; Middlebrooks, 1992), (b) localization errors in the F/B dimension are greater than in the L/R dimension (e.g., Best et al., 2010; Noble et al., 1994; Vaillancourt et al., 2011), and (c) aided localization performance by HI listeners does not reach normative performance (e.g., Bogaert et al., 2011; Byrne & Noble, 1998).

The sound localization experiments were carried out with two different stimuli in this study: a broadband car horn in the presence of traffic noise and a narrowband high frequency stimulus. The F/B error rate was lowest (24.17%) for the NH listeners when localizing the car horn stimulus in the unaided condition, and 41.65% when localizing the high frequency NBN also in the unaided condition. These listeners had access to a full range of natural spectral cues indicating the F/B location for the car horn stimulus, but not for the NBN stimulus, because it is a high frequency and a narrow band stimulus, and resolving the F/B confusions requires broadband high frequency stimuli, where the spectral shape of the stimulus changes according to the pinna shape.

The location of the hearing aid microphone outside the pinna in aided conditions prevented access to the natural spectral cues with a concomitant increase in errors. The high rate of F/B errors observed for the NBN stimulus for all listeners was expected because the NBN stimulus spectrum did not excite the broad range of high frequencies necessary to reveal the shape of the spectral cues produced by the source (Blauert 1969, Middlebrooks 1992).

The most salient result from the sound localization experiments was the significant decrease in F/B confusions within the HI group for the broadband car horn stimulus with the activation of the wireless synchrony feature. This result is similar to the one reported by Sockalingam et al. (2009) in which HI participants exhibited lower errors in localizing a bird chirp in the presence of speech-shaped background noise when wearing synchronized bilateral HAs. In their study to re-examine the duplex theory for sound localization, Macpherson and Middlebrooks (2002) found that biased ILD cues result in more F/B confusions in wide-band stimuli, perhaps due to the mismatch between ITD and ILD cues at low frequencies. It seems that a match between ITD and ILD cues is necessary for listeners in order to properly use spectral cues to solve F/B confusions. Similar results were found in sound localization experiments conducted by Macpherson and Sabin (2007). More recently, Wiggins and Seeber (2012) reported that static ILD bias, which simulates the effect of non-synchronized compression, can affect the spatial intelligibility of broadband signals. Therefore, results from the present study suggest that the synchronized WDRC reduces the bias in ILDs that would otherwise be present with independent bilateral WDRC, and this facilitates better F/B discrimination of broadband sounds. When compared to the NH listeners, the average aided performance was 34.63% for the car horn stimulus, and 45.54% for the high frequency NBN stimulus. However, it is worth mentioning that the aided performance of the HI listeners was generally better than the aided performance of the NH listeners. This could be a result of adaptation to the new cues provided by the hearing aids, and could be considered as evidence of auditory plasticity, which will be discussed in more detail in chapter three.

Analysis of the localization performance of HI listeners in the L/R dimension revealed a significant main effect of stimulus. The lateral angle gain was around 1 for the car horn

stimulus and around 0.8 for the NBN stimulus which implies a bias towards the midline for the NBN. This result can be explained from examining the audibility of two test stimuli. Sabin et al. (2005) reported that the lateral angle gain is biased toward the midline (about 0.5) when stimuli are near threshold of sensation for the HI participants, and gradually increases to 1 as the sensation level increases. In the present study, the participants' audiograms (Figure 2-1) show that the average hearing threshold for the 500 Hz is ~45 dB HL, and for the 4 kHz is ~60 dB HL. Considering that there is a spectral peak in the car horn stimulus around 400 Hz, (see Figure 2-2), and that the NBN centre frequency is 3150 Hz, it can be inferred that the car horn stimulus was presented at a higher sensation level than the NBN stimulus. In addition, the frequency response of a typical hearing aid rolls off beyond 4000 Hz (e.g. Dillon, 2001) impacting the audibility of high frequency sounds. This is evident from Figure 2-17, where the verification of the programmed HA gain for one of the HI participants is shown. Inadequate high frequency gain and narrower HA bandwidth both contribute to the lower sensation level of high frequency sounds, leading to poorer lateralization.

Unlike the F/B data, there was no effect of wireless synchronization on localization in the L/R dimension, even for the car horn stimulus. The lack of an effect of activating the wireless synchrony on the lateral angle gain with the car horn stimulus might be due to the availability of low frequencies. When available, ITD cues are weighted more heavily (~80%) than ILD cues (Macpherson & Middlebrooks 2002; Wightman & Kistler, 1992). Lateral angle bias was significantly reduced with the activation of the wireless mode.

The large standard deviation values in bias and scatter measurement reflect large variability in the participants' performance, and were found to be greater with ha#2. The reason may be the different WDRC strategies used in ha#1 and ha#2. Ha#1 utilizes a parallel system that includes a fifteen channel slow-acting compressor and a four channel fast-acting compressor. Ha#2 on the other hand, incorporates a sixteen channel compressor with syllabic compression time constants. The unavailability of fast-acting compression in ha#2 could be the reason for the greater variability in the individual performances.

The HINT data obtained from NH listeners are similar to the published normative data (Nilsson et al., 1994). As expected, there was a significant difference between the HINT scores obtained from NH and HI participants across listening conditions. Furthermore, activation of the binaural wireless synchrony feature did not produce a significantly different result for either NH or HI participants, although it is purported to better preserve the binaural cues that facilitate improved speech intelligibility in noise. This result contradicts the findings from Kreisman et al. (2010) study where a significant improvement in speech understanding in noise by HI listeners was reported with HAs incorporating wireless synchrony. However, Kreisman et al. (2010) compared the performance of two different models of HAs in their study, namely the Oticon Epoq and Oticon Syncro. Epoq was a newer generation model than Syncro; in addition to the wireless synchrony feature, Epoq also incorporated a newer DSP platform and wider bandwidth in comparison to Syncro. In contrast, the present study evaluated the performance of the wireless synchrony feature in isolation while keeping all other HA parameters constant.

Several factors may have contributed to the lack of a significant difference in intelligibility scores between the two wireless settings. First, both brands of HA pairs were programmed to be in omnidirectional mode regardless of the wireless setting. Thus, the matched microphone directionality configurations preserved the ITD cues (Keidser et al., 2006; 2009) for both speech and noise stimuli even when the wireless synchrony was disabled. Finally, both NH and HI participants were tested without a period of acclimatization to either HAs, similar to an earlier study by Van den Bogaert et al. (2011). While there are conflicting reports on the effect of acclimatization on speech recognition in noise (Munro (2008) provides a review of this literature), there is evidence that HI listeners improve over time in their speech recognition abilities when using multichannel WDRC (e.g., Yund et al., 2006). Furthermore, Neher et al. (2009) commented that a lack of acclimatization may impact the degree of spatial benefit experienced by HI listeners in complex listening environments.

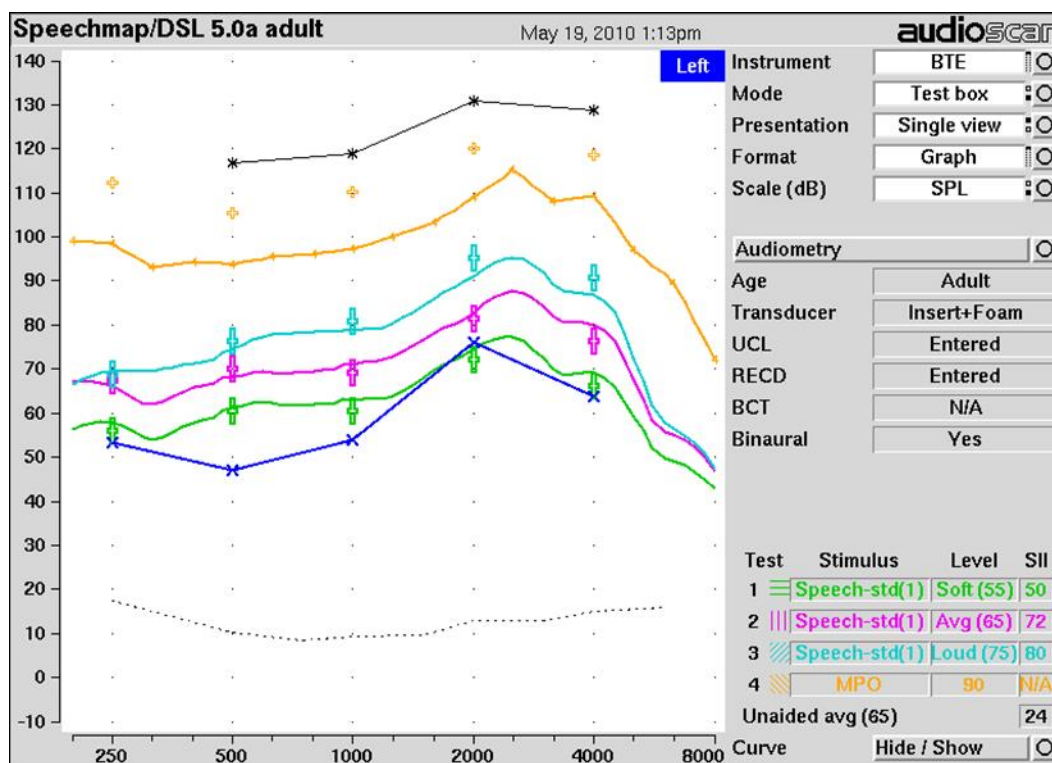


Figure 2-17: SpeechMap from AudioScan Verifit displaying the fit-to-targets for different levels of input speech.

A final comment with regards to the head movement in the localization tasks is worth mentioning. The minimum latency of head movement in response to an auditory stimulus is approximately 200 ms (Brimijoin et al., 2010; Zambarbieri et al., 1997), thus the 200-ms high-frequency stimuli were likely too short to allow head movement while they were played. The 450-ms car horn targets, however, might have been long enough to permit useful head movements before offset. By comparing the head positions measured at the onset and offset of the stimuli, head movement angles were calculated for the two stimuli in the study for all the participants and all the hearing aid conditions. The percentage of head movements that were greater than 10° , and therefore large enough to assist in F/B localization (Macpherson et al., 2011) were: 0.7% for the high-frequency noise, 28.4% for the car horn with wireless connectivity enabled, and 22.8% for the car horn with wireless connectivity disabled. It is noticeable that the longer the stimulus, the more the effective head movement, and hence the lower the F/B confusions. However, since the difference between the percentages of effective head movement with activation and with

deactivation of the wireless synchrony is insignificant, it is not likely that the head movement influenced the significant improvement with activating the wireless synchrony.

2.6 Summary and Conclusions

This chapter presented a study conducted to evaluate the benefit of wireless synchronization of WDRC in a bilateral hearing aid pair. Speech recognition in noise and localization abilities of NH and HI participants were measured with two different brands of bilateral wireless hearing aids. Speech recognition data showed no statistically significant preference for either “wireless on” or “wireless off” conditions. Localization results were analyzed for errors in the F/B and L/R dimensions. Activating the wireless synchronization significantly reduced the rate of F/B confusions among the HI group when the sound source was broadband. Localization results in the L/R dimensions were unaffected by the wireless setting. Together, these results suggest a benefit from wireless synchronization, at least in certain environments. Results are to be considered with caution, because participants were not acclimatized to the hearing aids and earmolds, and all advanced DSP (adaptive directionality, noise reduction, and feedback cancellation) were disabled. A subsequent study that investigate the effects of acclimatization, additional adaptive DSP, and complex listening environments (multiple sources in a reverberant setting) on the wireless synchronization of the signal processing features in the hearing aids will be presented in Chapter four.

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Chapter 3

3. Auditory Plasticity and Auditory Training

3.1 Introduction

This chapter provides a brief overview of neuroplasticity in mammals in general and in human beings in particular. First, studies that suggest the presence of auditory plasticity in adult listeners are reviewed. Second, this chapter reviews the literature on a related concept, auditory training, that can potentially lead to significant improvement in the auditory performance of HI listeners. Finally, it presents an auditory training program for horizontal sound localization with the purpose of improving auditory performance in sound localization and speech intelligibility in noise.

3.2 Neuroplasticity

The term “plasticity” in neuroscience is used to describe the brain’s capacity to adapt to external stimuli and, in the process, change its structure and function (Kolb & Whishaw, 1998). It refers to such phenomena as the recovery of function after brain injury, adult neurogenesis, synaptic changes associated with learning, and experience-dependent reorganization of sensory cortex maps (Parks et al., 2004). There are several types of plasticity. *Developmental plasticity* occurs during the first years of life. The number of synapses per neuron increases rapidly during the second and third years of life to 15,000 synapses per neuron compared to 2,500 at birth. As a person becomes older, learning and experience strengthen some connections, while other connections not used when receiving or transmitting information are eliminated by a process called *synaptic pruning*. Numerous studies conducted during the past two decades suggest that the brain never stops changing and adjusting. At least two types of modifications take place in the brain with learning: 1) an increase in the number of synapses between neurons, and 2) a change

in the internal structure of neurons, especially in the synapse area (Drubach, 2000). Newly acquired information is stored in the short-term memory, which enables a person to recall a few pieces of information. Short-term memory depends upon the electrical and chemical changes in the neuronal connections as opposed to the anatomical and biochemical changes that occur in the long-term memory later on in the brain. Another form of plasticity, *injury-induced plasticity*, has been studied extensively in rats. Brain cells surrounding the damaged area of the rats' brain undergo changes in their function and shape that allow them to take on the functions of the damaged area. Similar, although not so pronounced, changes were observed in humans (Tortora & Grabowski, 1996).

In the past, there was a general consensus among scientists that no new neurons are generated after birth and that only the number of synapses can increase (*synaptogenesis*), however, the later studies of brain activities have discovered the formation of new neurons in adulthood (*adult neurogenesis*) (Eriksson et al., 1998). Ponti, Peretto, and Bonfanti (2008) found evidence of neurogenesis in the cerebellum of adult rabbits. The function of adult neurogenesis is not clear, but some researchers link hippocampal adult neurogenesis to certain types of learning and memory. For example, Becker (2007) suggested that new neurons increase memory capacity, while Wiskott, Rasch, and Kempermann (2006) concluded that new neurons reduce interference between memories. Physical exercise like running promotes neurogenesis (Bjørnebekk, Mathé & Brené, 2005) in rats, while stress and lack of sleep may reduce hippocampal neurogenesis due to increased levels of glucocorticoids (Mirescu et al., 2006).

3.3 Auditory Plasticity

Neurogenesis was discussed as an example of the brain's ability to change its structure. Hair cells are the sensory receptors of the auditory and vestibular systems in all vertebrates. They are similar to neurons in several ways, such as : a) they are derived from the otic placode, a neuroepithelium, that gives rise to the ganglion cells of the vestibulocochlear nerve; b) the cilia on the upper surface of hair cells function as

mechanical transducers, while the inner surfaces of hair cells function as a chemical synapse, which is completed with a chemical transmitter (glutamate) and post-junctional receptors on the sensory nerve endings.

According to Vlastarakos et al. (2008), cochlear hair cells appear to be a terminally-differentiated cell population and have no capacity for spontaneous regeneration in mammals. However, genetic manipulation of the genes that control the exit from the cell cycle, induction of new hair cells through gene modification therapy, and introduction of neural stem cells into damaged cochleae offer exciting new alternatives for treatment of SNHL (Vlastarakos et al. 2008).

3.3.1 Binaural hearing and auditory plasticity

As previously explained in Chapter 1, the term “binaural hearing” refers to human ability to exploit the temporal and spectral differences between acoustic signals. Binaural hearing enables listeners to localize sound sources and detect sounds in challenging acoustic conditions. Binaural hearing also increases the range of hearing from 180° with one hearing aid to 360° with two hearing aids, and this increased range improves the sense of balance and sound quality (Kochkin, 2005), and makes listening more comfortable. Chapter 1 presented extensive details about ITDs and ILDs, the main cues that play an important role in sound localization. Both ITDs and ILDs vary with the angle of sound arrival, and their values depend on the size, shape, and separation of the two ears. Therefore, each individual will have different ITDs and ILDs (Akeroyd, 2006).

Like other perceptual skills, the neural circuits involved in spatial hearing are shaped during development by experience, and retain some capacity for plasticity later in life. Yet, the factors that enable and promote the plasticity of auditory localization in adults are still unknown (Kacelnik et al., 2006). There is evidence that supports the existence of binaural plasticity (Colpton & Silverman, 1977; Moore & Irvine, 1981; Silverman & Colpton, 1977) induced in developing and mature animals and humans by unilateral and bilateral sensorineural or conductive hearing loss. Plasticity in humans has been observed

following unilateral sound amplification, and it is likely that some forms of neural plasticity underlie the natural responses to growth-related changes in head size and other natural or artificial changes in interaural cues (Parks et al., 2004).

3.3.2 Central Nervous System (CNS) site for binaural plasticity

Listeners, who have binaural asymmetries due to conductive or sensorineural hearing loss, have altered neural processing of the acoustic localization cues. Häusler et al. (1983) tested the minimum audible angle (MAA), an aspect of localization performance, and the minimum discriminable ILD and ITD in a large sample of individuals with NH and HI listeners. They found that listeners with hearing loss more than 35 dB HL did poorly on most oral tests and there was a wide variation in individual performance. Slattery and Middlebrooks (1994) had similar results in their studies; where three out of five participants with unilateral congenital hearing loss were able to judge the location of broadband sounds more accurately than control participants, who had worn earplugs for up to 24 hours.

Wilmington et al. (1994) examined the effects of aural atresia (a severe form of congenital conductive hearing loss resulting from abnormalities in the external or middle ear) on localization performance. These researchers tested participants on various binaural tasks before and after surgery to restore sensitivity in the impaired ear to within 10 dB of the normal range. They reported that four weeks after surgery participants showed noticeable improvement in performance of all binaural tasks, although with considerable variations among them. The improvement in performance did not correlate with age or pure-tone thresholds.

Adaptation to disrupted localization cues can occur after a relatively short period. McPartland et al. (1997) found little adaptation to a unilateral ear plug worn constantly for a week. Two listeners out of six produced a small (3 dB), statistically significant adaptation during plugging, but normal binaural hearing resumed immediately after plug withdrawal.

Feedback from other sensory modalities is important for the adaptation process. In a study on the role of different areas in the auditory pathway in mediating plasticity, King et al. (2007) observed that reversible inactivation of the auditory cortex in ferrets resulted in a slower and incomplete adaptation than in a normal control group, whereas selective lesions of descending corticocollicular pathways prevented any improvement in localization performance. King et al. (2007) concluded that the auditory cortex may be involved in rapid training-induced plasticity in adults and suggested that the descending cortical pathways are likely to mediate training-induced auditory localization plasticity.

3.4 Auditory training and plasticity

As discussed in the previous sections, because the brain has the capacity for plasticity, training can induce changes in auditory performance. Auditory training (AT) is a treatment program that uses repetitive listening exercises to improve a listener's ability to perceive auditory events. Exercises are conducted either with a listening partner at home or in weekly sessions with an audiologist (Tremblay, 2006). Auditory functions processed at a higher level (i.e., the auditory cortex and brainstem) can be improved with AT (Tremblay, 2003). Recent studies in neuroscience suggest that training may improve auditory skills and even induce changes in the central auditory system (Hayes et al., 2003). Because auditory localization is processed at the brainstem, this function can be improved with training (Tremblay, 2003). Subcortical structures, such as the brainstem, exhibit experience-related developmental plasticity (Johnson et al., 2008; Song et al., 2008). Because people with hearing loss usually complain of difficulties in speech discrimination and not of decreased localization abilities (Dillon, 2001), the AT so far has been developed for the speech domain. Although AT can significantly improve auditory performance in HI listeners, only a small percentage (15.6%) of audiologists provided AT for their users (Sweetow & Sabes 2004). Moreover, many HI listeners, who commence AT, fail to complete the assigned training protocol and drop out from the program (Bancroft et al., 2011; Schow et al., 1993; Sweetow and Sabes, 2010). Bancroft et al. (2011) report two main reasons that motivate users to seek AT: a) to better understand the

spoken language during everyday interactions in the community or workplace, and b) to improve their abilities to understand the speech of a particular communication partner (PCP).

Several AT software programs have been developed to enhance speech intelligibility in different contexts (e.g., in silence, or in noise). The Computer-Assisted Speech Intelligibility Testing and Training at the Sentence Level, or CASPERSent, was designed by Dr. Arthur Boothroyd to improve speech intelligibility. Sentences are presented to listeners by lipreading only, hearing only, and a combination of the two. Users are instructed to hear and/or see a spoken sentence, repeat it as many times as possible, view the text, and then click on the correctly identified words. The CASPERSent can be self-administered or administered with the aid of another person (Boothroyd, 2006).

A second AT program is the Computer Assisted Tracking Simulation (CATS). Developed at the Central Institute for the Deaf in St. Louis, U.S.A., and subsequently updated by Dr. Harry Levitt, this program allows the user and another person to interact and the user to repeat verbatim the sentence or phrase spoken by the speaker (Dempsy et al., 1992).

A third AT program is called the Listening and Communication Enhancement (LACE). The users complete a series of short exercises with the aim of improving their auditory memory and speed of processing (Sweetow & Sabes, 2004). LACE can be used on any home computer, and performance results can be tabulated and shared with clinicians using the Internet. A study by Martin (2007) found that using the LACE for 60 days by new hearing aid users lowered the return-for-credit rate of hearing aids by four times in comparison to those who did not use LACE, this finding demonstrates that providing AT could improve the successful hearing aid fitting rate.

3.4.1 Improvement in localization with auditory training in NH individuals

The findings of the studies on the effects of AT on localization performance in NH individuals demonstrate that a short period of AT can lead to a significant improvement

in localization performance. Ohuchi et al. (2005) designed a virtual auditory display (VAD)-based game called “hoy-pippi”, that is responsive to a head movement. The characteristic feature of this game is touching sound. The player has to position his/her hand in the direction of sound source. Ohuchi et al. (2005) tested NH participants who were blindfolded. They divided them into two groups: a training group and a control group. The training group played the game for 15 minutes every day for 10 days. Localization performance for both groups was tested before and after the training period. The authors observed that the localization error decreased in every azimuth in the training group, while there was an insignificant difference in the control group performance before and after the training period. The data analysis revealed that a significant change occurred on the seventh day of training.

Shinn-Cunningham et al. (1998) investigated the effect of AT on the adaptation to supernormal localization cues. The supernormal cues are localization cues that are not constrained by the physics laws which determine the normal localization cues; they span a larger range of just-noticeable differences than do normal cues, allowing listeners to improve their ability to resolve nearby spatial positions that were created by remapping the relationship between source position and normal Head-Related Transfer Functions (HRTFs). The results demonstrated that participants were able to learn remapping between acoustic cues and physical locations as they were able to reduce the bias with AT. However, they did not completely overcome their systematic errors. These findings are consistent with previous research on sensorimotor adaptation, in which Welch (1986) showed that adaptation usually does occur, but it is rarely complete, as systematic biases remain after performance is stabilized.

Shin-Cunningham et al. (1998) attempted to develop a quantitative model of adaptation to altered (supernormal) localization cues. They found that following AT, the mean response was roughly proportional to the normal cue position of the acoustic stimuli. This suggests that participants cannot completely adapt to a nonlinear cue transformation, but they can adapt to a linear approximation of the applied nonlinear transformation, where the relation between the natural and the transformed cues are expressed by a linear

equation (simple scaling of the natural cue, not a complex function). These findings suggest that the plasticity of human participants in interpreting the auditory localization cues has its limitations.

Zahorik (2006) evaluated the efficacy of a sound localization training procedure that provided listeners with auditory, visual, and proprioceptive/vestibular feedback to correct sound source position. Zahorik had a training group and a control group. Stimuli were presented via stereo headphones, using non-individualized HRTFs. In the feedback-training (closed loop) procedure, the correct source location was provided to the listener by a paired auditory/visual stimulus. The subject had to verify the combined proprioceptive and vestibular feedback. Testing and training spatial locations were distributed throughout the 360° of azimuth and over $\pm 40^\circ$ elevation. Zahorik (2006) demonstrated that a brief perceptual training procedure of two 30-minute sessions, which provided auditory, visual, and proprioceptive/vestibular feedback for the true target location, could improve localization accuracy when spectral cues were manipulated. The improvement was limited to the F/B dimension, lasted for at least four months after training, and generalized to an improved performance for the untrained spatial locations. Zahorik's study illustrates the importance of providing feedback using different and combined methods in training programs.

3.4.2 Improvement in localization with auditory training in HI individuals

The studies reviewed in this section show that HI listeners can improve their localization abilities using appropriate training programs and procedures. Most of these studies focus on horizontal localization because localization in the horizontal plane is more commonly encountered in everyday life.

Providing new hearing aid technology, such as the bilateral coordination, as well as providing time for acclimatization to the new hearing aid and the new feature, are both considered passive ways of improving the auditory performance of HI listeners.

In a search for a more active way for HI listeners to improve their auditory performance, auditory training (AT) has been found to be an effective method of improving the auditory performance of HI listeners. This interest in AT is not new. Studies in the 1930s and 1940s demonstrated that providing training can result in an improvement not only in the human's physical abilities, but also in the human's sensory accuracy (Di Carlo, 1948; Pearce, 1937).

AT is believed to capitalize on the plasticity of the auditory system, whereby changes in the neural activities that result from regular repeated exposure to auditory stimuli in certain contexts improve auditory performance. Auditory plasticity has been measured and assessed by several electrophysiological or imaging (hemodynamic) measures. For example, Tremblay et al. (2001) reported an increase in N1-P2 wave amplitude after 10 days of auditory training for NH individuals, in synchrony with improvement in discrimination between 10 and 20 ms voice-onset-time syllabi. Song et al. (2011) also provide evidence of the occurrence of significant changes in electrophysiological measures after four weeks of AT. They measured brainstem responses to the syllable /da/ in both a quiet and a multitalker noise condition. After providing AT using the computer based program "LACE" (Listening & Communication Enhancement, Neurotone, Inc., 2005), significant training-related enhancements in the representation of pitch cues were recorded. These and similar studies confirm and demonstrate a physiologic basis for training induced plasticity in the auditory system that results in improved auditory performance.

Dufour et al. (2005) developed an auditory localization training program for bilateral cochlear implant users (who also had impaired vision) with the purpose of maximizing their independence and safety in travel situations. The training program consisted of graduated exercises based on the Auditory Localization Evaluation System (SELA) and was conducted for a period of one month during 12 sessions, each one hour long. Training and testing took place in a sound booth with 11 speakers 18° apart in a semicircular horizontal array. Ecological sounds were used as stimuli during training sessions. A bilateral cochlear implant user, who had a visual impairment, was trained

using SELA for two months. After completing an auditory localization training program, the participant met the success criteria and became more confident in her localization skills. The authors concluded that intensive AT can improve localization abilities in HI listeners.

Several studies reviewed by Wright and Zang (2006) focused on adaptation to, as well as training, in a variety of manipulations of both horizontal and vertical localization cues that simulated the difficulties faced by HI listeners. Wright and Zhang concluded that humans can adapt to alterations in cues to sound source position. These scientists noted that the human ability to adapt to altered localization cues has been well-established, while learning with normal cues (i.e. trying to improve localization without altering the localization cues or their intelligibility) is relatively limited. Adaptation to altered cues was found to have several characteristics: a) it is partial in the horizontal plane, but rather complete in the vertical plane; b) it occurs rapidly within one to two hours of testing; c) it has small and short lived aftereffects if present; d) it has a limited duration, and e) it has a large variability among participants.

The ability of human listeners to recalibrate the relationship between the localization cues and sound source positions provides evidence that localization training programs can be effective for individuals with impaired localization abilities and for those, who need accurate sound localization in their professions.

3.5 Sound localization in hearing aid users

As previously discussed, new hearing aid algorithms can implement binaural processing, where the input from both hearing aids (right and left) is evaluated, and decisions regarding implementing certain processing features is then implemented by the hearing aid circuit, with the aim of coordinating the response of the two hearing aids to preserve the benefits of binaural hearing as much as possible. The two hearing aids communicate wirelessly with the aim of maximizing the binaural cues, uses these cues to make global

processing decisions regarding all hearing aid features, such as microphone modes, DNR activation, as well as level and compression characteristics (Oticon, 2008; Siemens, 2009). Behrens (2008) used a simplified version of the SSQ to evaluate the advantage of binaural wireless communication and processing in Oticon Epoq hearing aids (Oticon 2008). He found that Epoq devices provided benefits across several dimensions of spatial hearing, such as locating a speaker around a table, and ignoring competing sounds, relative to conventional bilateral and unilateral fittings. However, in studies conducted by Sockalingam et al. (2009), improvement in localization ability with binaural wireless communication was only $\sim 2^\circ$. Although this improvement is statistically significant, it may be too small to be of great value in real life. Also, the relatively large standard deviations of the localization results' averages (8° and 10°) in binaural wireless coordination when it is on and off decrease the significance of that improvement. Using these spatial-cue preserving algorithms in hearing aids in combination with AT for localization will not only improve spatial localization performance, but also contribute to the enhancement of overall communication skills of HI listeners (Sweetow, 2008).

3.6 AT Generalizability

This section reviews studies that demonstrate how AT in one auditory task can lead to an improvement in another auditory task. This process is referred to as the generalization of AT. Stecker et al. (2006) reported that training HA users for syllable identification in noise using nonsense syllable test lead to a significant improvement in performance that generalized to untrained voices. Gil et al. (2010) tested the auditory performance of two groups of listeners with hearing impairment (a training and a non-training control group) before and after AT. The training period lasted one month and consisted of eight one-hour long sessions, during which different speech stimuli, frequency, and tonal patterns were used as training material. The training group showed a statistically significant improvement in performing various tasks, while the control group had no changes in performance. The training group also displayed a considerable improvement in other areas of auditory performance, including sound localization and speech-in-noise test. In

contrast, the control group did not show any significant improvement in those areas. These results support the benefits of AT for HI listeners. Furthermore, they suggest that training HI adults in auditory tasks, like speech understanding and frequency pattern recognition, can lead to a significant improvement in other auditory tasks, like sound localization. Montgomery et al. (1984) reported a substantial improvement after speech AT, where the talkers in the training sessions were different from the talkers in the test session. Walden et al. (1981) noted improved sentence recognition after syllable AT. These two studies point to AT generalization and suggest that AT in one aspect of auditory performance can have positive effects on the overall performance of HI listeners. However, Wright et al., (2010) reported that generalization of the benefits of AT to untrained stimuli lagged behind the improvement in performance for the trained stimuli, when they investigated the effect of AT on temporal-interval discrimination, and tested the generalization to untrained frequencies and temporal-intervals.

3.7 Auditory training program to improve the sound localization performance of hearing aid users.

Based on the current literature review, it can be concluded that AT can significantly improve the auditory performance of HI listeners, and some studies pointed out the generalizability of AT, where training in one auditory task can lead to an improvement in another auditory task. An AT program is proposed in this section. This program focuses on horizontal localization training with the aim of improving localization abilities of HI listeners. It is expected to generalize to an improvement in their speech intelligibility in noise performance. The objectives of this program are: 1) to improve localization abilities of hearing aid users, 2) to reduce front-back errors, as they are the most common localization errors, and 3) to test the generalizability of AT, by testing speech performance before and after sound localization training. The program will focus on horizontal localization as it is much more common in everyday life compared to vertical localization. The proposed AT program draws on the general design of SELA (Dufour et al., 2005) with changes made for hearing aid users, who have normal vision with or without eyeglasses. It consisted of twelve 30-minute lessons that were conducted during

a one month period. The AT covered the entire audible sound spectrum including broadband noise (BBN), low-pass noise filtered at 2 kHz (LPN), and high-pass noise filtered at 2 kHz (HPN). Training sessions were administered in the Beltone Anechoic Chamber of the National Center for Audiology that has 16 speakers spanning 360°, with 22.5° between speakers. The distance between speakers is close to the central visual field, and the whole circle (compared to the half-circle used by Dufour et al. (2005) was used in order to test all directions in one session, instead of repositioning the subject to test different directions. An open-choice paradigm was applied, because it was used in the study discussed in Chapter two for HI listeners, and found to be within the participant's abilities. The participants were required to turn their head or head and body, point at the source speaker by nose and then press a button to record the response. Because multimodal feedback was found to improve localization performance (Zahorik, 2006), visual and auditory feedback was provided by the light emitting from the source speaker with replaying the auditory stimulus. The participant was required to verify the feedback by the same procedure used to identify the source (proprioceptive and vestibular feedback). Each stimulus was played two times from each speaker (one time for testing, and the second time as a feedback with longer duration and the light emitted from the speaker), and the average was calculated for comparing the performance across the training period.

The AT program that focuses on sound localization rather than speech intelligibility has the potential to be useful for HI listeners and, especially, non-native English speakers, who may find it difficult to follow English speech-based training protocols. It can also give more insight into how training for certain auditory tasks, such as speech understanding or auditory sound localization, generalises to performance in another auditory task. Furthermore, the proposed AT is expected to make currently used hearing aid fitting procedure more effective by providing an optimum subject-dependent hearing aid fitting process that includes programming, molds and venting (whenever applicable), and activation of DSP features, such as noise reduction, feedback cancellation, and an acclimatization period. Finally, it provides an in-depth evaluation of binaural wireless

communication technology and how it contributes to the benefits of binaural hearing. Detailed description of the material and method is provided in Chapter 4.

3.8 Summary and conclusions

The review of the literature on auditory plasticity and AT demonstrated evidence that supports the plasticity of human binaural auditory system in the form of adaptation to different types of distorted localization cues that mimic the effect of hearing impairment and distorted cues that are provided by hearing aids (Butler, 1987; Byrne & Dirks, 1996). Research in neuroscience suggests that AT—a treatment program based on repetitive listening exercises to improve a user’s ability to perceive auditory events— may improve auditory skills and even induce changes in the central auditory system (Hayes et al., 2003). Specifically, AT in sound localization can be used to facilitate rehabilitation in users, whose intelligibility of the auditory space is compromised as a result of hearing loss (Hayes, 2003; Wright & Zhang, 2006). Some studies (Dufour et al., 2005; Ohochi et al., 2005) investigated the effect of training on horizontal localization abilities in normal and HI listeners and established that in most participants significant improvements can occur within a few days to several weeks. Different outcomes of the hearing aid fitting procedure for identical hearing loss configuration may be due to the individual differences in CNS plasticity. The possibility that AT can improve performance of users not getting significant improvement and satisfaction with hearing aids should be considered. A design for the training program to improve the localization abilities of hearing aid users, as well as their speech intelligibility in noise, has been proposed at the end of this chapter.

3.9 References

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CHAPTER 4

4. Evaluation of Sound Localization and Speech Discrimination with Hearing Aids that use Binaural Wireless Technology following Auditory Training

4.1 Introduction

This chapter presents a study that was performed in order to investigate the effects of several factors on the binaural hearing abilities of HI listeners. These factors include: 1) bilateral coordination of the hearing aids, 2) acclimatization, 3) AT, and 4) acoustic environment.

As discussed in Chapter two, applying synchronized processing in the hearing aids results in an improvement in the localization abilities of the HI listeners, with no apparent positive or negative effects on their abilities to understand speech in noise. However, no period of time for acclimatization to the new hearing aids was provided, nor was there an assessment of the synchronized processing of the DSP features apart from the wide range dynamic compression. Consequently, in the current study, a period for acclimatization was provided, and the auditory performance with and without the synchronization was tested afterwards. In Chapter three, the author explained how auditory training can result in a tangible improvement in auditory performance. Auditory training in one aspect of auditory performance can result in an improvement in that specific aspect, as well as in other aspects of auditory performance which were not included in the training procedure. However, improvement in the untrained tasks may lag behind the improvement in the trained task (Wright et al., 2010). Motivated by the results outlined in Chapter three, a training program for auditory localization was provided to some participants in the current study, and the auditory performance in both sound localization and speech intelligibility were tested. The results were compared with the results of the participants who had a period of acclimatization but did not receive auditory training.

4.2 Background

In attempts to restore the binaural benefits for HI listeners, and based on the understanding of the importance and benefits of listening to sounds with both ears, hearing aid companies launched the new feature of bilateral coordination. The aim of this feature is to try to restore more of the auditory functions that NH individuals enjoy. Having two copies of the signal from the two ears, with different timing, intensity, and spectral profile parameters, helps the brain to analyze the signal and detect its location in space. This could also help differentiate auditory sources in the environment, and select the signals of interest to follow, while minimizing less important signals.

In Chapter two, a study that aimed to evaluate the benefits of applying the binaural synchrony feature was presented, and it was found that the benefit gained from this feature was apparent for auditory localization, but not for speech understanding in noise. However, participants did not have any time to acclimatize to the new hearing aids.

Gil et al. (2010) found evidence for the generalization of the effect of auditory training. The auditory performance of two groups of listeners with hearing impairment (a training and a non-training control group) were tested before and after training. The results suggest that generalization can occur with AT in that training the participants on some auditory tasks (speech understanding and frequency pattern recognition) can lead to a significant improvement in other auditory tasks such as sound localization. Montgomery et al (1984) reported significant improvement after speech AT by a different talker, and Walden et al (1981) reported improved sentence recognition after Syllable AT. These two studies suggest that some form of AT may improve other aspects of auditory performance.

Given the aforementioned solid benefits of AT, Sweetow and Palmer (2005) suggest that the cost of AT may be the primary reason it is not a universal component of auditory

rehabilitation. Furthermore, they continue to suggest that computer based AT programs, such as LACE, could be the solution to this problem. Gil et al. (2010) suggest that the high cost of hearing aids could defer their acquisition by many HI participants and, they suggest that the AT component may enhance the confidence required by patients who are considering purchasing expensive hearing aids.

Amongst other recommendations made by Sweetow and Palmer (2005) for future AT studies, they suggest investigating the generalizability of AT to other auditory tasks. The previously mentioned studies Gil et al. (2010), Montgomery et al. (1984), and Walden et al. (1981) indicate AT generalization to other aspects of auditory performance.

Based on the evidence provided above, it could be inferred that an AT paradigm that focuses on sound localization, rather than speech intelligibility, and has the potential to be of great value, particularly for non-native English speakers who may have difficulty with English speech-based training protocols. Furthermore, an AT paradigm that focuses on sound localization is expected to provide more insight on the generalizability of AT to other aspects of auditory performance. Together with providing optimum subject-dependent hearing aid fitting procedure (programs, molds, venting, and activation of DSP features, such as noise reduction, and feedback cancellation, and an acclimatization period), the proposed study will provide and evaluate the most favorable outcome from a modern hearing aid fitting.

The current study aimed to provide an in-depth evaluation of binaural wireless communication technology and how it contributes to the benefits of binaural hearing. It also aims to test the effect of auditory training on one aspect of auditory performance which, in turn, improves other aspects of auditory performance.

The study objectives were to provide:

- State-of-the-art conditions for testing the auditory performance with hearing aids that implement binaural wireless synchrony. This was achieved by providing BTE with Receivers In The Ear (RITE). When initially introduced, RITE hearing

aids were successful only for individuals with mild high frequency hearing loss because of feedback problems. However, with improvements in digital feedback suppression technology, individuals with mild to severe hearing loss can now benefit from the advantages of open fitting, such as natural sound quality, better physical comfort, and eliminated occlusion effect (Schum, 2012).

- An effective yet appropriate period for hearing aid acclimatization in participants' real environments. Given that the maximum benefit from hearing aid acclimatization can be achieved after 30 days (as previously mentioned), a period ranging between 30-45 days (4-6 weeks) was provided for hearing aid acclimatization.
- An effective yet appropriate period for Auditory Training. This is expected to improve performance in auditory tasks. Given that the benefit of AT is observed within the first month, a period of 1 month was provided for AT.
- More insight about the generalizability of AT, by providing auditory training in one aspect of auditory performance (sound localization) and testing the auditory performance in two aspects (sound localization and speech intelligibility).

4.3 Material & Method

4.3.1 Participants

Nine participants joined this study; they were divided into two groups, a training and control group. Five participants joined the training group, three females and two males, with a mean age ($57.8 \text{ years} \pm 22.29$), and four participants joined the control group, one female and three males, with a mean age ($66 \text{ years} \pm 5.1$). All participants had bilaterally symmetrical (difference between right and left ear thresholds is ≤ 10 dB at all measured frequencies) moderate to severe hearing loss and a minimum of three months experience with hearing aid use. Figure 4-1 shows the mean audiograms for the participants with details given in Appendices C and D.

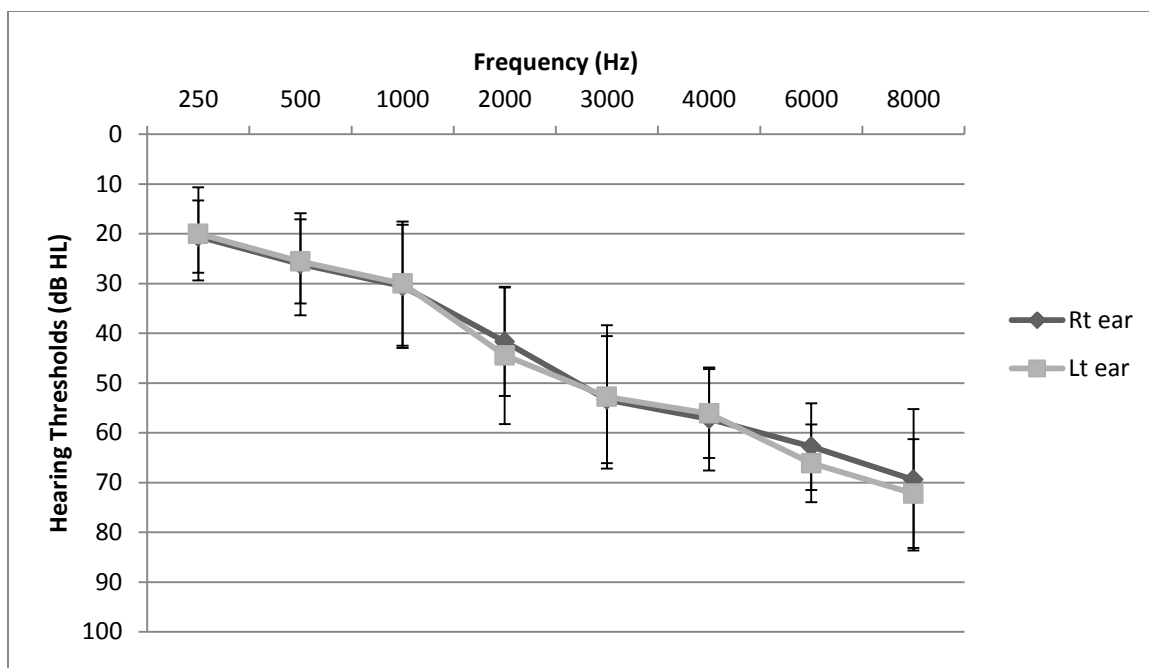


Figure 4-1: Means and standard deviations of pure tone thresholds of the participants.

4.3.2 Hearing aids

The hearing aids used for conducting this study were Oticon Agil pro RITE (Receiver In The Ear). Each participant received a pair of the hearing aids at the beginning of the study and used them regularly during the period of the study with a minimum of 8 hours/day. The data logging feature was enabled in order to check the average use/day for each participant, and all the participants were found to use the hearing aid with an average of 8-12 hours/day. The hearing aids were programmed to fit the targets specified by the Desired Sensation Level (DSL v5.0) formula (Scollie et al., 2005) for each participant and verified on the participants using Audioscan VeriFit. Participants' real ear to coupler differences (RECD) were obtained and entered into VeriFit in order to convert their thresholds from dB HL to dB SPL. The participant was then positioned directly in front of, and facing, the front sound-field speaker of the VeriFit at a distance of about 60 cm from the center of the head. With the participant wearing the hearing aids, gain was adjusted to fit the DSL v 5.0 targets. Probe tubes were inserted in the

participant's ears and positioned based on otoscopic examination to an insertion depth of 28 mm and 30 mm for females and males, respectively. Stimuli used for verification were speech inputs of 55, 65 and 75 dB SPL. All DSP features were enabled. The directionality was set to Auto (Tri-mode), which is a fully automatic directionality system. This system can alternate directionality between three modes: 1) an omni mode which is the default mode in soft to moderate level noise environment with low background levels, in strong wind situations, and when the dominant talker is determined to be behind the client, 2) a split directionality mode, in which the omni mode is applied in the low frequency band and the upper three bands are in full directional mode; this is the default mode in moderately noisy listening environment and in medium wind situations, 3) a fully directional mode in which directionality is applied in the four bands; this mode is the default for difficult listening environments with intense background noise or multiple noise sources (Oticon, 2012).

Noise management and 'My voice' features were enabled as well. The noise management applies the suitable attenuation strategy across 15 channels to achieve optimum output depending on whether speech is present or not: 1) if speech only is present, the noise management ensures optimum speech understanding, 2) if speech in noise is present, the noise management limits the degree of noise reduction to maintain speech understanding, and 3) if only noise is present, maximum attenuation is provided. The 'My voice' feature ensures maintaining the same level of noise reduction even when the user is speaking (where SNR will increase, and the noise reduction system may hence decrease the level of noise reduction).

The binaural broadband option was enabled during the whole study period. However, testing the auditory performance by disabling the binaural broadband option occurred both after the acclimatization period and after the training (or no training) period (Figure 4-2). The receiver tube length and the domes were supplied and adjusted to each participant's needs. Apart from one participant, who asked to decrease the gain one week after hearing aid fitting, all the other participants were satisfied with the hearing aid fitting provided. Two other participants requested a different size of the dome and were

provided with the requested dome size within the first week after the hearing aid fitting. The Agil Pro applies three levels of binaural interactions: 1) Binaural Processing: which is a fast communication that allows each DSP processor to use signal input from both instruments, and thereby, coordinate DSP processing between the instruments; 2) Binaural Synchronization which allows for synchronization of the action of the Multi-Band Adaptive Directionality and TriState Noise Management features, where the acoustic environment is constantly evaluated and the system selects the optimum response; and 3) Binaural Coordination which allows the user interactions to be coordinated between the instruments (Oticon, 2012).

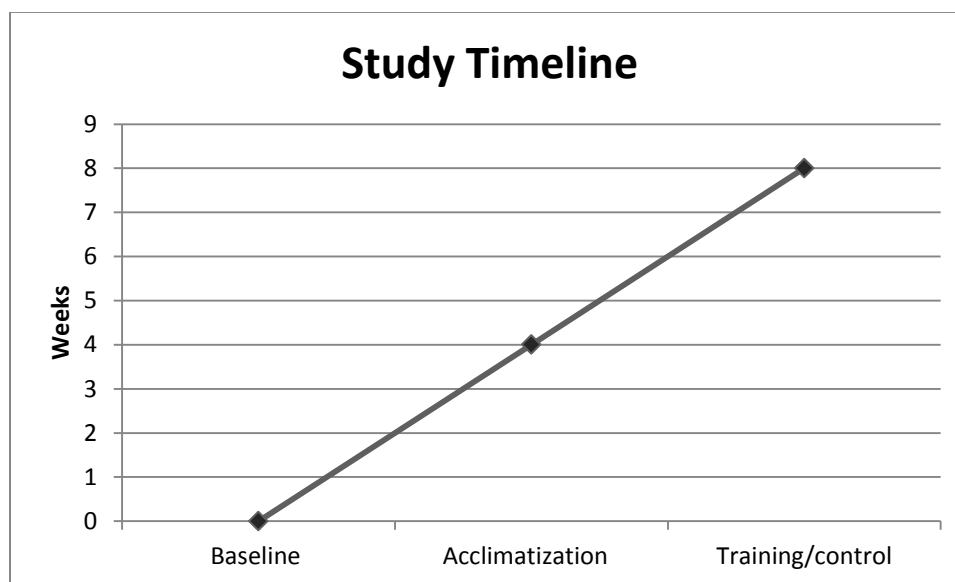


Figure 4-2: Timeline of the study.

4.3.3 Procedures

Each participant completed the study over a period of 7 to 9 weeks. The study period was divided into two parts: the acclimatization period and the training or no-training (control) period. The participants were divided into two groups: training and a control group based on their availability to join each group. During the acclimatization period, both groups received similar treatments: all participants received the hearing aid pairs, adjusted to their hearing loss profiles according to the DSL v5.0 targets, and were asked to use the

hearing aids in their everyday life for a minimum of 8 hours/day. Hearing aid batteries to cover the study period were supplied.

Testing the auditory performance of the participants took place three times throughout the study period: at the beginning (immediately after fitting the new hearing aids, which will be referred to later in the chapter as the baseline), after the acclimatization period, and at the end of the training/no-training period.

Participants were tested for their speech intelligibility in noise and horizontal sound localization abilities.

During the first session of the study, hearing tests were performed. Hearing thresholds, tympanometry, and RECDs were measured, the participants were informed about the study, decided whether they would join the training or the control group, and signed the information letter.

4.3.3.1 Speech intelligibility

Participants' speech intelligibility in noise was tested using the standard form of the Hearing In Noise Test (HINT) (Nilsson et al., 1994). Two test conditions were used. In the first, noise was presented from a single source (at 90°), and in the second, noise was presented from multiple sources (at 0°, 90°, 180°, and 270°). Speech was always presented from the front (0°). The noise used was a broadband stationary noise, and the noise presentation level was stable at 65 dBA. The speech level was varied according to the response of the participant; in order to detect the Signal-to-Noise Ratio (SNR) at which 50% of the speech is intelligible. Ten different sentences were presented with each noise scenario. 24 lists of 10 sentences each were randomly used for each participant, and no list was used twice for any participant. Testing for the HINT took place in two test rooms: 1) a semi-anechoic chamber, details of which are provided under the horizontal sound localization section below, and 2) a reverberation chamber. The reverberation chamber has a reverberation time (RT60) of 1.5 seconds. The RT60 was decreased using sound absorbing curtains, measured using SpectraPlus v 5.0 software and found to

be 667 ms. This RT60 (667 ms) represents average RT for common everyday acoustic environments, such as lobbies and conference halls (Nishiura & Fukumori, 2011). Participants were seated in the center of the room, surrounded by a circle of 16 speakers, with 22.5° between each two adjacent speakers. An FM system (PhonicEar Solaris PE 571T & PE 572R) was used to listen to the participants' responses, and the author reported their answers as either correct or incorrect to the HINT software.

4.3.3.2 Sound localization

The participants' horizontal sound localization ability was tested in a semi-anechoic chamber, where a circular array of 16 Tannoy i5 AW speakers was used. The speakers received signals from a computer through an Echo AudioFire 12 sound card (for digital to analog conversion), Soundweb 9008 networked signal processor (for speaker equalization and level control), QSC CX168 power amplifiers (for power amplification and impedance matching), and the target signals were played through the Tucker Davis Technologies RX6 real time processor. Participants stood in the middle of the speaker array on an adjustable stand. This setup was utilized for both the speech intelligibility (HINT) and sound localization experiments. Four different stimuli were used: 1) a car horn of 450 ms duration in stereo traffic noise, at +20 dB SNR. This is the same stimulus used in the first study discussed in Chapter two, 2) a broadband noise burst of 250 ms duration, 3) a 2 kHz high-pass noise of 250 ms duration, and 4) a 2 kHz low-pass noise of 250 ms duration. Although stimuli were too short to allow for head movement while they were played (except for the car horn stimulus), participants were free to move their heads and/or body to locate the stimulus.

The car horn in traffic noise was chosen to simulate common everyday situations where localization abilities play an important safety role. For this test condition, the stereo traffic noise was played from two fixed speaker locations (at $+90^\circ/-90^\circ$ azimuths), which were placed below the speakers used for localization testing.

The remaining three stimuli were chosen to test the separate effects of ITD cues (the low-pass noise), the ILD cues (the high-pass noise), and the joint effect of both cues (the broadband noise).

Each stimulus was presented 32 times (2 times from each speaker, in a randomized order) at a presentation level of 67 dB SPL. Participants stood in the middle of the speaker array wearing a head tracker (Polhemus Fastrak) helmet with an LED and a control button in hand. Upon hearing the stimulus, the participants turned their head to the perceived source speaker. The red light of the LED provided visual feedback as to the participant's head position relative to the speaker. Participants then registered their response with a button press. The next stimulus was presented 600 ms after a button press following return to the center of the speaker array. Similar to the intelligibility test, localization experiments were performed under two conditions: with the wireless feature on, and with the wireless feature off.

Prior to the actual testing, the localization task was demonstrated to the participants to familiarize the participant with the task. Participants were asked to orient toward 0° azimuth at trial initiation, and after stimulus onset they were free to move their heads to localize. Participants were not given instructions regarding head movements because it was meant to measure the natural response as it would be in real life. Custom MATLAB was used to control the localization tests.

4.3.3.3 Auditory training procedures

The participants in the training group completed nine training sessions of 30 minutes each. Three stimuli were used for training: broadband noise, 2 kHz low-pass, and 2 kHz high-pass noises 250 ms each. The 2 kHz low- and high- pass noise were chosen to investigate the differences in the relative plasticity of processing ITDs and ILDs (Wright & Fitzgerald, 2001). Each stimulus was played 2 times from each speaker, one time as a test and the second time as a feedback. Audio-visual feedback was provided in which the stimulus was repeated and an LED fixed on the speaker that produced the test stimulus was illuminated. Sound and light were played continuously until the participant

turned his/her head to the target speaker and pressed the control button in their hands. The next stimulus was played 600 ms after the participant returned to the center. Training sessions were scheduled at the participants' convenience, and were separated by 2-5 days.

4.4 Results

Two strategies for data analysis were applied. First, a group-level results analysis was performed. Second, individual participants' results were analyzed using a modified two standard deviation band technique (Portney and Watkins, 2000).

4.4.1. Group level analysis

4.4.1.1 Speech Intelligibility

4.4.1.1.1 Anechoic environment

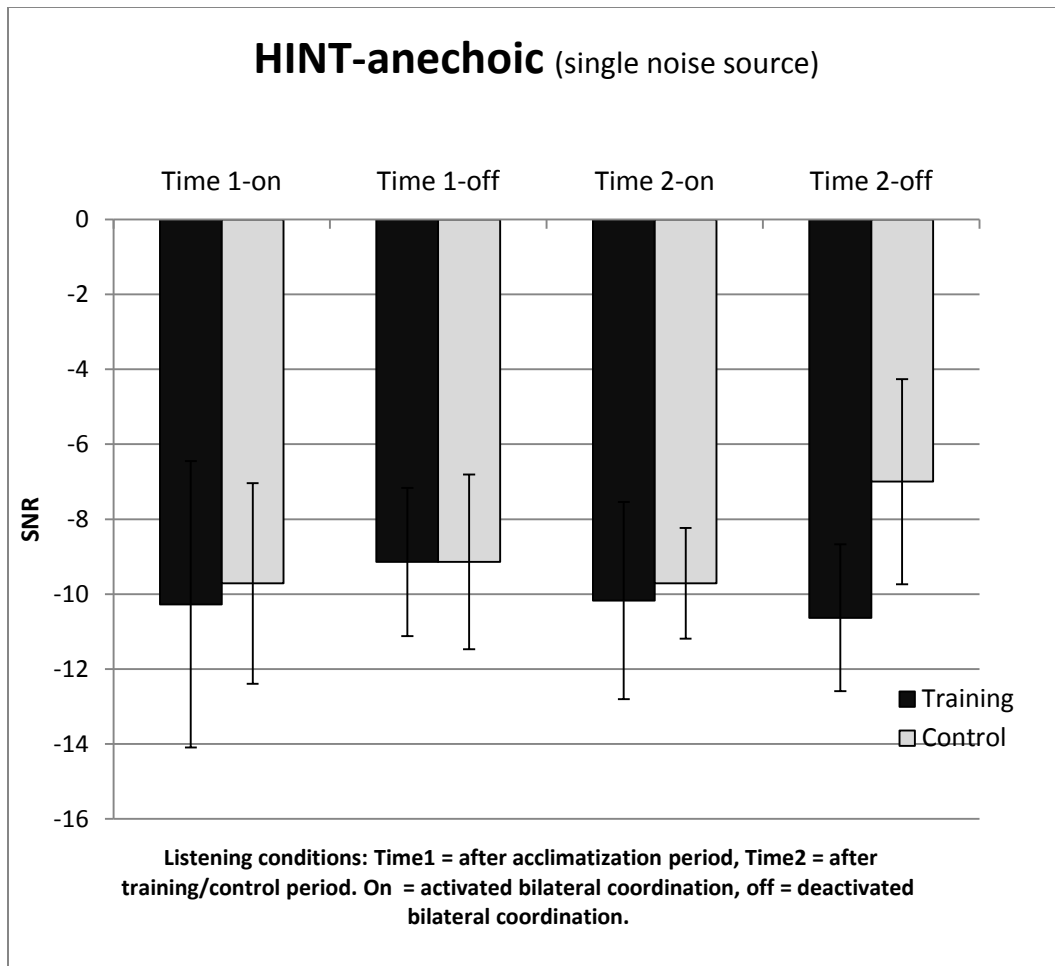
Figure 4-3 displays the average HINT results in the anechoic environment across the study period for both the training and control groups. The error bars represent the standard deviations. HINT was measured three times across the study: immediately after fitting the new hearing aids, after the acclimatization period, and after the training/control period. Participants' performances after the acclimatization and after the training/control period was measured with activation/deactivation of the bilateral coordination. Repeated-measures ANOVA was performed on the anechoic HINT scores with one between-participants factor (whether the participant belonged to the training (1) or the control (2) group), and four within-subject variables (noise angle, coordination condition, acoustic environment, and time period (after acclimatization or after training)).

The results revealed a main significant effect of the angle: $F(1,7) = 15.52, p = 0.006$, where the performance with a single noise source was significantly better than the performance with a diffuse noise source. There was also a significant interaction between the time period, and the between-subject factor (training vs. control group): $F(1,7) =$

21.32, $p = 0.002$, where the performance of the training group was significantly better than the performance of the control group after the training/control period. There was also a significant four-way interaction between the effects of the angle, the coordination, the time period, and the between-subject factor (training vs. control group): $F(1,7) = 8.214$, $P = 0.024$. In order to further investigate this four-way interaction, figures 4-5 and 4-6 illustrate the HINT results for both the training and the control groups at time 1 (after the acclimatization period), and time 2 (after the training/control period). In the anechoic environment, the performance of the training group in the diffuse noise source was significantly better than the performance of the control group with deactivation of the bilateral coordination. Post-hoc analysis for the training group performance using Bonferroni correction did not reveal a statistically significant difference between the training group performance in the anechoic chamber for the diffuse noise source between the post-acclimatization and the post-training performances: $t(18) = 1.2504$, $p > 0.05$.

4.4.1.1.2 Reverberant environment

Repeating the same analysis for the reverberant HINT scores revealed a significant main effect of angle: $F(1,7) = 19.8$, $p = 0.003$, where the performance with a single noise source was significantly better than the performance with a diffuse noise source. There was also a significant interaction between the angle and the between-subject factor (training vs. control group): $F(1,7) = 7.32$, $p = 0.03$, where the training group performance was significantly better than the performance of the control group in the diffuse noise source.



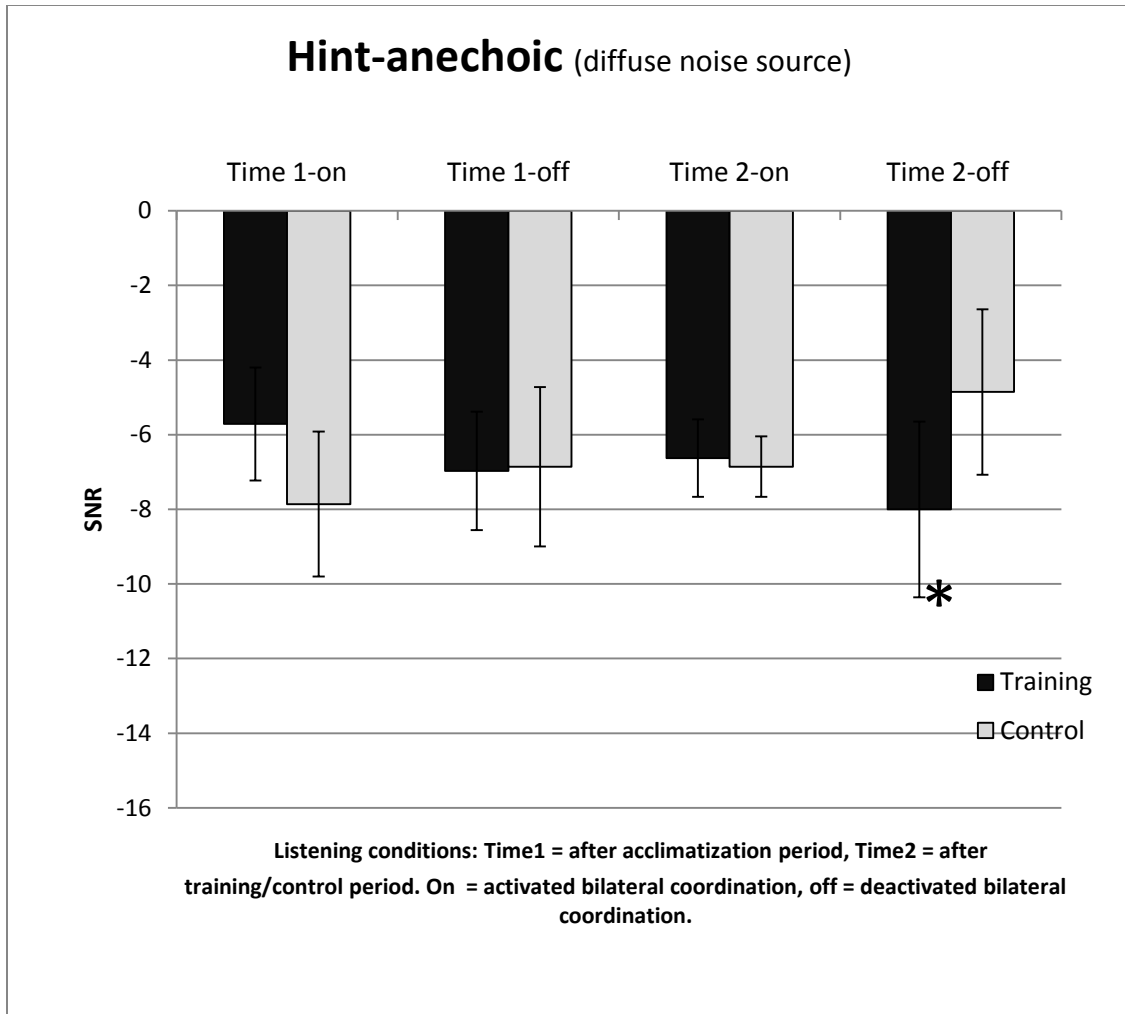
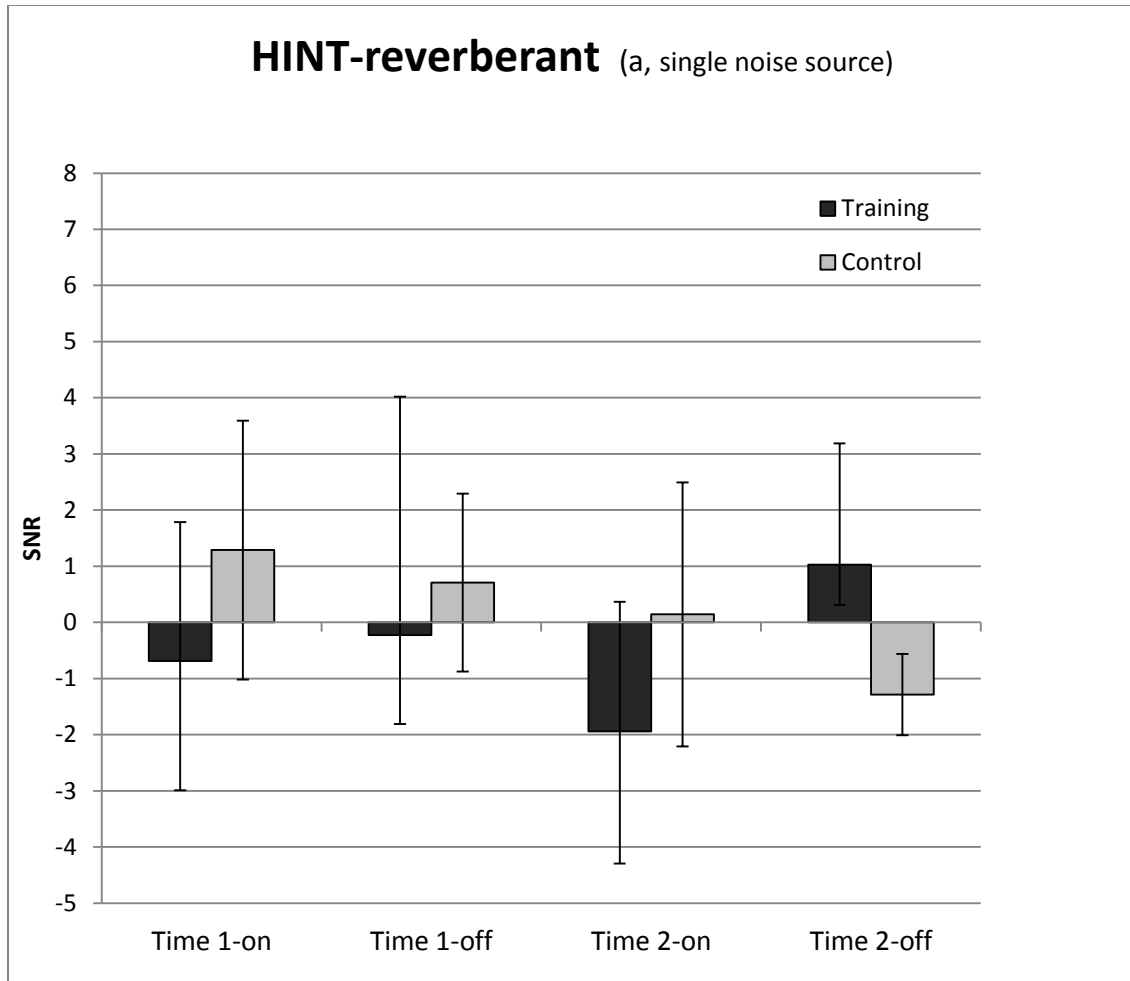


Figure 4-3 a & b: HINT results in the anechoic environment for the single (a) and diffuse (b) noise sources.



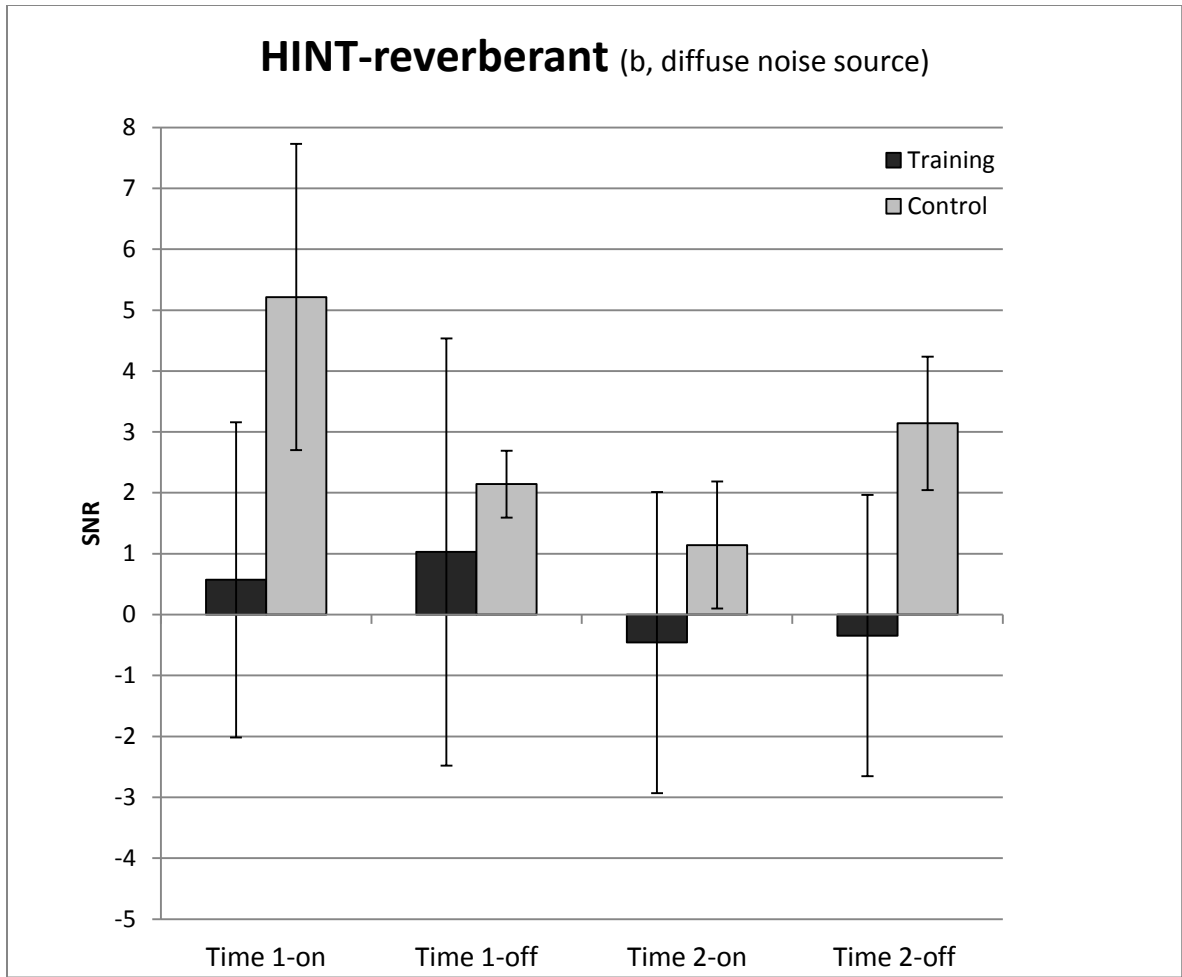


Figure 4-4 a & b: HINT results in the reverberant environment for the single (a) and diffuse (b) noise sources.

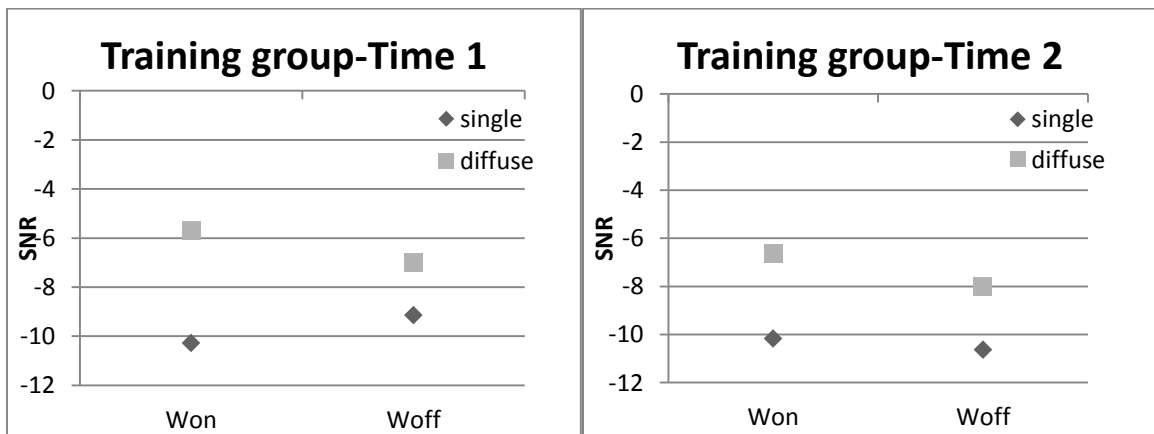


Figure 4-5: HINT results for the training group after acclimatization (Time 1), and after training (Time 2).

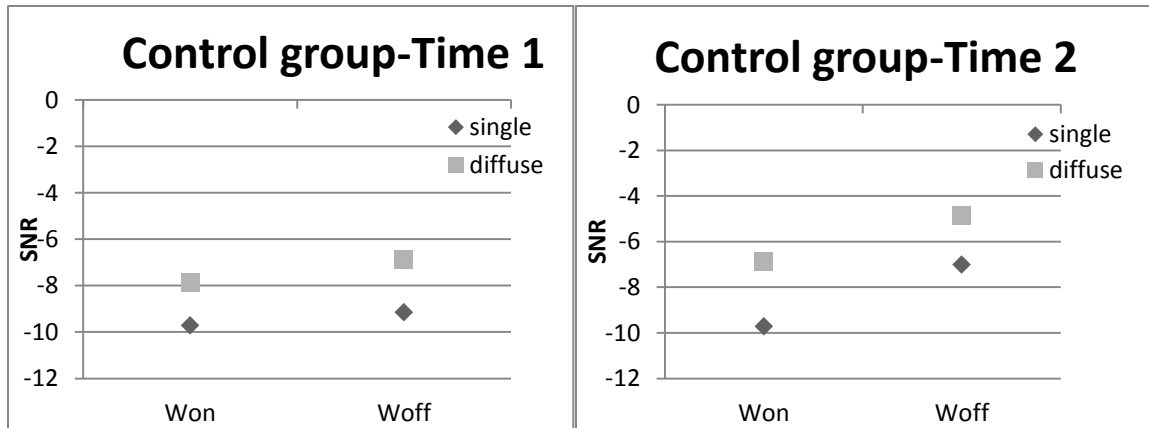


Figure 4-6: HINT results for the control group after acclimatization (Time 1), and after training (Time 2).

4.4.1.2 Sound Localization

Since L/R confusions are very scant in both unaided and aided performance (Vaillancourt et al., 2011), only F/B confusions were analyzed. To calculate the rate of F/B errors, the data set was reduced to those trials on which both target and response were within the ± 67.5 and/or ± 112.5 degree ranges. The number of target/response hemisphere mismatches was computed within this range and then divided by the total number of trials. Figure 4-7 displays the F/B error percentages for both the training and the control groups immediately after fitting the new hearing aids (Oticon Agil-Pro). Figures 4-8 and 4-9 display the F/B error percentages for the control and the training groups, respectively following the acclimatization period, and the training/control period. Repeated-measures ANOVA was performed with one between-subjects factor (whether the participant belonged to the training (1) or the control (2) groups), and four within-subject variables (stimulus, coordination condition, and time period (after acclimatization or after training)). Results revealed a significant main effect of time: $F(1, 7) = 8.032$, $p = 0.025$, where the error rates decreased significantly after the training/control period. There was also a significant main effect of stimulus: $F(3, 21) = 5.35$, $p = 0.022$, where the car horn stimulus resulted in significantly less F/B errors compared with the other three stimuli. Also, a significant interaction between stimulus and time was reported: $F(3, 21) = 4.52$,

$p = 0.021$, where the error rates decreased significantly by the end of the study for both the BBN and LPN stimuli.

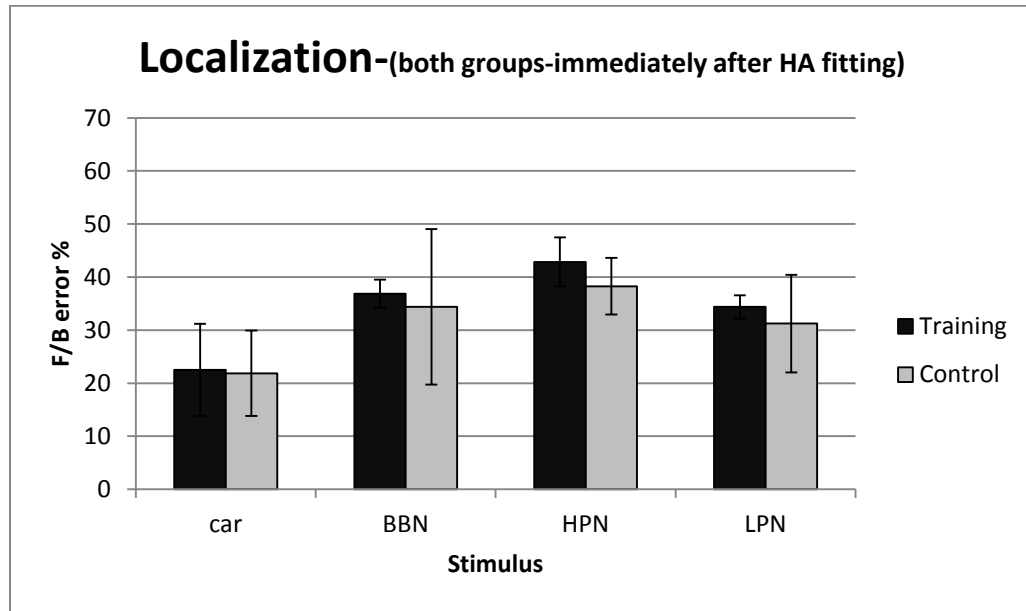


Figure 4-7: F/B error percentages for both the training and the control groups immediately after fitting the new hearing aids (Oticon Agil-Pro). Dark columns represent the training group, and the light columns represent the control group performances.

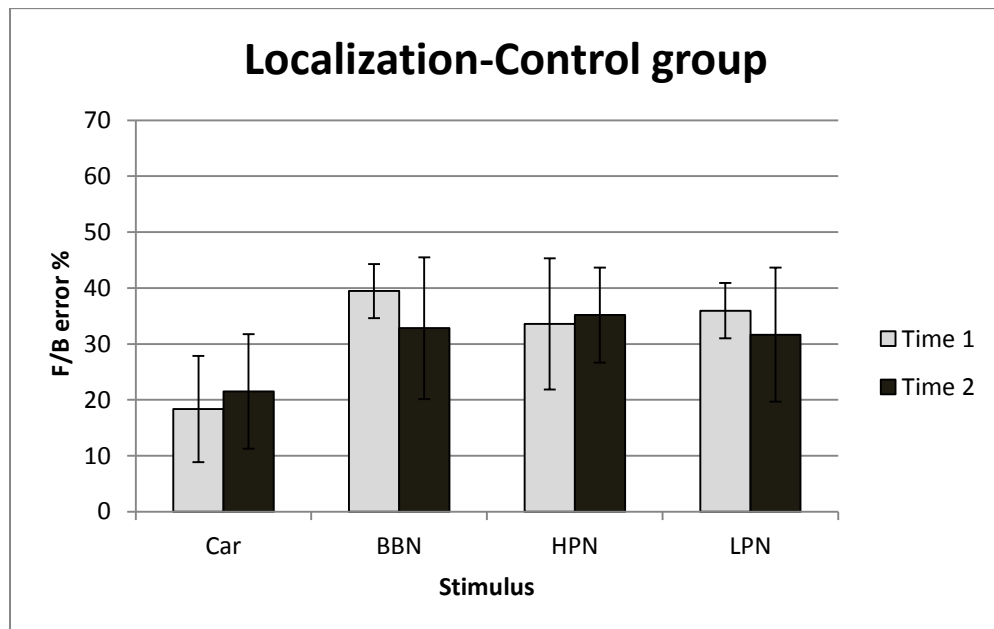


Figure 4-8: F/B error percentages for the control group after Time 1 (the acclimatization period, light columns) and after Time 2 (the control period, dark columns).

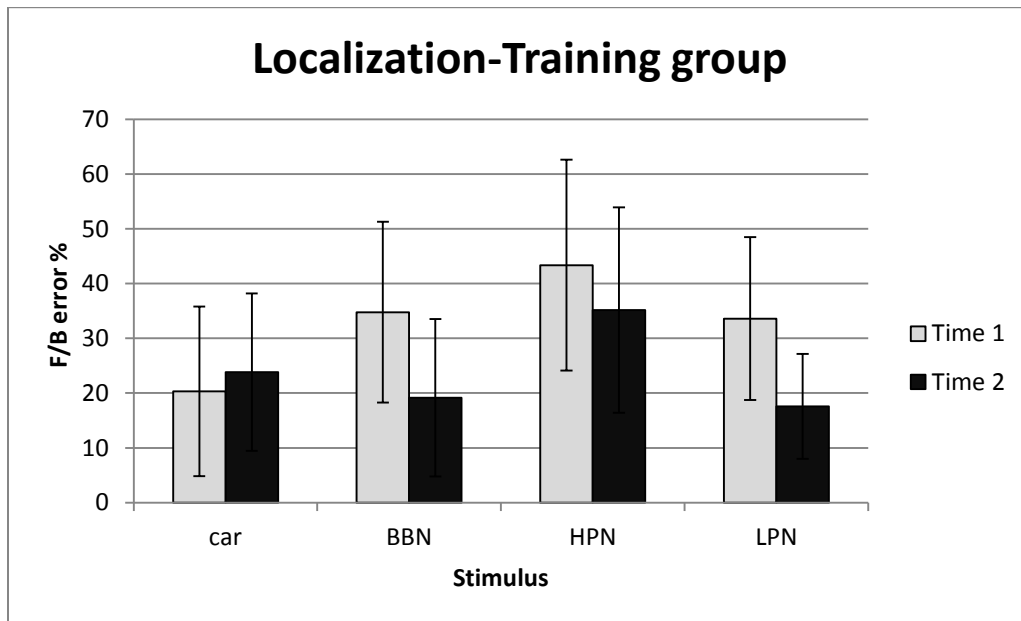


Figure 4-9: F/B error percentages for the training group after Time 1 (the acclimatization period, light columns) and after Time 2 (the training period, dark columns).

4.4.2 Individual level analysis strategies

Individual participant level analyses were conducted for the localization data only. The equation used for this analysis requires a percent correct score, which is not available with the adaptive HINT scores. HINT scores are expressed by thresholds rather than percent correct. Also, the equation requires the number of repetitions, and HINT scores were not repeated. The modified two-standard deviation (2-STDEV) band analyses (Portney and Watkins, 2000) were used for the individual analyses of each participant's data. In order to perform this analysis, a baseline of stable performance was determined. The 2-STDEV band was calculated based on the binomial theorem (Thornton and Raffin, 1978). The following calculation was used to determine the confidence interval based on the binomial theorem, where A is the percent correct score, which represents the percent of the localization trials performances without an F/B error, and B is the number of repetitions of the task (32 times):

$$STDEV = 1.96 \times (100 \times (\sqrt{(A/100 \times (1-A/100))/B}))$$

Confidence intervals were calculated at 0.95 for each participant, where the STDEV value calculated for each start point (participant's performance immediately after HA fitting) from the above equation, then multiplied by 2, to find the $\pm 2STDEV$ band that represent the 0.95 confidence interval, beyond which values are significantly different from that start point.

4.4.2.1 Training group individual results

Participant 1: Figure 4-10 displays the performance of training participant # 1 for the four localization stimuli across the study period. Data points that represent significant improvements are presented in black. This participant's results did not reveal any significant improvement immediately after the acclimatization period. However, these results revealed a significant improvement in the localization performance in the three AT stimuli (broadband, 2 kHz low-pass, and 2 kHz high-pass noises). This improvement was obvious during both activation and deactivation of the bilateral coordination. For the car horn in traffic noise stimulus, there was a significant improvement only with deactivation of the bilateral coordination.

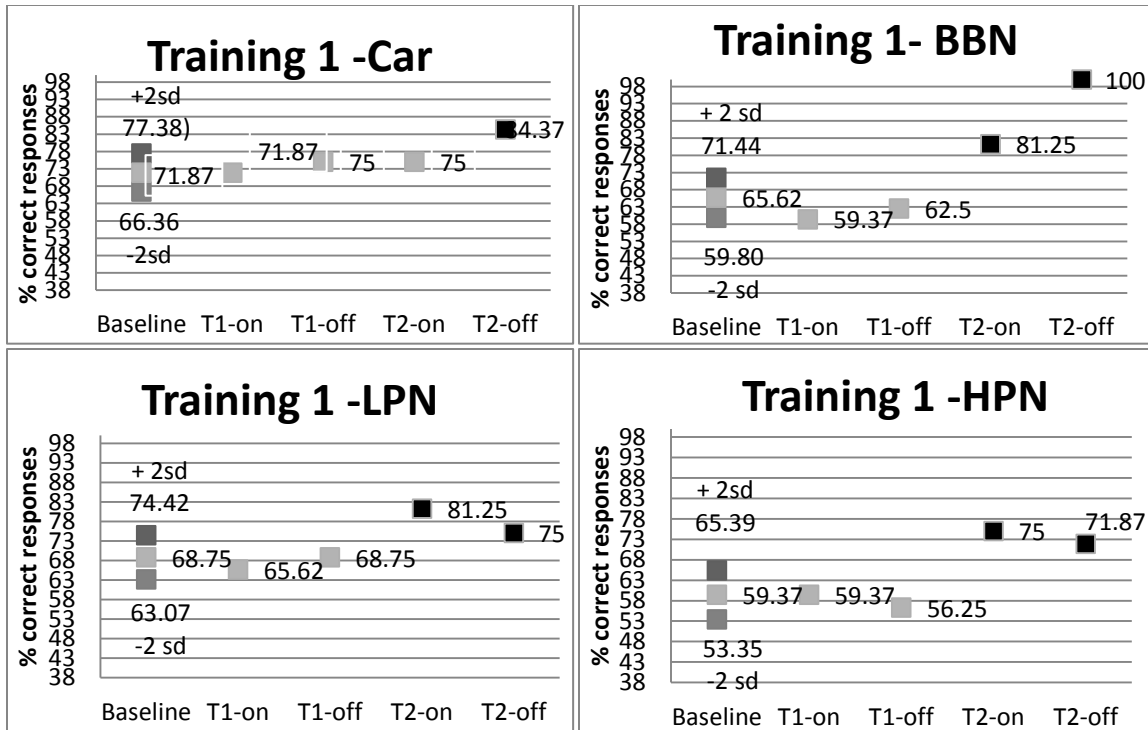


Figure 4-10: The performance of training participant # 1 in the four localization stimuli across the study period. “Baseline” represents the performance immediately after fitting ± 2 standard deviations. “T1-on” is the performance after time-1 (after acclimatization) with activation of the bilateral coordination. “T1-off” is the performance after time-1 (after acclimatization) with deactivation of the bilateral coordination. “T2-on” is the performance after time-2 (after training) with activation of the bilateral coordination. “T2-off” is the performance after time-2 (after training) with deactivation of the bilateral coordination.

Participant 2: Figure 4-11 displays the performance of training participant # 2 in the four localization stimuli across the study period. Data points that represent significant improvements are presented in black. This participant’s results revealed a significant improvement in the localization performance after the acclimatization period in two specific conditions: the car horn in traffic noise, and the low-pass noise, both with deactivation of the bilateral coordination. After AT, a significant improvement was recorded in the broadband noise only with deactivated coordination, in the low-pass and

the high-pass noise for both activated and deactivated coordination, and for the car horn only with activated coordination.

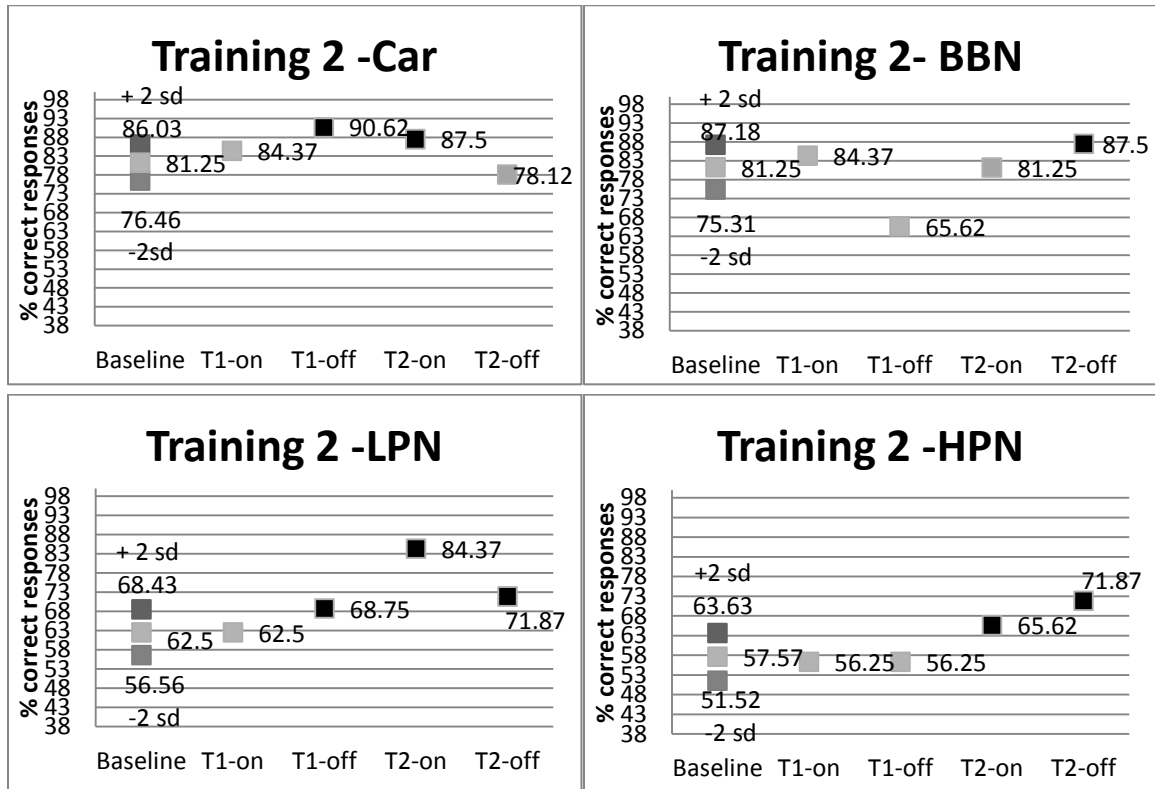


Figure 4-11: The performance of training participant # 2 in the four localization stimuli across the study period. “Baseline” represents the performance immediately after fitting ± 2 standard deviations. “T1-on” is the performance after time-1 (after acclimatization) with activation of the bilateral coordination. “T1-off” is the performance after time-1 (after acclimatization) with deactivation of the bilateral coordination. “T2-on” is the performance after time-2 (after training) with activation of the bilateral coordination. “T2-off” is the performance after time-2 (after training) with deactivation of the bilateral coordination.

Participant 3: Figure 4-12 displays the performance of training participant # 3 in the four localization stimuli across the study period. Data points that represent significant improvements are presented in black. This participant’s results revealed no significantly improved localization performance after the acclimatization period. After AT, a significant improvement for the broadband, low-pass, and high-pass noises was recorded

for both activated and deactivated coordination. The car horn localization did not improve after AT.

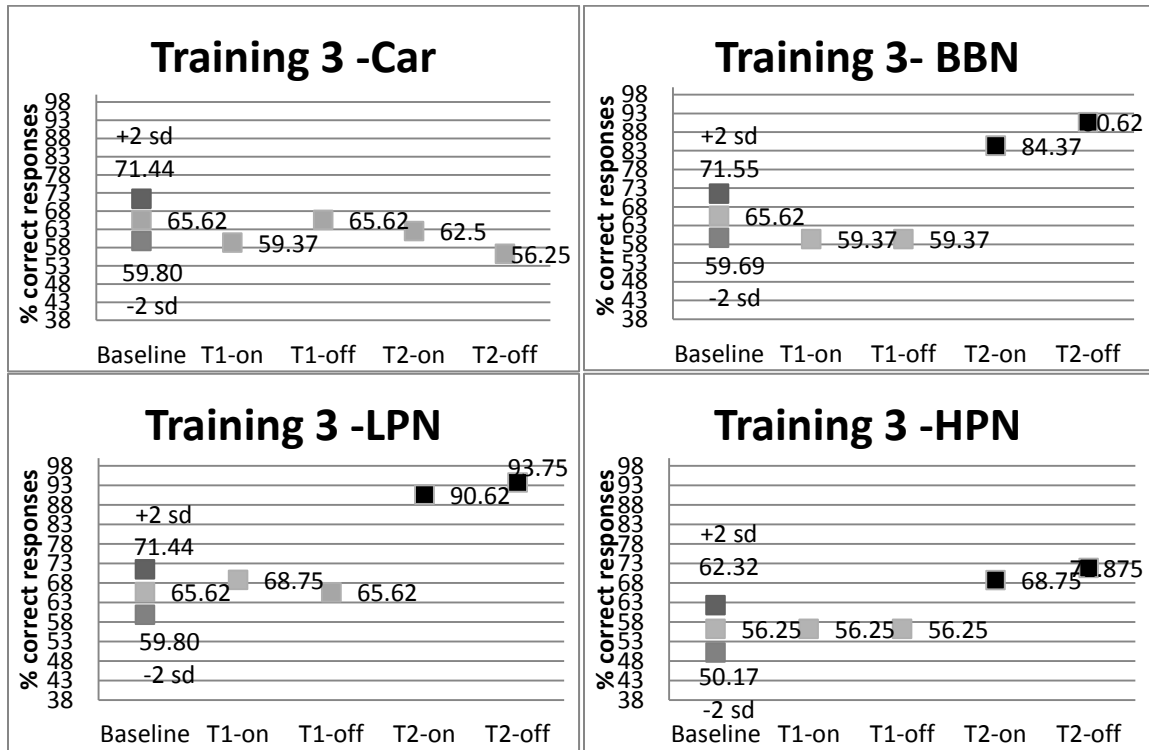


Figure 4-12: The performance of training participant # 3 in the four localization stimuli across the study period. “Baseline” represents the performance immediately after fitting ± 2 standard deviations. “T1-on” is the performance after time-1 (after acclimatization) with activation of the bilateral coordination. “T1-off” is the performance after time-1 (after acclimatization) with deactivation of the bilateral coordination. “T2-on” is the performance after time-2 (after training) with activation of the bilateral coordination. “T2-off” is the performance after time-2 (after training) with deactivation of the bilateral coordination.

Participant 4: Figure 4-13 displays the performance of training participant # 4 in the four localization stimuli across the study period. Data points that represent significant improvements are presented in black. After the acclimatization period, only one condition: the car horn stimulus with deactivated coordination, revealed a significant improvement. After AT, there was a significant improvement in the low-pass noise localization performance only, both with activated and deactivated coordination.

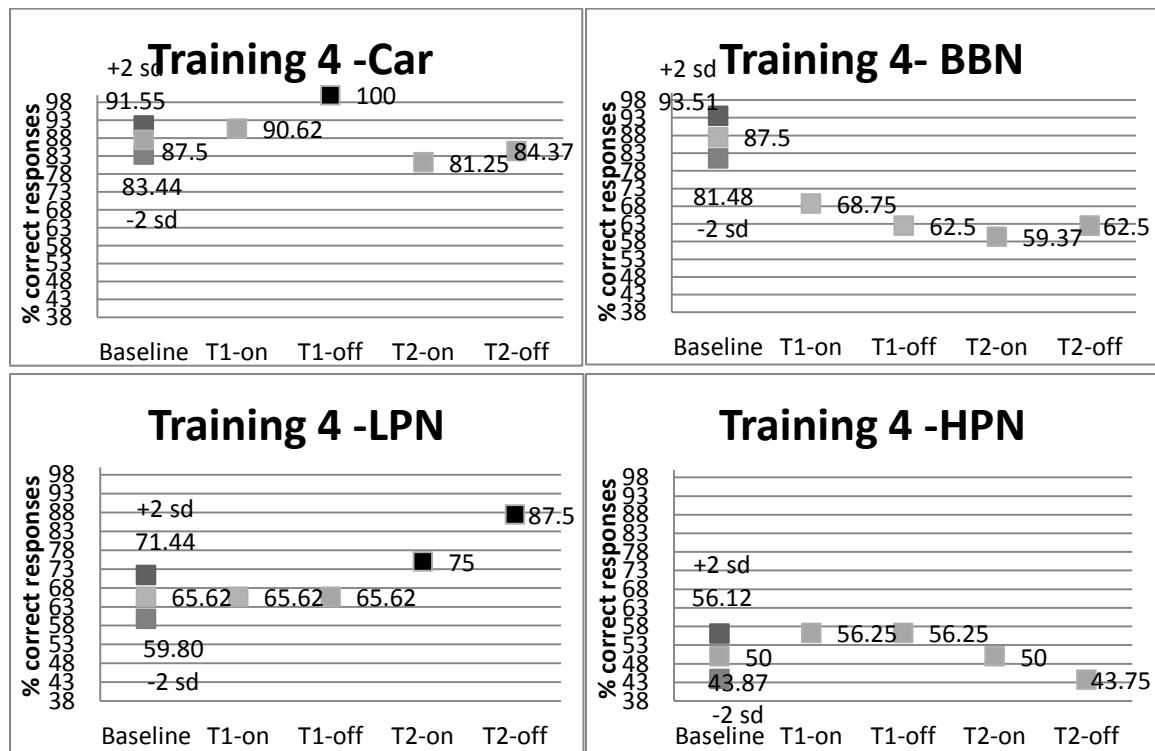


Figure 4-13: The performance of training participant # 4 in the four localization stimuli across the study period. “Baseline” represents the performance immediately after fitting ± 2 standard deviations. “T1-on” is the performance after time-1 (after acclimatization) with activation of the bilateral coordination. “T1-off” is the performance after time-1 (after acclimatization) with deactivation of the bilateral coordination. “T2-on” is the performance after time-2 (after training) with activation of the bilateral coordination. “T2-off” is the performance after time-2 (after training) with deactivation of the bilateral coordination.

Participant 5: Figure 4-14 displays the performance of training participant # 5 in the four localization stimuli across the study period. Data points that represent significant improvements are presented in black. The results of this participant after acclimatization

revealed no significant improvement. After AT, a significant improvement in both the low-pass and the high-pass noise, both with activated and deactivated coordination was recorded.

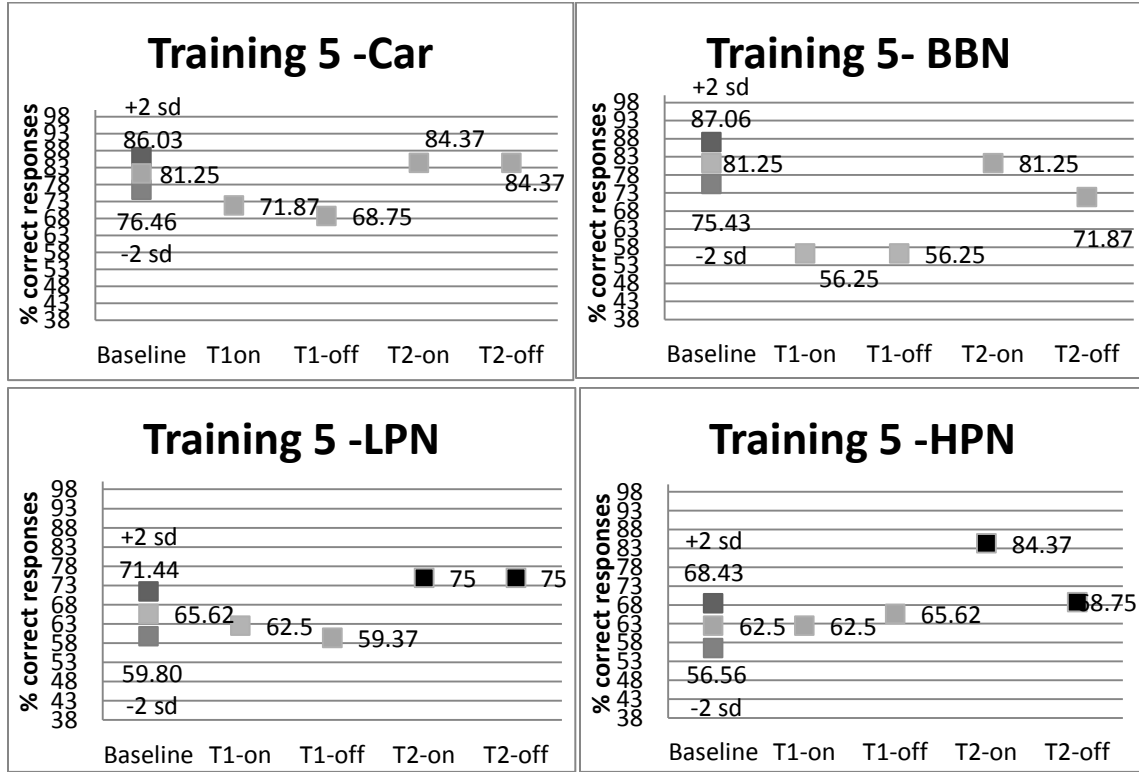


Figure 4-14: The performance of training participant # 5 in the four localization stimuli across the study period. “Baseline” represents the performance immediately after fitting ± 2 standard deviations. “T1-on” is the performance after time-1 (after acclimatization) with activation of the bilateral coordination. “T1-off” is the performance after time-1 (after acclimatization) with deactivation of the bilateral coordination. “T2-on” is the performance after time-2 (after training) with activation of the bilateral coordination. “T2-off” is the performance after time-2 (after training) with deactivation of the bilateral coordination.

4.4.2.2 Control group individual results

Participant 1: Figure 4-15 displays the performance of control participant # 1 in the four localization stimuli across the study period. Data points that represent significant improvements are presented in black. The only significantly improved performance for this participant was recorded for the broadband noise, after the control period, with deactivated coordination.

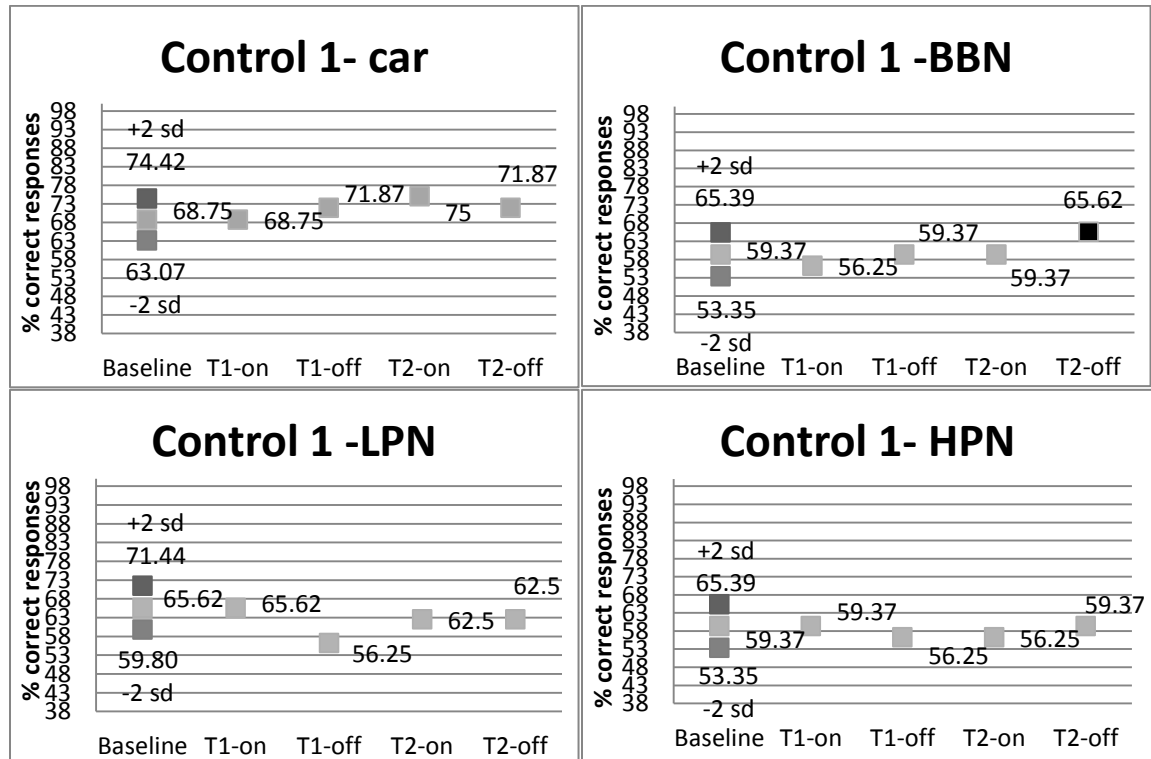


Figure 4-15: The performance of control participant # 1 in the four localization stimuli across the study period. “Baseline” represents the performance immediately after fitting ± 2 standard deviations. “T1-on” is the performance after time-1 (after acclimatization) with activation of the bilateral coordination. “T1-off” is the performance after time-1 (after acclimatization) with deactivation of the bilateral coordination. “T2-on” is the performance after time-2 (after control) with activation of the bilateral coordination. “T2-off” is the performance after time-2 (after control) with deactivation of the bilateral coordination.

Participant 2: Figure 4-16 displays the performance of control participant # 2 in the four localization stimuli across the study period. Data points that represent significant improvements are presented in black. After acclimatization, this participant's results revealed a significant improvement in the car horn stimulus, with both activated and deactivated coordination, in the broadband noise with deactivated coordination, and in the high-pass noise with activated coordination. After the control period, a significant improvement with both activated and deactivated coordination was recorded for both the car horn, and the broadband noise.

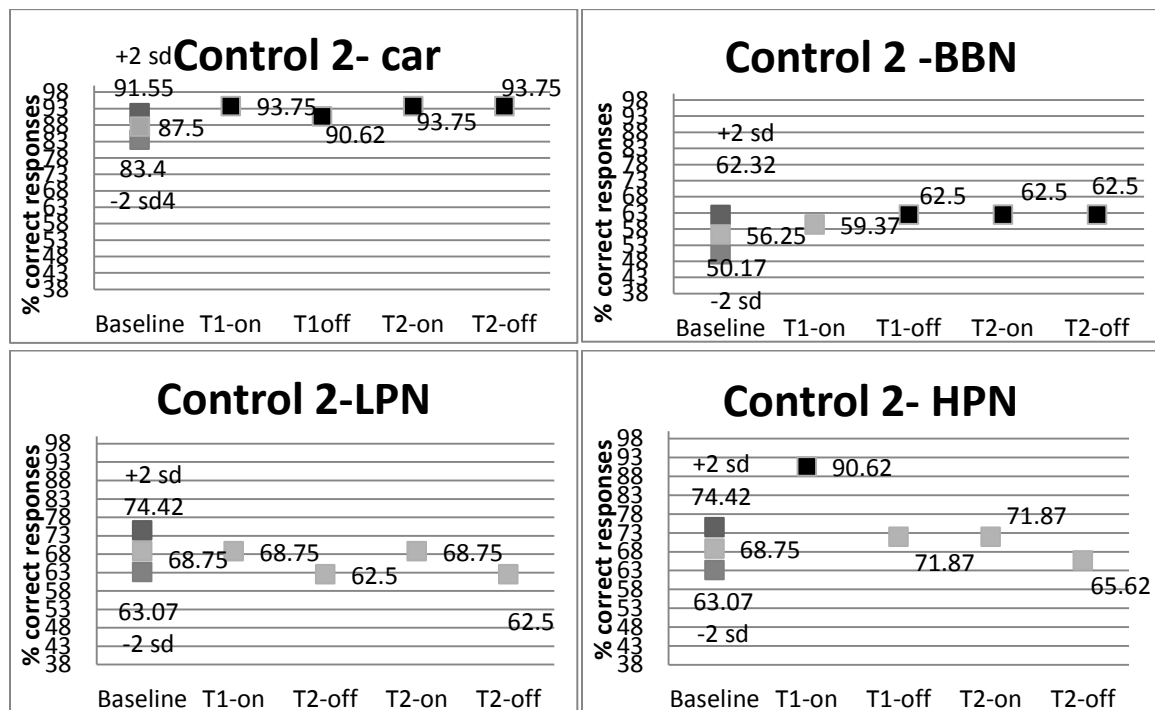


Figure 4-16: The performance of control participant # 2 in the four localization stimuli across the study period. “Baseline” represents the performance immediately after fitting ± 2 standard deviations. “T1-on” is the performance after time-1 (after acclimatization) with activation of the bilateral coordination. “T1-off” is the performance after time-1 (after acclimatization) with deactivation of the bilateral coordination. “T2-on” is the performance after time-2 (after control) with activation of the bilateral coordination. “T2-off” is the performance after time-2 (after control) with deactivation of the bilateral coordination.

Participant 3: Figure 4-17 displays the performance of control participant # 3 in the four localization stimuli across the study period. Data points that represent significant improvements are presented in black. The results of this participant did not reveal any significant improvement after acclimatization or the control period.

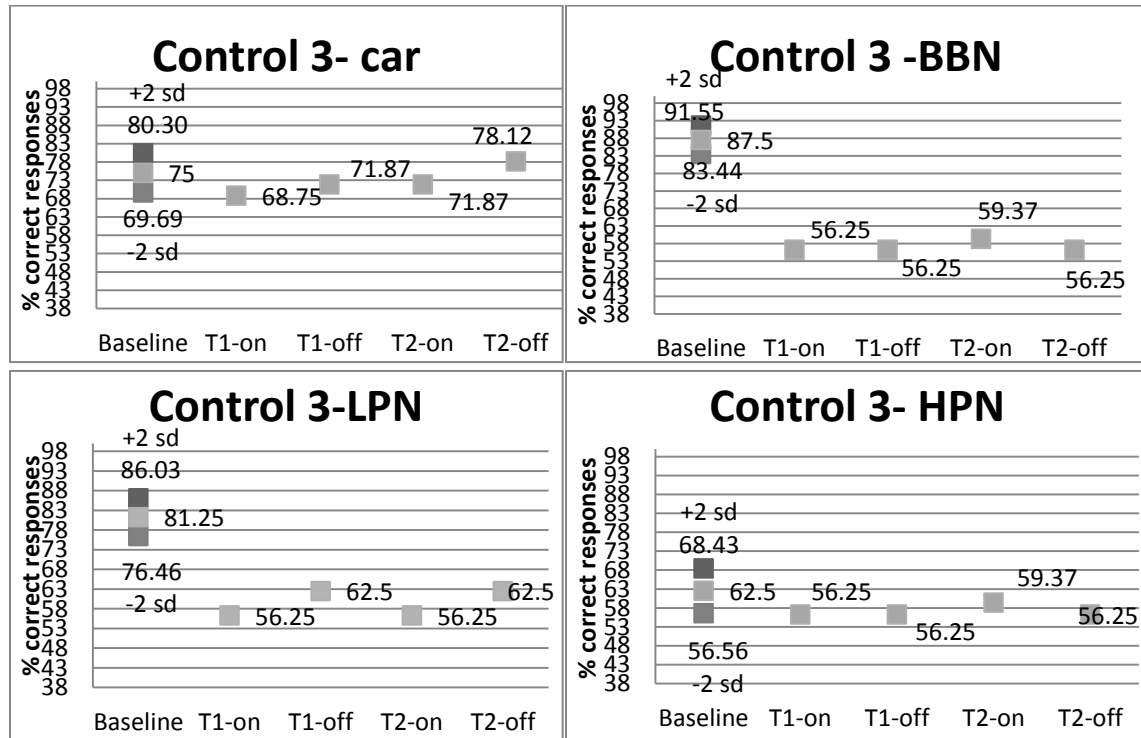


Figure 4-17: The performance of control participant # 3 in the four localization stimuli across the study period. “Baseline” represents the performance immediately after fitting ± 2 standard deviations. “T1-on” is the performance after time-1 (after acclimatization) with activation of the bilateral coordination. “T1-off” is the performance after time-1 (after acclimatization) with deactivation of the bilateral coordination. “T2-on” is the performance after time-2 (after control) with activation of the bilateral coordination. “T2-off” is the performance after time-2 (after control) with deactivation of the bilateral coordination.

Participant 4: Figure 4-18 displays the performance of control participant # 4 in the four localization stimuli across the study period. Data points that represent significant improvements are presented in black. After the acclimatization period, this participant's results revealed a significant improvement in the broadband, low-pass, and high-pass noises, with deactivated coordination. After the control period, the participant's performance in all these three stimuli revealed a significant improvement, both with activated and deactivated coordination. These results suggest an ongoing improvement due to acclimatization.

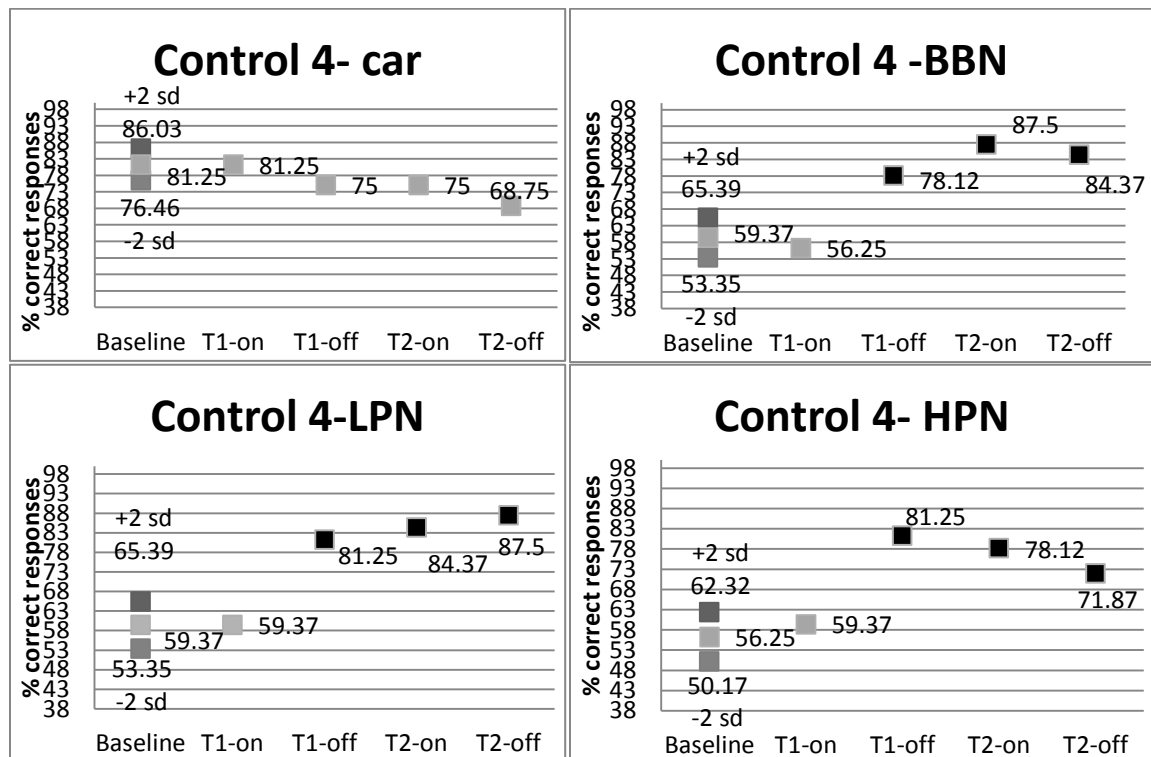


Figure 4-18: The performance of control participant # 4 in the four localization stimuli across the study period. “Baseline” represents the performance immediately after fitting ± 2 standard deviations. “T1-on” is the performance after time-1 (after acclimatization) with activation of the bilateral coordination. “T1-off” is the performance after time-1 (after acclimatization) with deactivation of the bilateral coordination. “T2-on” is the performance after time-2 (after control) with activation of the bilateral coordination. “T2-off” is the performance after time-2 (after control) with deactivation of the bilateral coordination.

4.5 Discussion

The purpose of this study was to examine the interaction between the bilateral coordination between a pair of hearing aids, providing a period for acclimatization, and providing AT for HI listeners. Two auditory tasks were used to evaluate the participants' performances: speech intelligibility in noise using the HINT and a sound localization task. Participants were divided into two groups: training, and a control group, where both groups received a pair of hearing aids that apply bilateral coordination, and were provided one month period to acclimatize to the hearing aids. Following acclimatization, the training group received nine 30-minute sessions of AT for sound localization over a period of one month, while the control group continued to use their hearing aid pairs in their everyday life and did not receive any AT sessions. Two approaches for analysis of the results were used. First, a group level analysis was performed, and revealed a significant improvement in the speech intelligibility in certain acoustic environments with different settings of the bilateral coordination. The localization performance was analyzed using two approaches, ANOVA, and an individual level analysis. ANOVA results revealed a significant effect of time, where the F/B performance improved significantly after the training/control period compared to the performance after the acclimatization period. The car horn stimulus resulted in lower F/B error percent compared to the other three noise burst stimuli. A possible reason for this could be the relatively longer duration of the car horn stimulus (450 ms) compared to the other noise stimuli (250 ms). This longer duration allowed for head movement during the stimulus, thus improving the localization performance in the F/B dimension (Brimijoin et al., 2010; Perrett & Noble, 1997; Wallach, 1939; Zambarbieri et al, 1997). Using the individual level analysis for the localization task, it was apparent that most of the training group experienced a significant improvement especially in the stimuli they were trained for, after AT sessions. The control group results revealed scattered occasional significant improvements in the localization task. The improvement in the AT group performances was not restricted to a particular setting of the bilateral coordination of the hearing aid pair.

The variability in individual performance in both the training and the control groups is in accord with the literature. Not all the individuals receiving AT improve at the same pace or amount and acclimatization might reveal a significant improvement over time with some individuals (Chang et al., 2010; Sweetow and Palmer, 2005). Reasons for this individual variability could be the differences in the auditory system plasticity among different individuals, as well as other factors such as age and cognitive abilities (Sweetow and Palmer, 2005).

Gil et al. (2010) tested the generalizability of AT. The current study also suggests a form of generalizability of AT, whereby AT for sound localization led to a significant improvement in particular settings for speech intelligibility in noise. The possible correlation between localization and the ability to understand speech in noise has been investigated since the early 1950s (Hirsh, 1950). Hirsh hypothesized that the binaural system utilizes the interaural differences between the two ears to locate sound sources and separate signals based on locations. The ability to detect signals may be mediated by localization-based signal segregation Cherry (1953). More recent studies support the idea that localization could be one of the attributes needed to separate multiple auditory sources and help segregate competing speech sounds (Bregman, 1990; Drennan, Gatehouse, & Lever, 2003). Although the difference in performance between the training and the control groups after the training/control period is relatively small (1.75 dB SNR), and the improvement in the training group after training compared to after acclimatization period is about 0.8 dB, these values could be clinically significant, because an improvement of 1 dB SNR accounts for 8-10% improvement in speech intelligibility scores (Ross, 2004).

Further work is needed in this area of research, in order to establish a solid body of evidence suggesting the generalizability of AT, the different factors that might affect the auditory plasticity-and hence the expected amount of improvement after AT, and designing AT programs that use simple auditory tasks (e.g. sound localization), as a

means for improving other more complex domains of auditory performance (e.g. speech intelligibility).

Deactivation of the bilateral coordination did not seem to affect either the localization or the speech intelligibility results. This finding is consistent with the results of the study presented in Chapter 2 with regards to the speech intelligibility results, where activation of the bilateral coordination did not positively or negatively affect the SNR scores of the participants. However, the results of the first study revealed a significant improvement in localization for one stimulus (the car horn). Several reasons could have contributed to the difference in the results between the first and the second studies. One reason could be the activation of the DSP features in the second study. As mentioned, directional microphones significantly improve sound localization performance. It could be concluded that the benefit derived from activation of the directional microphone in the second study outweighed the benefit derived from the activation of the bilateral coordination between the two hearing aids that was tested in the first study. Hence, when the directional microphones were activated in the second study, the performance improved considerably in both conditions, so the significant difference between activation and deactivation of the bilateral coordination became no longer significant. The F/B error percentages support this explanation. In the first study, the error percentage for the car horn stimulus ranged from 34.6% to 41.35%, while in the second study, the F/B error percentage for the car horn stimulus ranged from 21.1% to 23.2%. Another reason that could have accounted for the different results of the activation of bilateral coordination is the relatively lower number of participants in the second study. It is possible that having a larger number of participants in the second study could lead to greater power to identify a significant improvement with the activation of the bilateral coordination. Further research work in this area is required, in order to quantify the benefits gained from activation of the bilateral coordination under different acoustic conditions, and the relative contribution of activating the bilateral coordination compared to the benefits gained by the other DSP features.

Further investigation of the localization results of the training group, it was found that the improvement in localization performance after AT was greatest for both the BBN (15.6% decrease in F/B error percentage) and the LPN (16% decrease in the F/B error percentage), compared to the HPN (8.2% decrease in the F/B error percentage). The HPN stimulus resulted in the highest F/B error percentage both before and after training. Wright and Fitzgerald (2001) found that improvements in ILD-learning occur at a slower rate compared to ITD-learning. This finding is consistent with the results of the second study, where the improvements in BBN and LPN localization performance were more prominent compared to the improvements in HPN localization performance. As discussed in Chapter 1, fair correlation exists between the localization performance in the horizontal plane and HTL, where good low frequency hearing sensitivity was associated with better frontal horizontal plane localization, and good low and mid-to-high frequencies hearing sensitivity was associated with better localization in the lateral horizontal plane (Noble et al., 1994). The findings of Noble et al. can explain these results. Given that the HI listeners had better HTL at low frequencies, the localization performance was generally better when the stimulus had low-frequency components (BBN and LPN), compared to the HPN, where low-frequency components were not available. Other factors could have contributed to the degradation in HPN performance, such as reduced frequency selectivity, reduced intensity and temporal resolution (Arsenault & Punch, 1999; Bronkhorst & Plomp, 1989).

4.6 Summary and Conclusion

The current study investigated the interaction between providing the most recent hearing aid technologies and providing AT for the HI listeners. The results revealed a significant improvement following the administration of AT sessions for most participants who received AT, and a few significant improvements in the control group.

The AT group revealed a significant improvement in certain settings for the speech intelligibility task, suggesting a form of generalizability of AT, where administering AT for certain auditory task can result in an improvement in another auditory task for which AT was not provided.

Although AT training for localization seemed to generalize to an improved speech intelligibility in noise, it did not generalize to an improvement in the localization of the car horn in traffic noise. The reason for this could be that there is no room for further improvement in the car horn localization performance, because the normal hearing individuals performance in the first study (24.17%) is very close to the average performance of both the training and control groups (20.9%) in the second study.

The current study also investigated the effect of activating/deactivating the bilateral wireless coordination between a pair of hearing aids. Although the first study presented in Chapter 2 reported a significant improvement in localization performance in one stimulus with activation of the bilateral coordination, the current study did not duplicate this finding. The reasons for this discrepancy in the results between the two studies can be attributed to the differences in the study designs. While only WDRC was activated in the hearing aids used in the first study, all the DSP features; such as directional microphone, noise cancelling, were activated in the current study in addition to the WDRC. Activating the directional microphone could have considerably improved the F/B localization performance; hence the improvement provided by activating the bilateral coordination became no longer statistically significant. Another reason for this discrepancy could be the relatively lower number of participants who joined the second study compared to the first study.

These results generally agree with the literature in the following points:

- AT can result in a significant improvement in the particular task for which the listener received AT (Sweetow & Palmers, 2005).
- A period as short as 30 minutes, 2-3 times per week for four weeks of AT can result in a significant improvement in the auditory performance.
- Not all the listeners will improve with AT, and they will not improve with the same pace or amount (Saunders, 2012).

- Acclimatization alone can result in a significant improvement in some individuals (Keidser et al., 2006), and this improvement can continue over a period of eight weeks.
- AT in one aspect of auditory performance (sound localization) can be generalized to an improvement in another aspect of auditory performance (speech intelligibility in noise) (Gil et al., 2010). However, for the current study, that was limited to certain settings of the speech intelligibility in noise.
- Directional microphones could provide a significant improvement in the localization performance, because they help resolve the F/B confusion (Boymans & Dreschler, 2000, Quintino et al., 2010, Ricketts & Hornsby, 2003, Tawfik et al. 2010, and Valente & Mispagel, 2008).
- The presence of low-frequency components in an auditory signal improves the localization performance for this particular signal (Noble et al., 1994).
- Auditory signals that are long enough to allow for useful head movements (such as the car horn in the current study, 450 ms), can be localized with less F/B confusion (Brimijoin et al., 2010; Zambarbieri et al., 1997).

4.7 References

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Chapter 5

5. General Discussion

The purpose of this dissertation was to gain better understanding of the effects of modern amplification on the binaural processing, and to investigate the effects of auditory training on some auditory tasks that require binaural processing. The specific goals of the two studies presented in Chapter 2 and Chapter 4 were: 1) to inspect the performance of HI listeners in some auditory tasks that reflect the process of binaural hearing, 2) to measure and evaluate the benefits of a hearing aid feature that enables two (right and left) hearing aids to communicate together in order to synchronize the signal processing features for the aim of preserving the benefits of binaural hearing, 3) to measure and evaluate the benefits of providing a period for acclimatization and auditory training together with the bilateral wireless coordination feature, 4) and to inspect and evaluate the possibility of improvement in one aspect of auditory performance (speech intelligibility in noise) after receiving auditory training in another aspect (horizontal sound localization).

This chapter summarizes the key findings of the two studies presented in Chapter 2 and Chapter 4. The chapter also provides the overall contribution of these two studies to the current literature that looks into the effects of different hearing aid features on the auditory performance of HI listeners, and the effects of auditory training on the auditory performance of HI listeners.

5.1 Overview and main results

The benefits of binaural hearing are well-documented in literature. Amongst the benefits of binaural hearing is improving the ability to localize sounds, and follow conversations in noisy background or among multiple talkers (Devore et al., 2009; Keidser et al., 2006).

SNHL negatively affects horizontal sound localization abilities in the hearing impaired individuals. This degradation is not completely attributable to decreased audibility; other factors contribute to this degradation, such as reduced frequency selectivity, reduced intensity and temporal resolution. HI listeners also have worse speech intelligibility in noise during binaural listening mainly due to their inability to take full advantage of the ILD cue (Arsenault & Punch, 1999; Bronkhorst & Plomp, 1989).

Several studies investigated the effect of different DSP features in the hearing aids on horizontal sound localization. WDRC did not significantly degrade localization. However, when applying short attack time and large compression ratio (CR), this tends to negatively affect the horizontal localization abilities (Keidser et al., 2006; Musa-Shufani et al., 2006). When inspecting the different microphone configurations, it was found that for the L/R localization, the matched microphone mode resulted in a better performance when compared to mismatched microphone modes. However, the presence of a directional microphone in one or both hearing aids would significantly improve the F/B localization performance, obviously due to amplifying sounds from the front more (Keidser et al. 2006 & 2009). Digital noise reduction was found to worsen the L/R performance, and improve the F/B performance, however the differences in RMS errors were small, and the clinical effect of noise reduction on horizontal localization was clinically unimportant (Bentler & Chiou, 2006; Dillon, 2001; Keidser et al., 2006).

The effect of the different DSP features on speech intelligibility in noise was also documented in the literature. WDRC was expected to improve speech intelligibility in noise, but had been shown to either degrade or have no effect on it. Reasons for this could be noise amplification during speech pauses, or decreased effective compression ratio when applied to speech in noise versus speech in quiet (Souza et al., 2000 & 2006). Directional microphones are the only signal processing feature shown to significantly improve speech intelligibility in noise. Even when applied asymmetrically, it provides a significant benefit when compared to omnidirectional microphones (Boymans & Dreschler, 2000; Quintino et al., 2010; Ricketts and Hornsby, 2003; and Tawfik et al., 2010). As for digital noise reduction, there were no consistent findings regarding its

effect, however, it was found to be either of no effect or of minimal positive effect on speech understanding in noise (Boymans & Dreschler, 2000; Tawfik et al., 2010).

The study presented in Chapter 2 focused on testing the improvement in the auditory performance of HI listeners, when the signal processing was coordinated between two hearing aids in a bilateral fitting. The main objective of coordinating the DSP response between the two hearing aids was to preserve the benefits of binaural hearing. Two auditory tasks that reflect the benefits of binaural hearing were tested; horizontal sound localization, and speech intelligibility in noise. These two tasks were tested while enabling the bilateral coordination and while disabling it. Two different hearing aid models that apply bilateral coordination were tested. Testing took place in a hemi-anechoic chamber (Beltone anechoic chamber) at the National Centre for Audiology. The HINT (Hearing In Noise Test) was used to test the speech intelligibility in noise performance, and custom-designed Matlab software was used to test sound localization. Results for sound localization revealed a significant improvement with the activation of the bilateral coordination option with one stimulus (car horn in traffic noise), and an insignificant improvement with another stimulus (the high frequency NBN). Results for speech intelligibility in noise neither improved nor degraded with the activation of the bilateral coordination option. From the results of this study, we concluded that the activation of the bilateral coordination of WDRC between the right and left hearing aids can lead to a significant improvement in sound localization that is limited to certain listening conditions. Some limitations should be considered when interpreting the results of this study. First, the participants were not given time for acclimatization to the new hearing aids. Second, apart from the WDRC, all the DSP features that are normally enabled in the hearing aids, such as directional microphone, noise reduction, and feedback cancellation were disabled. The reason for disabling these features was to avoid contamination of the results by other features. However, all the DSP features were enabled in the second study in order to investigate the effect of coordinating all the features as opposed to independently-working features in the right and left ears, and also to provide a comfortable hearing aid fitting for the participants who were required to use the hearing aids in their everyday life for two months. Taking into consideration the limitation of the first study, the second study (presented in Chapter 4) was designed. Four

weeks were provided for acclimatization with the new hearing aids, after which, a group of participants joined an AT program while the other group did not receive AT. The designed AT program was a localization program, where three (NBN, 2-kHz LPN, and 2-kHz HPN) of the four stimuli used for testing the localization performance were used. Training took place at the same anechoic chamber where testing took place. The AT session lasted for a maximum of 30 min. during the session, each stimulus was played two times from each speaker, first time as a test, followed by a second time as a feedback. The feedback stimulus was played continuously until the participant identified it; with a visual feedback (through an LED on the speaker). Each participant received nine training sessions over a period of four weeks. Performance with and without the bilateral coordination was tested before and after acclimatization, and before and after AT. Participants were tested for sound localization, using the three stimuli used for AT, and a fourth stimulus (car horn in traffic noise), in the anechoic chamber. Participants were also tested for speech intelligibility in noise using the HINT, in both the anechoic chamber and a reverberant chamber. The general results revealed a significant improvement in the localization performance for most participants who received AT, and either a slight improvement or no change in their speech performance. The participants who did not receive AT had either slight improvement or no change in their localization performance, and their speech performance either did not change or exhibited a slight degradation. Deactivation of the bilateral coordination did not seem to affect either the localization, or the speech intelligibility results. This finding is consistent with the results of the study presented in Chapter 2 with regards to the speech intelligibility results, where activation of the bilateral coordination did not positively or negatively affect the SRT of the participants. However, the results of the first study revealed a significant improvement in localization for one stimulus (the car horn). Several reasons could have contributed to the difference in the results between the first and the second studies. One reason could be the activation of the DSP features in the second study. As mentioned above, directional microphones significantly improve the sound localization performance. It could be concluded that the benefit derived from activation of the directional microphone activation in the second study outweighed the benefit derived from the activation of the bilateral coordination between the two hearing aids that was tested in the first study.

Hence, when the directional microphones were activated in the second study, the performance improved considerably in both conditions, so the significant difference between activation and deactivation of the bilateral coordination became no longer significant. The F/B error percentages support this explanation. Another reason could have accounted for the different results of the activation of bilateral coordination is the relatively lower number of participants in the second study. While twelve participants joined the first study, only nine participants joined the second study. It is possible that having a larger number of participants in the second study could lead to a significant improvement with activation of the bilateral coordination.

In addition to investigating the effects of activating the bilateral coordination between a pair of hearing aids, and the effects of a designed sound localization AT on the auditory performance in both localization and speech intelligibility in noise, several other findings were reported in both studies, which replicate previous findings in the literature.

First, it was reported in both studies that the localization performance, expressed by resolving the F/B confusion, for the car horn in traffic noise was generally better than the localization performance for the noise-burst stimuli. This finding cannot be attributed to the frequency component alone, because in the second study, a broad-band noise stimulus was present, and the F/B error for this stimulus was higher than the F/B error for the car horn stimulus. The reason is most probably the relatively longer duration of the car horn stimulus (450 ms) compared to the NBN stimulus in the first study (200 ms), or the three noise-bursts stimuli (BBN, LPN, and HPN) in the second study (250 ms). This longer duration allowed for useful head movement that helped resolving the F/B confusion (Brimijoin et al., 2010; Zambarbieri et al, 1997).

Another finding in the second study was that the localization performance for the BBN and the LPN was better, compared to the HPN localization performance. The improvement in localization performance after AT for these two stimuli, was greater than the improvement in the HPN stimulus. This finding can be explained by the correlation between the HTL and the localization performance (Noble et al., 1994). Since the HI

participants generally had better HTL at the low frequencies, localizing stimuli that had low-frequency component was more convenient for the HI participants.

5.2 Contribution to literature and future research

The studies presented in this dissertation are among the first studies that investigated the benefits of bilateral coordination of the right and left hearing aids DSP features. The first study reported a significant improvement in sound localization for one of the two stimuli used, where the second study did not report a significant change in localization performance, perhaps due to activation of the DSP features that were disabled in the first study. These findings help both the audiologist and the hearing aid user better understand that the benefits of the bilateral coordination between the hearing aids pair is limited to sound localization, with no significant effect on speech intelligibility in noise. Further research work where different stimuli/hearing aids settings are tested is needed in order to have clearer insight on the benefits of coordinating the DSP features in a pair of hearing aids.

The second study is conducted to investigate the effect of AT on the auditory performance, and the first study to test the generalizability of AT for sound localization to an improvement in speech intelligibility. A significant improvement in the localization performance after receiving the localization AT, and a significant improvement in speech intelligibility in noise that was limited to the anechoic environment were reported. These findings replicated and supported previous findings (e.g. Gil et al., 2010) and highlighted the importance of AT as a useful tool to improve the auditory performance of the HI listeners.

Chapter Three highlighted both the benefits of providing AT to the HI listeners who plan on purchasing hearing aids, and the lack of studies that investigate the benefits of AT. Chapter Three also explained that only a small percentage of audiologists provide AT for the HI listeners due to several factors such as the limited clinical time and the subject compliance. Several speech training programs are available, however they require a

clinical setting where an audiologist or another person helps the listener. Providing an evidence for improvement in speech intelligibility in noise after AT for sound localization, provides a basis for creating AT software that can be administered at home without the need of an audiologist or another person to help the HI listener administer the training session. Such AT software will depend on virtual auditory space (VAS) technique to simulate sounds perceived from different locations in the environment. Providing an AT software that focuses on sound localization rather than the speech would have several advantages: 1) it would be useful and suitable for non-native English speakers, who may find it difficult to follow English speech-based training protocols. 2) Because the task of locating sounds is easier and less stressful than understanding speech, it is very probable that the participants' compliance will increase, and hence their auditory skills and performances will improve.

5.3 Strengths and limitations

5.3.1 Strengths

The strength in the first study is testing more than one hearing aid model that applies the bilateral coordination of the signal processing features. This helped confirm the results and compare the performance with these two hearing aids. Disabling the DSP features in the first study, as well as providing blocked earmolds ensured that the benefits gained by activating the wireless synchrony were not contaminated by other factors. Testing speech intelligibility in noise using the standard HINT setting, where the speech is always presented from the front, simulates the most commonly encountered everyday-life situations.

The second study investigated several theories. Alongside comparing the auditory performance with and without activating the bilateral coordination of the two hearing aids, the effects of auditory acclimatization and the effects of providing AT were investigated. The effect of the acoustic environment on speech intelligibility was also investigated. The participants were provided a suitable period for acclimatization and for

training/control. The study was conducted over a period of eight weeks, four weeks of acclimatization, and four weeks of training/control period. Testing for localization using several (four) stimuli, with different frequency components and durations provided clearer information on the relations between localization, HTL, and the head movement. Testing for speech intelligibility in noise was conducted in two different acoustic environments: anechoic and reverberant, to better represent the different acoustic environments encountered in everyday-life situations.

5.3.2. Limitations

In interpreting the results of the two studies presented in this dissertation, several limitations should be considered. For the first study, and in order to limit any localization benefit to the bilateral coordination, several DSP features in the hearing aid were disabled, such as the directional microphone, feedback cancellation, and noise reduction. Completely blocked earmolds were used to ensure that the benefit gained was not due to the pinna spectral shape cues. In a regular fitting, usually most of DSP features would be enabled, and vented molds would be provided. The use of closed molds can negatively affect localization performance because it blocks the access to the natural undistorted ITD cues, and hence the listener depends on the amplified ITDs, which could be affected by the hearing aids' signal processing features (Noble et al. 1998). Also, the HINT setting used in the study is the standard HINT configuration, where speech comes always from the front. This setting did not allow for testing the hearing aid performance when speech is coming from different locations.

For the second study, individual performances were tracked and compared to find the amount of improvement/degradation in performance. The relatively low number of participants is a potential reason for not extracting significant differences between the different hearing aid settings (activation/deactivation of the bilateral coordination), and between the training and control groups.

The results of both studies are confined to the specific situations, stimuli, and settings tested.

5.4 Conclusions

The results of the two studies presented in this dissertation provide guidance to audiologists and hearing aid users on the expected benefits from applying bilateral coordination of the DSP between a pair of hearing aids with regards to horizontal sound localization and speech intelligibility in noise.

It is recommended that the audiologists clarify to the hearing impaired listeners that the expected improvement with activation of the bilateral synchronization is limited. There is no statistically significant difference in HINT performance, which represent speech intelligibility in noise performance, in the two studies presented in this dissertation. The benefit derived from activating the bilateral coordination in horizontal localization is limited to one stimulus (the car horn) in the first study. It could be concluded that the benefit derived from directional microphones outweighed the benefit derived from activating the bilateral coordination.

It is also important to highlight the benefit derived from the AT. Receiving AT for a relatively short duration can result in a significant improvement in the localization performance, and can generalize to an improvement in speech intelligibility in noise under certain conditions. It is recommended that the audiologists provide information regarding the different AT options available to the hearing impaired listeners.


The results also provide longitudinal tracking of the auditory performance for two months following amplification in horizontal sound localization and speech intelligibility in noise. The results demonstrate the potential improvement in auditory performance following a relatively short period of AT, and the potential generalizability of AT in one aspect to other aspects of auditory training. In accord with previous literature, HI listeners had fewer F/B errors when low-frequency components were available. Fewer F/B errors were also reported for localization stimuli with duration long enough to allow for useful head movement.

5.5 References

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Appendix A



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Use of Human Subjects - Ethics Approval Notice

Principal Investigator: Dr. V. Pársa
Review Number: 15039E **Review Level:** Expedited
Review Date: April 9, 2008

Protocol Title: Evaluation of speech intelligibility, sound quality and localization abilities with hearing aids using binaural wireless technology.

Department and Institution: Communication Sciences & Disorders, University of Western Ontario
Sponsor: NATIONAL SCIENCE AND ENGINEERING RESEARCH COUNCIL
Ethics Approval Date: June 18, 2008 **Expiry Date:** December 31, 2009

Documents Reviewed and Approved: UWO Protocol, Letter of Information and Consent, Poster.

Documents Received for Information:

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced study on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the HSREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of monitor, telephone number). Expedited review of minor change(s) in ongoing studies will be considered. Subjects must receive a copy of the signed information/consent documentation.

Investigators must promptly also report to the HSREB:

- a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
- b) all adverse and unexpected experiences or events that are both serious and unexpected;
- c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to this office for approval.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

Chair of HSREB: Dr. John W. McDonald

Ethics Officer to Contact for Further Information

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UWO HSREB Ethics Approval - Initial
V.2007-10-12 (rptApprovalNoticeHSREB_Initial)

15039E

Page 1 of 1



Use of Human Participants - Ethics Approval Notice

Principal Investigator: Dr. Vijay Parsa
File Number: 102252
Review Level: Delegated
Approved Local Adult Participants: 16
Approved Local Minor Participants: 0
Protocol Title: Evaluation of the Sound Localization and Speech Discrimination abilities with Hearing Aids Using Binaural Wireless Technology and Auditory Training - 18762E
Department & Institution: Health Sciences/Communication Sciences & Disorders, Western University
Sponsor:
Ethics Approval Date: May 11, 2012 **Expiry Date:** August 31, 2012
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Addition of Co-investigator	Paula Folkeard has been added as a Collaborator and for data collection.	

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices, Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the University of Western Ontario Updated Approval Request Form.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

The Chair of the HSREB is Dr. Joseph Gilbert. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

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Appendix B

Pure Tone thresholds for the HI participants- chapter 2(Left & Right ears).

subject/freque ncy (kHz)	Left						Right					
	.25	.5	1	2	4	8	.25	.5	1	2	4	8
1	40	55	60	60	65	NR	40	55	60	60	95	95
2	45	50	60	60	55	65	50	60	65	65	60	80
3	35	35	45	60	50	55	25	25	40	55	60	55
4	30	45	55	60	60	70	35	45	55	60	60	65
5	30	30	35	45	60	60	35	40	40	55	65	65
6	10	15	30	35	50	65	15	20	35	30	55	70
7	55	60	65	70	70	80	65	60	60	65	70	75
8	10	15	30	35	50	65	15	20	35	30	55	70
9	55	60	65	70	70	80	65	60	60	65	70	75
10	25	35	50	55	55	NA	25	35	45	50	60	NA
11	40	50	55	55	55	NA	45	50	55	55	50	NA
12	55	55	60	70	60	NA	60	70	55	65	70	NA

Appendix C

HINT scores (in dB SNR) for NH and HI listeners – chapter 2

condition angle	90°-mean	90°-s.d.	270°- mean	270°-s.d.	Both-mean	Both-s.d.
unaided	-11.54	1.45	-11.79	0.92	-9.13	1.99
Ha1-on	-11.36	3.32	-12.66	3.38	-8.78	2.69
Ha1-off	-12.23	2.32	-13.32	3.42	-8.60	1.75
Ha2-on	-10.78	3.21	-11.43	2.91	-7.41	4.14
Ha2-off	-10.60	1.81	-11.42	2.51	-6.14	5.81

HINT scores (in dB SNR) for NH individuals – chapter 2

condition angle	90°-mean	90°-s.d.	270°-mean	270°-s.d.	Both-mean	Both-s.d.
unaided	-1.69	6.75	-2.62	6.26	-2.14	4.9
Ha1-on	-6.42	2.70	-5.91	3.42	-3.02	2.63
Ha1-off	-8.19	2.95	-6.29	3.40	-3.75	2.79
Ha2-on	-6.69	3.29	-5.41	3.46	-5.18	3.53
Ha2-off	-5.96	3.65	-5.70	4.07	-4	3.98

HINT scores (in dB SNR) for HI individuals – chapter 2

Appendix D

Means and standard deviations of the localization data for NH listeners – chapter 2

Condition stimulus	Traffic-mean	s.d.	highfrequency-mean	s.d.
unaided	12.5	4.9	17.70875	7.7
ha1w.on	17.44875	5.6	22.65625	5
ha2w.on	20.8325	4.9	22.1375	4
ha1w.off	21.095	7.9	21.615	8.1
ha2w.off	21.355	6	22.91625	6.3

F/B error percentages – NH listeners

Condition stimulus	Traffic-mean	s.d.	High Frequency-mean	s.d.
unaided	1	0.06	1.02	0.06
HA#1-on	0.95	0.11	0.95	0.15
HA#1-off	0.92	0.12	0.99	0.09
HA#2-on	0.94	0.12	0.87	0.17
HA#2-off	0.88	0.15	0.93	0.2

Lateral angle gain – NH listeners. The values represent a ratio (slope of linear fit) between target and response in degree azimuth. A value of 1 represents perfect performance; a value less than 1 represents a response compressed towards the midline; and a value more than one represents a response further than midline compared to the target (overshooting).

Condition stimulus	Traffic-mean	s.d.	High Frequency-mean	s.d.
unaided	-0.56	2.91	-1.3	3.38
HA#1-on	0.06	8.04	-0.34	3.32
HA#1-off	0.79	9.2	2	5.01
HA#2-on	-0.3	10.36	-1.02	6.04
HA#2-off	-3.78	12.43	-1.74	5.01

Lateral angle bias- NH listeners. Bias represents the shift (in degree azimuth) in lateral response either towards the left (negative values) or right (positive values) hemisphere.

Condition stimulus	Traffic	s.d.	High Frequency	s.d.
unaided	13.67	2.25	17.55	6.17
HA#1-on	13.69	1.99	16.06	4.33
HA#1-off	12.56	2.9	15.39	7.46
HA#2-on	15.91	3.5	17.5	5
HA#2-off	14.46	1.41	16.11	5.54

Lateral angle scatter – NH listeners. Scatter represents the root-mean-square deviation (in degree azimuth) of the response lateral angles from the values predicted by the regression

Appendix E

Means and standard deviations of the localization data for HI listeners –chapter 2

Condition stimulus	Traffic-mean	s.d.	highfrequency-mean	s.d.
ha1w.on	34.63	9.8	45.54	8.46
ha2w.on	39.41	10.59	45.77	4.93
ha1w.off	41.35	13.1	50.11	5.59
ha2w.off	41.35	8.35	45.93	4.77

F/B error percentages – HI listeners

Condition stimulus	Traffic-mean	s.d.	High Frequency-mean	s.d.
HA#1-on	1.04	0.06	0.88	0.19
HA#1-off	1.01	0.09	0.89	0.22
HA#2-on	0.98	0.14	0.81	0.22
HA#2-off	1	0.13	0.77	0.19

Lateral angle gain – HI listeners. The values represent a ratio (slope of linear fit) between target and response in degree azimuth. A value of 1 represents perfect performance; a value less than 1 represents a response compressed towards the midline; and a value more than one represents a response further than midline compared to the target (overshooting).

Condition stimulus	Traffic-mean	s.d.	High Frequency-mean	s.d.
HA#1-on	-0.23	9.88	2.89	11.58
HA#1-off	-0.43	10.94	-1.29	9.74
HA#2-on	-1.89	14.11	-1.79	11.6
HA#2-off	-4.22	7.42	-2.78	10.95

Lateral angle bias- HI listeners. Bias represents the shift (in degree azimuth) in lateral response either towards the left (negative values) or right (positive values) hemisphere.

Condition stimulus	Traffic	s.d.	High Frequency	s.d.
HA#1-on	21.46	6.35	21.2	5.73
HA#1-off	20.07	3.81	21.08	4.19
HA#2-on	22	5.75	18.97	3.84
HA#2-off	20.64	7.1	19.17	5.56

Lateral angle scatter- HI listeners. Scatter represents the root-mean-square deviation (in degree azimuth) of the response lateral angles from the values predicted by the regression.

APPENDIX F

Pure Tone thresholds (in dB HL) for the training group- chapter 4 (Right & Left ears).

Right ear	.25 kHz	.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	6 kHz	8 kHz
participant								
1	35	40	40	35	35	40	60	95
2	20	25	30	45	55	65	75	75
3	15	20	20	45	50	60	60	60
4	15	20	30	55	70	70	75	80
5	20	25	20	25	50	50	60	45

Left ear	.25 kHz	.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	6 kHz	8 kHz
participant								
1	40	35	45	50	55	50	75	95
2	20	25	30	55	60	70	75	75
3	15	15	15	35	45	50	55	55
4	20	30	25	65	65	60	70	75
5	10	20	25	25	40	55	65	65

Appendix G

Pure Tone thresholds (in dB HL) for the control group-chapter 4 (Left & Right ears).

Right ear	.25 kHz	.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	6 kHz	8 kHz
participant								
1	25	40	40	35	35	45	70	70
2	10	10	10	30	70	65	50	65
3	25	35	50	55	55	55	55	60
4	20	20	35	50	60	65	60	75

Left ear	.25 kHz	.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	6 kHz	8 kHz
participant								
1	25	35	35	25	25	40	70	75
2	10	15	10	55	70	65	55	65
3	25	35	45	45	50	55	60	70
4	15	20	40	45	65	60	70	75

Appendix H

Anechoic HINT scores (in dBSNR) for the training and control groups, respectively-
chapter 4

participant	90°-un	diffuse-un	90°-new-ON	diffuse-new-ON	90°-acc-ON	diffuse-acc-ON	90°-acc-off	diffuse-acc-off	90°-train-on	diffuse-trian-on	90°-train-off	diffuse-train-off
1	-5.14	-4.75	-6.29	-6.29	-4.5	-4	-7.43	-8	-5.71	-5.71	-7.43	-8
2	-3.43	-4.57	-9.14	-7.43	-9.14	-5.14	-8.57	-6.29	-10.29	-5.71	-11.43	-6.29
3	-9.14	-6.29	-10.29	-4.57	-14.86	-6.29	-8.57	-4.57	-12.57	-6.29	-10.29	-6.29
4	-14.29	-8	-13.14	-9.14	-11.43	-8	-8.57	-8.57	-11.43	-8	-11.43	-12
5	-4.57	-7.43	-10.86	-7.43	-11.43	-5.14	-12.57	-7.43	-10.86	-7.43	-12.57	-7.43

participant	90°- un	diffuse- un	90°- new- ON	diffuse- new- ON	90°- acc- ON	diffuse- acc-ON	90°- acc- off	diffuse- acc-off	90°- train- on	diffuse- train-on	90°- train- off	diffuse- train-off
1	-9.71	-8.57	-9.14	-9.14	-10.29	-6.29	-8.57	-7.43	-8	-5.71	-4.57	-5.14
2	-10.29	-5.14	-8.57	-5.71	-13.14	-10.29	-12.57	-6.86	-11.43	-7.43	-10.86	-6.86
3	-6.86	-7.43	-8	-4.57	-8.57	-8.57	-8	-9.14	-10.29	-7.43	-6.86	-5.71
4	-10.29	-5.14	-10.86	-8	-6.86	-6.29	-7.43	-4	-9.14	-6.86	-5.71	-1.71

Appendix I

F/B error percentage for the training and the control groups, respectively- chapter 4

Subject	N-on-car	N-on-BBN	N-on-HPN	N-on-LPN	AC-on-car	AC-on-BBN	AC-on-HPN	AC-on-LPN	AC-of-car	AC-of-BBN	AC-of-HPN	AC-of-LPN	TR-on-car	TR-on-BBN	TR-on-HPN	TR-on-LPN	TR-of-car	TR-of-BBN	TR-of-HPN	TR-of-LPN
1	28.125	34.375	40.625	31.25	28.125	40.625	40.625	34.375	25	37.5	43.75	31.25	25	18.75	25	18.75	15.625	0	28.125	25
2	18.75	37.5	42.424242	37.5	15.625	15.625	43.75	37.5	9.375	34.375	43.75	31.25	12.5	18.75	34.375	15.625	21.875	12.5	28.125	28.125
3	34.375	37.5	43.75	34.375	40.625	40.625	43.75	31.25	34.375	40.625	43.75	34.375	37.5	15.625	31.25	9.375	43.75	9.375	28.125	6.25
4	12.5	40.625	50	34.375	9.375	31.25	43.75	34.375	0	37.5	43.75	34.375	18.75	40.625	50	25	15.625	37.5	56.25	12.5
5	18.75	34.375	37.5	34.375	28.125	43.75	37.5	37.5	31.25	43.75	34.375	40.625	15.625	18.75	15.625	25	15.625	28.125	31.25	25

Subject	N-on-car	N-on-BBN	N-on-HPN	N-on-LPN	AC-on-car	AC-on-BBN	AC-on-HPN	AC-on-LPN	AC-of-car	AC-of-BBN	AC-of-HPN	AC-of-LPN	TR-on-car	TR-on-BBN	TR-on-HPN	TR-on-LPN	TR-of-car	TR-of-BBN	TR-of-HPN	TR-of-LPN
1	31.25	40.625	40.625	34.375	31.25	43.75	40.625	34.375	28.125	40.625	43.75	43.75	25	40.625	43.75	37.5	28.125	34.375	40.625	37.5
2	12.5	43.75	31.25	31.25	6.25	40.625	9.375	31.25	9.375	37.5	28.125	37.5	6.25	37.5	28.125	31.25	6.25	37.5	34.375	37.5
3	25	12.5	37.5	18.75	31.25	43.75	43.75	43.75	28.125	43.75	43.75	37.5	28.125	40.625	40.625	43.75	21.875	43.75	43.75	37.5
4	18.75	40.625	43.75	40.625	18.75	43.75	40.625	40.625	25	21.875	18.75	18.75	25	12.5	21.875	15.625	31.25	15.625	28.125	12.5

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-Ibrahim, I., Cheesman, M., Parsa, V., Macpherson, E., & Farid, A. S. (2010, October). Evaluation of speech intelligibility and localization abilities with hearing aids using binaural wireless connection. Poster session presented at the Canadian Academy for Audiology, Montréal.

-Suelzle, D., Ibrahim, I., Pietrobon, J., Parsa, V., Cheesman, M., & Farid, A. S. (2010, August). Objective and subjective sound quality measurement for binaural wireless hearing aids. Poster session presented at the International Hearing Aid Conference, California.

Journal Publications:

I. Ibrahim, R. Malcolmson, M. B. Jennings, M. F. Cheesman (in press). Noise-Reduction headphones effect on localization abilities of portable audio device users. Canadian Hearing Report. (accepted).

I. Ibrahim, V. Parsa, E. Macpherson, M. Cheesman (2013). Evaluation of speech intelligibility and sound localization abilities with hearing aids using binaural wireless technology. Audiology Research. Available:

<http://www.audiologyresearch.org/index.php/audio/article/view/audiores.2013.e1>