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Horizontal Localization and Hearing in Noise Ability in Adults with Sensorineural Hearing Loss Using Hearing Aids with Binaural Processing

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Horizontal Localization and Hearing in Noise Ability in Adults with Sensorineural Hearing Loss Using Hearing Aids with Binaural Processing

by

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This research is dedicated to my loving and supportive parents.

Leland and Catherine Mullin

and

the toughest sister in the world,

Jennifer Lee Wright

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It seems that most people in the field of audiology stumble upon the profession accidentally. This is the story of how I got here.

When I received my bachelor's degree in 2002, my sister Jennifer was about to finish her MBA in finance. On the day of my undergraduate graduation, I specifically remember telling my parents, "I'm just letting you know now that I am *not* going to grad school like Jennifer." I thought that they might expect me to go since my sister had. After graduation, I worked on two independent documentary projects in Austin and for a friend's courier company for about nine months before I realized I should probably go to graduate school. I looked into graduate programs and speech-language pathology sounded interesting. I re-enrolled at The University of Texas at Austin in the spring of 2004 to take prerequisites for graduate school in speech-language pathology. During the fall 2004 semester, I took Introduction to Audiology with Dr. Frederick N. Martin and as the story goes for many Martin "converts," I was hooked on audiology. And I haven't looked back. I entered graduate school in the fall 2005 semester. During my first year in graduate school, I had the honor of being Dr. Martin's last teaching assistant with Debra Davila. I hinted to Dr. Martin that I was considering pursuing a Ph.D. in audiology and he encouraged me to take the leap of faith and continues to be a great support.

I have also received strong support and patience from my family. My parents and sister were somewhat shocked when I let them know that I wanted to pursue the Ph.D. in audiology. But once they realized that I was serious about pursuing the degree, they have been most supportive. My sister has been especially supportive, despite her ongoing battle with cancer throughout my years in graduate school.

I would like to thank David Cox and his team in the Radio-Television-Film department who helped build the amplifier tower and the speaker system for the equipment setup. I met David Cox in 2002 when I was an undergraduate RTF major. Little did I know I would be working with him again, seven years later. I would also like to thank Dr. Craig Champlin who has been the most optimistic and supportive adviser I could have ever asked for.

Horizontal Localization and Hearing in Noise Ability in Adults with Sensorineural Hearing Loss Using Hearing Aids with Binaural Processing

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The purpose of the study was to determine whether hearing aids with binaural processing improve performance during a localization and a hearing in noise task. The study included 16 participants, ages 29 – 67, with bilateral, essentially symmetrical, sensorineural hearing loss who had no prior hearing aid experience. Participants were fit with Oticon Epoq XW hearing aids bilaterally and completed the localization and the hearing in noise task with three listening conditions: (1) without hearing aids (NO), (2) with hearing aids that were not linked (BIL), and (3) with hearing aids that were linked (BIN). For the localization task, 1.5 second pink noise bursts at 75 dB SPL were used as the stimulus. A 180° 11-speaker array was set up to the right or left side of the participants. A twelfth speaker on the contralateral side of the array introduced constant background pink noise at 65 dB SPL. Results revealed that participants performed the best with the NO condition, followed by BIL, then BIN. There was a significant difference between NO and BIL and NO and BIN.

For the hearing in noise (HIN) task, sentences from the Hearing in Noise Test (HINT) were used as target stimuli. Continuous discourse by one male and two female talkers were used as maskers. There were four masker conditions for this task: (1) signal at 0°, masker at 90° (S_0-N_{90}), (2) signal at 0°, masker at 180° (S_0-N_{180}), (3) signal at 0°, masker at 270° (S_0-N_{270}), and (4) signal at 0°, maskers at 90°, 180°, and 270° (S_0-$N_{90,\,180,\,270}$). Results revealed that there was no significant difference between listening conditions when all masker conditions were considered. When the one-masker conditions were included, there was a significant difference between the NO and BIL and the NO and BIN conditions with the best performance for BIL, followed by BIN, then NO. Results also revealed a significant difference between masker conditions with the best performance for S_0-N_{270}, next best for S_0-N_{90}, followed by S_0-N_{180}, then S_0-$N_{90,\,180,\,270}$.

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1. Adaptive Directional Microphone (ADM)
2. Air-bone Gap (ABG)
3. Auditory Scene Analysis (ASA)
4. Automatic Gain Control (AGC)
5. Behind-the-Ear (BTE)
6. Bilateral (BIL)
7. Binaural (BIN)
8. Binaural Broadband (BB)
9. Compression Ratio (CR)
10. Decibel (dB)
11. Electroacoustic Analysis (EA)
12. Hearing Impairment (HI)
13. Hearing in Noise Test (HINT)
14. Hearing Level (HL)
15. Hertz (Hz)
16. Interaural Level Difference (ILD)
17. Interaural Time Difference (ITD)
18. Just Noticeable Interaural Difference (JND)
19. Most Comfortable Loudness (MCL)
20. Multichannel Wiener filter (MWF)
21. Multichannel Wiener filter with partial noise estimate (MWF-N)
22. Narrowband (NB)
23. Normal Hearing (NH)
24. Receiver in the Ear (RITE)
25. Repeated Measures Analysis of Variance (ANOVA)
26. Root Mean Square (RMS)
27. Sensation Level (SL)
28. Sensorineural Hearing Loss (SNHL)
29. Signal at 0° and masker at 90° (S_0-N_{90})
30. Signal at 0° and masker at 180° (S_0-N_{180})
31. Signal at 0° and masker at 270° (S_0-N_{270})
32. Signal at 0° and maskers at 90°, 180°, and 270° (S_0-$N_{90, 180, 270}$)
33. Signal-to-Noise Ratio (SNR)
34. Sound Level Meter (SLM)
35. Sound Pressure Level (SPL)
37. Speech Recognition Threshold (SRT)
38. Speech, Spatial, and Qualities of Hearing scale (SSQ)

I. INTRODUCTION

Difficulty understanding speech in noise is one of the primary complaints of patients who wear hearing aids. There have been many advances in hearing aid technology, such as directional microphones and noise reduction that have made it somewhat easier for patients to hear better in noise. A new trend in hearing aids is for bilateral hearing aids to be linked together via a wireless connection, commonly referred to as "binaural processing." For the remainder of this paper, bilateral refers to two hearing aids that are not linked and binaural refers to hearing aids that are linked via a wireless connection. The rationale behind hearing aids with binaural processing is that they can help patients localize sounds, and further, can help patients hear better in noise. The link between improved localization and improved hearing in noise is explored in this paper. The purpose of the study is to determine whether hearing aids with binaural processing can help participants in a localization task and in a hearing-in-noise task when compared to wearing hearing aids without binaural processing.

II. REVIEW OF THE LITERATURE

2.1 Localization

Horizontal localization refers to the plane at the level of the listener's ears and nose, while *vertical localization* refers to the vertical plane in front of, above, and behind the listener. Interaural time differences (ITDs) and interaural level differences (ILDs) are used in the horizontal plane because sounds from the side reach the two ears at different times and at different intensity levels. For vertical localization, humans use cues that originate from the way the pinna and outer ear affect high frequency sounds.

2.1.1   Localization in the Horizontal Plane

There are two acoustic cues that humans use in order to localize a sound source in the horizontal plane. When a sound originates on one side of the head, it stimulates the close ear first and the far ear second. This difference in time of arrival at the two ears is referred to as interaural time difference (ITD), also known as interaural phase difference. The ITD cue is especially present at low frequencies, below 1000 – 1300 Hz (Sandel, Teas, Fedderson, & Jeffress, 1955; Stevens & Newman, 1936). Sandel et al. (1955) tested five participants with varying degrees of hearing sensitivity. Four out of the five participants completed three experiments, all involving localization tasks using loudspeakers that presented different tones. The stimuli for the third experiment were tones presented out of phase, simulating ITD. Results from the experiments revealed that participants localized best at lower frequencies up to approximately 1500 Hz. At frequencies greater than 1500 Hz, random errors increased. The results from this study suggest that for stimuli below 1500 Hz, humans use ITD cues for localization.

The other acoustic cue used in localizing a sound source in the horizontal plane is interaural level difference (ILD). When a sound is presented to one side of the head, the intensity of the sound will be greater at the close ear and softer at the far ear. The attenuation of sound from one side of the head to the other is due to the difference in the wavelength of the signal compared to the size of the head (the "head shadow effect"). The higher the frequency of the sound, the greater this head shadow effect. The ILD is especially apparent at frequencies greater than 1500 Hz (Stevens & Newman, 1936). Mills (1960) investigated the minimum ILD that a human listener can perceive for tones. This study included five participants with normal hearing. A one second tone pulse was presented to both ears through headphones, starting at 50 dB sensation level (SL). The two tones were presented and increased or decreased in one ear or the other until the participant heard the sound from the center of the head. From this point, the just noticeable interaural difference (JND) threshold for intensity was measured with 20 pairs of tone pulses. The highest JND threshold was approximately 1 dB at 1000 Hz. The JND threshold for frequencies lower than 1000 Hz was approximately 0.75 dB and for frequencies higher than 1000 Hz, 0.5 dB.

McFadden and Pasanen (1976) conducted a study to investigate whether or not ITD cues can be used with high-frequency stimuli. These authors reported that in past research that supports the duplex theory of localization, tones were used as stimuli. The duplex theory states that ITD cues are used for low frequencies and ILD cues are used for high frequencies. Because tonal stimuli are not examples of real-world sounds, the researchers in this study used a narrowband (NB) noise (centered at 500 and 4000 Hz), two-tone complexes, two-tone complexes where the higher frequency tone changed in amplitude, two-tone complex and NB noise where the overall levels were changed, and two NB noises presented simultaneously (500 Hz and 4000 Hz). Results revealed that when complex stimuli are used, ITD cues *can* be used even with high frequency stimuli.

Wightman and Kistler (1992) studied ITDs and ILDs in a lateralization task presented through headphones. Eight participants completed Experiment 1 and six participants completed Experiment 2. The stimuli used in the experiments were Gaussian (wideband) noise bursts presented at approximately 70 dB SPL. The noise bursts were manipulated to present ITD cues that represented one location in space, and ILD and spectral shape cues that represented the opposite location in space. Results revealed that when lateralization cues conflict, the ITD cue dominates lateralization ability. When low frequencies (<5000 Hz) are removed from the stimulus, participants rely on ITDs less, and ILD cues and spectral shape cues are more apparent.

It is also important to note a phenomenon that exists when testing localization in the front and back of the listener. If a sound is presented to the back of the listener at 180° azimuth (re: the listener’s nose), the listener might perceive the sound as being in the front at 0° azimuth (the exact opposite location of the source). Researchers can minimize this “front/back confusion” by using a broad bandwidth stimulus. Butler

(1986) tested 6 participants with normal hearing in a horizontal localization task. Twenty-one speakers were arranged on the left side of the participant in a half-circle arc. The stimuli used were 8000 Hz noise bursts with varying bandwidths (2000 Hz, 4000 Hz, 6000 Hz, and 8000 Hz). The participants were tested binaurally (at 40 dB SL) and monaurally (at 30 dB SL) for all of the different bandwidths. Results revealed a significant difference between listening conditions, between stimuli bandwidths, and between speaker placement (front and rear versus side). The relevant result from the study is that as the bandwidth of the stimulus increased, front/back confusions decreased. This study suggests that in order to minimize front/back confusions in a horizontal localization task, researchers can use a broad bandwidth stimulus. That is the reason why pink noise was used for the horizontal localization task in the current study. Also similar to the current study, the speaker array was located to the side of the participants.

2.1.2 Localization in the Vertical Plane

All of the above information applies to horizontal localization. Horizontal localization refers to the plane at the level of the listener’s ears and nose, while *vertical localization* refers to the vertical plane in front of, above, and behind the listener. For vertical localization, humans rely on spectral cues that result from the shape of the pinna and outer ear. Roffler and Butler (1968) discussed an experiment in their study that involved localization in the vertical plane of 13 low-pass filtered noises with varying upper cut-off frequencies (from 500 to 12,000 Hz). Six participants were included in this study. Half of the 80 stimuli presentations were at 20 dB SL and the other half at 30 dB SL. Results revealed that participants performed most accurately with stimuli that included frequencies greater than 7000 Hz. This suggests that for accurate localization in the vertical plane, the complex stimulus must include frequencies greater than 7000 Hz. Improving the ability to localize sounds in the vertical plane is a topic that the proposed hearing aids address with an extended high frequency range (up to 10,000 Hz) but was not included in this study. In most conversations, especially in a noisy situation, the talker(s) of interest are typically on the same plane as the listener, so vertical localization was not investigated in this study.

2.1.3 Localization and Hearing Impairment

Localization ability in patients with hearing loss is important to understand because it is one essential aspect of hearing-in-noise ability. For a person with hearing impairment, parts of the signal of interest are already attenuated when compared to a person with normal hearing. If the person with hearing impairment cannot follow the location of the talker of interest when listening to a multi-talker conversation, then the signal is further attenuated because the patient is not directly facing the talker (Mencher & Davis, 2006).

According to Noble, Byrne, and Lepage (1994), localization ability is somewhat correlated with a person’s type and degree of hearing loss. This study included 6 participants with normal hearing, 66 participants with sensorineural hearing loss (SNHL), and 21 with conductive or mixed loss. Horizontal and vertical localization abilities were measured using pink noise bursts. Results revealed that hearing loss has an effect on localization ability, particularly in the vertical plane. Regarding the type of hearing loss, a conductive or mixed loss further decreases localization ability when compared to SNHL, probably due to decreased low frequency ITD cues. Participants with SNHL have access to ITD and ILD cues with ITD being dominant. Results also revealed that the type and degree of hearing loss can only moderately predict localization ability. The researchers concluded that other factors must be involved in the ability to localize, such as: degree of hearing loss in particular frequency regions, the characteristics of the sound environment, and the level of the signal.

2.1.4 Hearing Aids and Localization Ability

Byrne, Noble, and Lepage (1992) completed a horizontal and vertical localization study that included 87 participants with hearing impairment. Before the study, the participants were fit with either behind-the-ear (BTE) or in-the-ear (ITE) hearing aids, some bilaterally and some unilaterally. All but one of the participants' hearing aids used omnidirectional microphones, with the exception using directional microphones. The testing was completed using 20 speakers with pulsed pink noise presented at two levels: most comfortable loudness (MCL) and ½ MCL. The researchers completed a pilot study with participants with normal hearing and found that for horizontal localization, all participants scored near 100%, and for vertical localization, scored near 70%. Results from the participants with hearing impairment revealed that with moderate to severe hearing loss, a bilateral fitting was significantly better than a unilateral fitting. Regarding level of the test stimulus, scores from the MCL condition were significantly better than those for the ½ MCL condition. The results also suggest that a high frequency SNHL above 4000 Hz leads to greater front/back confusion as previously discussed. The researchers concluded that for patients with moderate to severe hearing loss, bilateral amplification is more beneficial than unilateral amplification when considering localization ability. For the current study, participants with essentially symmetrical SNHL were included and fit with bilateral hearing aids to maximize their ability to localize sounds in the horizontal plane.

Keidser et al. (2006) investigated the effect of different hearing aid settings on horizontal localization ability. The study included 12 participants with bilateral sensorineural hearing loss (SNHL). Participants had at least six months of hearing aid experience and wore BTEs, ITEs, or in-the-canal (ITCs) hearing aids. For the purposes of the study, participants were fit with Siemens Triano S BTE hearing aids with custom earmolds. Pink noise was used as the stimulus and was presented through 20 speakers arranged in a full circle around the participants in the horizontal plane. The participants were tested under seven conditions: (1) linear compression with noise reduction (NR) off and omnidirectional microphones, (2) syllabic wide dynamic range compression (WDRC) with NR off and omnidirectional microphones, (3) linear with NR off and cardioid microphones, (4) linear with NR off, figure-eight microphone in one ear and a cardioid microphone in the other ear, (5) linear with NR off, omnidirectional microphone in one ear and cardioid microphone in the other ear, (6) linear with NR off and omnidirectional microphones at 72 dB SPL with 65 dB SPL of background noise, and (7) linear with NR on maximum and omnidirectional microphones with 72 dB SPL stimulus and 65 dB SPL of background noise. All stimuli were presented at 65 dB SPL unless otherwise noted. The participants were tested at two weeks and two months post-fitting. Results revealed that front/back errors frequently occurred in this hearing impaired population but these errors decreased over time, specifically with the cardioid microphone fitting. Left/right inaccuracies were most prominent with the asymmetric hearing aid fitting. These results suggest that for horizontal localization, an asymmetric hearing aid fitting (omnidirectional microphone in one aid and directional microphone in the other aid) does not prove beneficial. Omnidirectional microphones were used in both aids in the current study for the localization task.

Musa-Shufani, Walger, von Wedel, and Meister (2006) examined whether compression ratio (CR) or attack time (AT) affects horizontal frontal localization cues in participants with hearing impairment. The study included five participants with normal hearing and seven participants with hearing impairment. Experiments I and II were left/right discrimination tasks that estimated the interaural just noticeable difference (JND) for ILD and ITD. Experiment III measured head-related transfer functions (HRTFs) with a mannequin head. The stimuli used in the experiments were narrowband (NB) noises (one centered at 500 Hz and one centered at 4000 Hz). The stimulus presentation level was 75 dB SPL for participants with normal hearing. For the participants with hearing impairment, the presentation level was at a comfortable listening level. Participants were tested under three CR conditions (1:1, 3:1, and 8:1) and three AT conditions (2, 20, and 200 ms). Results revealed that participants with hearing impairment had larger JNDs than participants with normal hearing. Also, the JND for ILD decreased as CR decreased and as AT decreased. For ITD, the JND was lower for 500 Hz than for 4000 Hz. In conclusion, both CR and AT affect localization ability based on ILDs but not based on ITDs in participants with hearing impairment.

Another study (Van den Bogaert, Klasen, Moonen, Van Deun, & Wouters, 2006) investigated whether or not hearing aids preserved localization cues. Ten participants with normal hearing and ten participants with hearing impairment participated in this study. The participants with hearing impairment are the focus of this discussion. All of these participants had experience wearing bilateral hearing aids. For the study, six of the participants were fit with Phonak Perseo hearing aids, three were fit with GN Resound Canta 7, and one was fit with Widex Diva hearing aids. Thirteen speakers were set up in a frontal horizontal arc. The stimuli used in this study included narrowband (NB) noises (one centered at 500 Hz, one centered at 3150 Hz), and a broadband (BB) telephone ringing with and without the presence of babble from the sides. Participants were tested unaided and aided. There were two aided conditions, including (1) both aids with an omnidirectional microphone setting and (2) both aids with an adaptive directional microphone (ADM) setting. Results revealed that for the low frequency NB noise, localization ability was significantly better in the unaided condition than the ADM condition. For the high frequency NB noise, no significant differences were found between any conditions. There was a significant difference between the unaided and omnidirectional microphone condition for the BB telephone stimulus. Participants performed significantly better in the unaided condition than the omnidirectional condition for the BB telephone stimulus presented in babble. For the same stimulus, participants performed significantly better in the omnidirectional condition versus the ADM condition. The researchers concluded that bilateral hearing aids do not preserve ITD and ILD localization cues. In the current study, the Oticon Epoq XW hearing aids with binaural processing were used because they supposedly “preserve” ILD cues.

An Oticon white paper (Sockalingam, 2009) suggests that binaural processing in hearing aids can preserve binaural cues and improve localization performance. In the study conducted by Oticon, the Oticon Dual XW hearing aids were used which have a similar chip in them as the Epoq XW hearing aids. The main difference between the Dual XW and Epoq XW hearing aids is that the external housing of the device is different in size and shape. Thirty participants completed this study, 16 of which were experienced hearing aid users, and the other 14 of which were inexperienced users. Half of the participants started the study with binaural processing turned off (BIL), and the other half started the study with binaural processing turned on (BIN). Before localization testing, the participants wore the hearing aids for at least two weeks in the BIL and BIN conditions. For the localization testing, eight speakers were used in a 105° degree arc, with the first speaker at 0° azimuth (re: the participant’s nose) and speaker 8 at 105° azimuth. The participants were tested with the speaker array to the right side and to the left side. The target stimulus was a chirp that was presented three times in a row at 60 dB SPL. Unmodulated speech-shaped noise was continuously presented during testing from the speaker at 105°. The scoring of the localization task involved summing of the localization error and not an RMS error like in the current study. The study also included a subjective measure of the naturalness of the hearing aids in the BIL and BIN conditions for three different listening environments: (1) café, (2) garden, and (3) street. Results for the localization study revealed that the participants performed significantly better in the BIN condition than in the BIL condition. Regarding the subjective measure, the BIN condition was rated significantly better than the BIL condition in the café environment. The BIN condition was also rated better than the BIL condition for the street condition, but the difference was not statistically significant. There was no difference in naturalness of sound between BIL and BIN for the garden condition. A weakness of this study is that the participants were not tested unaided like in the current study. Would they have performed better or worse in an unaided condition? Also, the experienced and inexperienced hearing aid users were grouped together, so there was no analysis that explored whether there was a difference in performance between experienced and inexperienced hearing aid users.

Open-fit hearing aids can help overcome the decrease in localization ability with hearing aids for certain types of hearing loss. A study by Byrne, Sinclair, and Noble (1998) tested 23 participants with low frequency SNHL (>30 dB HL between 250 – 2000 Hz) and normal or mild high frequency hearing sensitivity (<30 dB HL at 6000 and 8000 Hz). Horizontal localization was measured with 11 speakers in a front arc, and vertical localization was measured using 11 speakers in the medial plane. The stimulus used was pink noise. Participants were bilaterally fit with Bernafon/NAL SB13 BTE hearing aids and were tested under three earmold conditions: occluded, partially occluded, and unoccluded. Results revealed that participants performed significantly better in the unaided condition than for the occluded condition for vertical localization. Participants scored virtually the same for the unaided and unoccluded condition for vertical localization. There was also a slight improvement in horizontal localization ability for the unoccluded condition versus the partially occluded and completely occluded condition. The results of this study support the hypothesis that humans depend on spectral shape/pinna cues for vertical localization. The limitation of this study is that these results can only be generalized to a limited population of patients who have a reverse slope SNHL. Similar to this study, the current study used pink noise as the stimulus and an 11-speaker array (but in a side arc instead of a front arc).

2.1.5 Compression and Interaural Level Difference Cues

With bilateral hearing aids, if a sound originates from one side of the patient's head, the hearing aid on that side will amplify the signal by x amount. The hearing aid on the opposite ear (working independently) will amplify the same signal by y amount. In most cases, y will be greater than x because there will be a level difference between the signal that reaches the near hearing aid and the sound that reaches the far hearing aid. If the hearing aids work independently, then the final output of each hearing aid will be relatively equal. This takes away from the natural ILD cue that humans use to localize sounds in the horizontal plane. Hearing aids with binaural processing, in theory, can preserve ILD cues. If two hearing aids are linked, then the patient might be able to more easily detect that a sound originated from one side of the head versus the other. The hearing aid on the near ear can amplify the sound slightly more than the hearing aid on the far ear (especially in the frequency range above 1500 Hz), and the patient's brain can use this ILD to understand that the sound originated from the side of the near ear. Because ILDs are most effective in the frequency range above 1500 Hz, the hearing aids with binaural processing should take advantage of this by "preserving" the ILD cues above 1500 Hz.

If this binaural processing system helps improve horizontal localization ability, then patients might be better able to localize where a sound comes from. Furthermore, patients might be able to follow a multi-talker conversation easier because they would be able to switch attention between talkers more quickly than before. The patient will in turn miss less information because the patient will not be "wasting time" trying to figure out who is talking next. In other words, the patient might spend less time trying to figure out where the next person's voice is coming from and will not miss as much of the speech stream.

2.1.6 Measuring Localization Performance

Localization testing has been completed for more than a century. Localization performance with hearing aids and with cochlear implants has been the focus of the most recent research. Five studies are described here for the purpose of providing plans for the testing protocol for the current research.

Van den Bogaert et al. (2006) tested horizontal localization ability in participants wearing bilateral hearing aids. The investigators used 13 speakers, 15° apart, one meter from the participant, and in a 180° arc. The stimuli used in this study were a low frequency noise band centered at 500 Hz and a high frequency noise band centered at 3150 Hz. Similar to this study, the speaker array was positioned one meter from the participants in the current study.

Tyler, Dunn, Witt, and Noble (2007) tested speech perception and localization ability in participants with bilateral cochlear implants. The researchers used everyday sounds as stimuli which included: a Westminster chime, dog barking, buzzer, telephone ringing, cello playing, guitar playing, bird chirping, glass breaking, train crossing warning, cock crowing, water pouring, many birds, sawing wood, rain and thunder, child laughing, and a duck quacking. These sounds were presented at 70 dB(C). The stimuli were presented through eight speakers that were positioned 15.5° apart, 1.4 meters from the participant, and in a 108° arc.

Laszig et al. (2004) investigated the benefits of bilateral cochlear implant use on localization. The researchers used a 12 speaker setup, positioned 30° apart, one meter from the participant, and in a 360° arc. The stimuli used in this study were shortened sentences from the Hochmair-Schulz-Moser sentence list presented at 55 – 70 dB SPL, depending on the participants' aided speech recognition threshold. The speakers in the current study were located one meter away from the participant like in this study.

Dunn, Tyler, and Witt (2005) tested the benefit of wearing a hearing aid on the un-implanted ear of unilateral cochlear implant users. Localization testing was completed using eight speakers, 15.5° apart, 1.4 meters from the participant, and in a 108° arc. The stimulus was the same as in the Tyler et al. (2007) study, presented at 60 dB(A).

Wazen, Ghossaini, Spitzer, and Kuller (2005) tested localization ability in patients wearing the bone-anchored hearing device (BAHA). The stimuli used in this study were two narrowband noises (NBN), one with a center frequency of 500 Hz and the other with a center frequency of 3000 Hz, presented at 60 dB HL with duration of two seconds. Eight speakers were positioned 45° apart, four feet away from the participant, and in a 360° arc.

For the localization test in the current study, 1.5 second pink noise bursts were used as the stimulus so that it included a broad spectrum of frequencies and was long enough in duration to engage the compression system of the hearing aids. Eleven speakers were positioned in a side arc one meter from the center of the participant's head, each of the speakers located 18° apart. The speakers created a 180° arc to the side of the participant (the right side for participants 1 – 8 and the left side for participants 9 – 16). The speaker array was positioned to one side of the participant so that a speaker on the contralateral side of the speaker array could present constant background pink noise. This additional speaker on the contralateral side presented the background pink noise so that the hearing aid circuitry would notice a difference or asymmetry in the acoustical environment.

2.2 Hearing in Noise

2.2.1 Hearing in Noise Ability with Directional and Omnidirectional Hearing Aid Microphones

Bentler, Egge, Tubbs, and Flamme (2004) investigated speech-in-noise performance with different types of directional microphone fittings. The study included 19 participants between the ages of 50 and 83 years with symmetrical sensorineural hearing loss (SNHL). Ten of the participants were new hearing aid users and nine of them were experienced users with one or more years of experience. All participants in this study were fit bilaterally with Unitron F/X™ in-the-ear (ITE) hearing aids. The aids were programmed to the National Acoustics Laboratory nonlinear targets (NAL-NL1; Dillon, 1999). Testing was completed in an anechoic chamber with eight speakers in order to create a free field environment. The eight speakers formed the corners of a cube. Speech-in-noise testing was administered using the Hearing in Noise Test (HINT) and the Connected Speech Test (CST). Participants completed the HINT and CST under five hearing aid conditions: (1) omnidirectional microphones in both hearing aids (O-O), (2) cardioid directional microphones in both hearing aids (CD-CD), (3) hypercardioid directional microphones in both hearing aids (HD-HD), (4) supercardioid directional microphones in both hearing aids (SD-SD), and (5) directional in the right hearing aid and omnidirectional in the left hearing aid (D-O). Participants also rated eight features of sound quality for three stimuli: speech in quiet, speech in noise (at +8 dB signal-to-noise ratio), and music. Results revealed that participants performed significantly better for the HINT and CST in all four directional fittings than with O-O. Regarding sound quality, there were no significant differences between any of the microphone conditions. This study suggests that fitting patients with D-O does not have a detrimental effect on speech intelligibility in noise when compared to performance with bilateral directional microphone fittings. Similar to this study, the current study used the HINT sentences as stimuli, and the hearing aids were both programmed to be in directional microphone mode for the hearing-in-noise task.

Cord, Walden, Surr, and Dittberner (2007) used the Institute of Electrical and Electronic Engineers (IEEE) sentences to assess speech-in-noise ability for 12 participants with bilateral symmetrical SNHL. The participants ranged in age from 56 – 82 years with 1.5 – 20 years of hearing aid experience. The unique characteristic of these participants is that they rarely or never used the directional (D-D) setting on their hearing aids and 11 out of 12 of the participants were male. The hearing aids used in this study were the participants' own hearing aids, differing in manufacturer, model, and style. All of the hearing aids had the ability to be manually switched between omnidirectional microphones in both hearing aids (O-O) and D-D. For the speech-in-noise testing, the speaker for the speech presentation was placed at 0° azimuth (re: the participant's nose), and the speakers for the noise presentation were located at 90°, 180°, and 270° azimuth. Three IEEE sentence lists were presented for both of the hearing aid microphone conditions: (1) O-O and (2) half of the participants with directional microphone in the right ear and omnidirectional in the left ear (D-O) and half of the participants with the opposite (O-D). The participants also completed the Hearing Aid Use Log (HAUL) for both of the hearing aid conditions in terms of: location of signal of interest, distance of signal, and absence or presence of background noise. Results revealed that participants scored significantly better with O-D/D-O than with O-O for the speech-in-noise task. According to the HAULs, participants reported significantly greater ease of listening with D-O/O-D than with O-O. The researchers concluded that an asymmetric hearing aid fitting does not have a negative effect on speech-in-noise ability. This study prompts the question: is there a different way to improve speech intelligibility in noise, possibly in a significant way? Might a contralateral microphone system (binaural processing) significantly improve speech-in-noise ability significantly? This study presents an optimal speaker setup for speech-in-noise testing and was used in the current study. Also, this study included participants with bilateral symmetrical SNHL like those in the current study.

Hornsby and Ricketts (2007) also studied hearing-in-noise performance with different types of hearing aid fittings. Sixteen participants who were between the ages of 73 and 82 years old with mild to severe symmetrical flat or sloping SNHL completed the study. The participants' hearing aid experience ranged from 0 to 48 years (average 11.3). The participants were fit bilaterally with Siemens Triano P behind-the-ear (BTE) hearing aids. The aids were programmed to match the National Acoustics Laboratory nonlinear targets (NAL-NL1) targets with noise reduction and feedback suppression algorithms disabled. The directional microphones were used in adaptive directional mode (ADM) for the study. The participants were tested in a sound-treated room with the speech target speaker placed 1.2 meters from the participant, and three other speakers presenting the noise stimuli. The participants' speech intelligibility in noise was measured using the Hearing in Noise Test (HINT) sentences as target stimuli and recorded noises as the different maskers. The participants were tested under three noise conditions: (1) speech front, noise surround (NC1), (2) speech front, noise both sides (NC2), and (3) speech right, noise left (NC3). The noise stimuli used for NC1 and NC2 was recorded cafeteria babble that was filtered to provide long-term average spectral shape similar to HINT noise stimuli, while the noise stimulus used for NC3 was recorded traffic noise. Participants completed the speech-in-noise testing with four hearing aid conditions: (1) omnidirectional microphones in both hearing aids (O-O), (2) directional microphones in both hearing aids (D-D), (3) directional in the right ear, omnidirectional in the left ear (D-O), and (4) omnidirectional in the right ear and directional in the left ear (O-D). Participants performed the worst for the NC3 (speech right, noise left) noise condition for all of the hearing aid conditions. For NC1 (speech front, noise surround) and NC2 (speech front, noise both sides), participants performed the poorest in the O-O condition and significantly better with D-D, D-O, and O-D. Unlike the Bentler et al. (2004) and Cord et al. (2007) studies, participants performed significantly poorer for the NC1 and NC2 noise conditions with O-D and D-O than with D-D. Interestingly, for NC3, participants performed the best with O-O which was significantly better than D-O which was significantly better than D-D. In conclusion, when the talker is located in front of the participant, the asymmetric hearing aid fitting can decrease the advantages of binaural processing. This can lead to a decrease in speech-in-noise ability. The D-O type of fitting might not be the best fitting for preserving localization cues or for improving speech-in-noise ability. For the current study, the hearing aids were both in directional microphone mode for the hearing-in-noise task.

2.3 Masking of Speech

2.3.1 Types of Masking

Masking occurs when an unwanted signal (speech or noise) interferes with the intelligibility of a target signal. There are two types of masking: energetic masking and informational/perceptual masking. *Energetic* masking is caused by energy in the masker that overlaps frequencies that are also in the target signal (Brungart, 2001). This type of masking happens at the periphery of the auditory system. *Informational* or perceptual masking is the additional amount of masking that cannot be accounted for by energetic masking. This happens when the unwanted signal is, for example, speech, and it takes place at the central level (Carhart, Tillman, & Greetis, 1969). For the purposes of this study, only informational masking will be discussed further.

2.3.2 Informational Masking

There are different characteristics of the informational masker signal that can affect how much it interferes with the target signal, including the gender of the talker, intonation, pauses, and voice quality. In a 2001 study, Brungart tested the ability of participants to understand speech in noise, using coordinate response measure (CRM) sentences and five different maskers, including (1) a different (than target) gender masker, (2) same gender masker, (3) same masker, (4) noise masker, and (5) modulated noise. The CRM target sentences follow the structure: “Ready [callsign] go to [color] [number] now.” The callsign is a certain word that signifies that that sentence is the target sentence. This study included “baron” as the target callsign. The task was for the participant to identify the correct color and number of the target sentence. The study included nine participants with normal hearing. Results revealed that speech-in-noise performance was significantly better with the different gender masker than with the same gender masker. Further, performance with the same gender masker was significantly better than with the same talker masker. In other words, participants could understand speech in noise best when the interfering talker was the most different than the target. The results suggest that when using speech maskers, intelligibility will likely be better if the masker is a different gender and a different voice than the target. The limitation of this study is that it was only performed on participants with normal hearing. For the current study, different talkers than the target talker were used as maskers to maximize the participant’s ability to understand speech in noise and to mimic a more real-world situation. And because the HINT sentences (male voice) were used as the target stimuli, two female voices and only one male voice were used as maskers.

A relevant study by Cherry (1953) investigated how much information participants could recall about the speech masker after its presentation. This was included in the second experiment of the study and involved presentation of a speech signal to one ear and a speech or pure tone masker to the other ear. Participants were first asked to repeat the target sentence. They were later asked about certain qualities of the masker. Interestingly, the participants could not recall any words or phrases of the masker, nor could they recall the language or any semantic content of the speech masker. They could, however, recall if the masker was male versus female and some of the participants recognized that the reversed speech masker seemed “different.” The participants also generally recognized when the masker was a 400 Hz pure tone instead of speech. These results suggest that the human brain is superior at suppressing the unwanted signal so it can focus on the target signal.

A study by Summers and Molis (2004) included participants with normal hearing and participants with sensorineural hearing loss in a speech-in-noise task. The purpose of the study was two-fold. First, does masking type (speech noise versus speech) have an effect on speech intelligibility and secondly, does masker presentation level (60, 75, and 90 dB SPL) affect speech intelligibility in noise? The study included six participants with normal hearing (NH) and six participants with up to a moderate sensorineural hearing loss (HI) with no prior experience with hearing aids except for one. The target stimuli used in this study were the Institute of Electrical and Electronic Engineers (IEEE) sentences. There were three different maskers: (1) forward speech with a voice that had a different fundamental frequency than the target, (2) reverse speech with the same voice as the target, and (3) unmodulated/steady-state noise. The three different masker conditions were presented at three different intensity levels (60, 75, and

90 dB SPL) under headphones. For the NH group, results revealed that they required a better SNR for the noise masker versus the speech masker and as the presentation level increased, their performance decreased. Of interest are the results from the HI group. This group showed a decrease in performance with the noise masker versus the speech masker. The advantage of the speech masker was observed for the 90 dB SPL condition, was reduced for the 75 dB SPL condition, and was absent at 60 dB SPL. For all types of maskers, the HI group did not show a benefit from presentation level. Overall, the HI group showed a decrease in performance when compared to the NH group. Also, the HI group showed a decrease in performance when forward speech was used versus reverse speech. This is probably due to informational masking. The significance of this study is that if sounds are made audible for patients with HI (like with hearing aids), then these participants will not necessarily perform better in a speech-in-noise task. This lack of improvement could be due to a decrease in spectral and/or temporal resolution in the cochlea which is discussed in a later section of this paper. This study suggests that using a speech masker instead of a noise masker can improve speech-in-noise performance even for participants with HI. That is one reason why speech was used as the masker in the current study. Also similar to this study, the current study used participants with up to a moderate sensorineural hearing loss and with no prior hearing aid experience.

Another speech-in-noise study that included participants with normal hearing and participants with sensorineural hearing loss was completed by Festen and Plomp (1990). The purpose of this study was similar to the Brungart (2001) study in that the researchers wanted to determine if the type of masker had an effect on speech intelligibility. There were two sets of target stimuli from a list of “everyday sentences.” One list was read by a female voice and the other, by a male voice. There were five masker conditions: (1) steady-state noise, (2) single-band modulated noise, (3) 2-band modulated noise, (4) quiet, and (5) normally running speech. Each masker was matched with both target conditions, for a total of 10 conditions. Stimuli were monaurally presented under headphones. Twenty participants with normal hearing (NH) and 20 participants with sensorineural hearing loss (SNHL) completed the study. Results revealed a significant difference in performance between the NH and SNHL groups for all conditions tested. There was essentially no difference seen between types of maskers in this study. The implication of this study is that participants with SNHL performed significantly worse than NH in the speech-in-noise task. Also, in contrast to the Summers and Molis (2004) study, the researchers in this study found no significant difference between types of maskers.

Hornsby, Ricketts, and Johnson (2006) investigated whether or not hearing aids helped participants with hearing impairment better understand speech in noise, especially in cases of informational versus energetic masking. Fifteen participants with normal hearing (NH) and 15 participants with hearing impairment (HI; mild to moderately severe, flat or sloping sensorineural hearing loss) participated in this study. The HI group was aided with Phonak Claro behind-the-ear (BTE) hearing aids and was tested aided and unaided. The target stimuli were modified sentences from the Hearing in Noise Test (HINT). The target sentences were presented in two masker conditions: (1) ongoing discourse by a male talker and (2) speech-shaped noise. There were also three different speaker configurations for the signal and masker(s). For all of the speaker conditions, the target signal was presented at 0° azimuth (re: the participant's nose). One of the speaker conditions included two maskers (at 315° and 135°), another included four maskers (at 315°, 225°, 135°, and 45°), and the third speaker condition had seven maskers (one every 45°). Because of the focus of the current study, only the results from the HI group will be discussed. For the unaided condition, the HI group performed better with the speech masker than with the noise masker in the 2-masker condition. For the 7-masker condition, the HI group performed significantly better with the noise masker than with the speech masker. Unlike the NH group, the performance of the HI group (unaided and aided) did not improve as the number of maskers decreased. For the HI group, performance was significantly better when the participants were aided for the speech noise masker condition (for the 2- and 4-masker conditions only). For the speech masker, aided performance was not significantly better than unaided performance for the HI group. In general, for the HI group, speech intelligibility was significantly better for the 2- and 4-masker conditions than for the 7-masker condition. This study affirms that everyday speech contains energetic and informational masking. Speech used as a masker adds informational masking to energetic masking and can increase the overall amount of masking. Also, there is limited improvement with hearing aids with omnidirectional microphones when masking is both energetic and informational. In the current study, directional microphones were used during the hearing-in-noise task to potentially help overcome this lack of improvement with hearing aids.

2.4 Spatial Awareness/Spatial Hearing

Humans are constantly analyzing the acoustic environment around them to make sense of the sounds in their world. In order to do this, the human brain relies on localizing where different sounds come from and grouping the different sound sources into auditory “objects.” Shinn-Cunningham (2009) refers to this process as “auditory scene analysis” (ASA). Humans use ASA especially when trying to understand speech in the presence of background noise. By grouping different sounds into different units, the brain can then suppress the unwanted sounds/units and focus on the target signal/unit.

Numerous research studies have suggested that separation of the target signal from the masker signal(s) improves speech intelligibility in noise, particularly in participants with normal hearing. Freyman, Balakrishnan, and Helfer (2001) examined whether spatial separation of the target and the masker could improve speech intelligibility in participants with normal hearing. Further, if speech intelligibility did improve, did the type of masker affect performance (i.e. forward speech, speech-shaped noise, or reversed speech)? The target stimuli used in this study were nonsense sentences recorded from a female talker and the maskers were also nonsense sentences recorded from two other female talkers. The target and masker were presented via speakers. For the first speaker condition, the target and masker were presented from a speaker at 0° (re: the participant’s nose). For the second speaker condition, the target and masker were presented from the speaker at 0° and the masker was also presented from a speaker at 60°. The onset of the masker presented from the speaker at 60° occurred 4 ms before the onset of the signal and masker presented from the speaker at 0°. This lead time had the effect of participants perceiving that the masker originated from the speaker to the right at 60°, creating a perceived spatial separation of the target and masker (also referred to as the precedence effect). Results revealed that if the signal and masker were perceived as spatially separate (signal at 0° and masker at 60°), there was an improvement in speech intelligibility when the masker was speech (either forward or reversed). However, there was no improvement when the masker was speech-shaped noise. This suggests that spatial separation between the target and the masker can cause a release from the effectiveness of masking ("spatial release from masking" or SR). SR only occurred when the masker was speech. As discussed in the masking section of this paper, speech contains energetic as well as informational masking. This study suggests that perceiving separation between the target and the masker can improve speech intelligibility when the masker contains informational masking (speech). The signal and masker in the current study were separated by at least 90° to maximize the spatial release from masking.

The Freyman et al. (2001) study only included participants with normal hearing (NH). A 2005 study by Arbogast, Mason, and Kidd investigated the spatial release from masking phenomenon with participants with NH and participants with bilateral sensorineural hearing impairment (HI). The researchers were also interested in the effect of the type of masker on spatial release from masking (SR). The three types of maskers in this study included: (1) different band speech (DBS; assumed to contain primarily informational masking), (2) different band noise (DBN; assumed to have minimal energetic and informational masking), and (3) same band noise (SBN; presumed to contain mostly energetic masking). The stimuli used in this study were CRM sentences (see details from the Brungart, 2001 article). There were two speakers in this experiment, speaker 1 at 0° azimuth (re: the participant's nose) and speaker 2 at 90° azimuth. For the first speaker condition, the signal and the masker were presented from speaker 1 and for the spatially separate condition, the signal was presented from speaker 1 and the masker was presented from speaker 2. The spatial release from masking (SR) was calculated by subtracting the signal to masker ratio (S/M) for the second speaker condition from the S/M for the first speaker condition. Results revealed that for the DBS masker, the SR was significantly better than for the DBN or SBN (for the NH and the HI group). Also for the DBS masker, the NH group performed significantly better than the HI group. For the DBN and SBN maskers, the SR was low and there was no significant difference between the NH and HI group. This study suggests that even the HI group can benefit from SR if speech is used as the target and masker. However, this study provides no evidence that this can be maintained with a spatial separation less than 90°. That is the reason that in the current study, speech was used as the masker and the target and masker(s) were separated by 90 – 180° to maximize the effectiveness of SR for the participants with HI.

Shinn-Cunningham and Wang (2008) found that speech intelligibility improves when speech-modulated noise is used as a masker versus unmodulated noise. This was completed in the first part of their experiment with five participants with normal hearing. The Institute of Electrical and Electronic Engineers (IEEE) sentences were used as target stimuli and were altered to include gaps. The gaps were either filled in with silence, unmodulated noise, or speech-modulated noise. The sentences were played binaurally through headphones. Results from this part of the experiment confirmed that speech-in-noise performance was significantly better with speech-modulated noise than for unmodulated noise. Also, participants performed significantly better with noise versus silence filling in the gaps in the sentences. This is another reason that speech was used as the masker in the current study.

The purpose of the second part of the study (Shinn-Cunningham & Wang, 2008) was to determine if spatial separation of signal and masker could improve speech intelligibility. Four participants with normal hearing participated. IEEE sentences were used as target stimuli in this part of the study as well. The different combinations of target and masker were played under headphones in two different listening conditions: (1) diotic or "collocated" where the signal and masker were presented to the same ear and (2) the signal and masker were presented to both ears but the masker was presented to the right ear with a slight time delay so that the participants perceived the noise as coming from a different location (right) than the signal (front). Results from this experiment revealed that perceived spatial separation caused a significant improvement in hearing-in-noise performance for the unmodulated noise, but not for the modulated noise masker. The best performance was seen in the "collocated" listening condition with speech-modulated noise followed by "collocated" with unmodulated noise, then the spatially separate condition with unmodulated noise, and finally, the spatially separate condition with speech-modulated noise. The lowest performance was for the spatially separate condition using speech-modulated noise and was somewhat unexpected based on previous research about spatial separation of signal and masker (Freyman et al., 2001; Arbogast et al., 2005). The researchers of this study include an explanation of the unexpected results. They state that when speech-modulated noise fills in the gaps and the signal and masker are coming from the same direction, this encourages participants to fill in the missing speech information. But if the signal and the masker are spatially separated, the brain thinks "that is noise coming from another direction, it must be a *masker*." This theory is based on the way humans spatially organize auditory information into objects. For the "collocated" listening condition with unmodulated noise, the researchers hypothesize that the participant is still encouraged to fill in the gaps of missing speech. There are a few things to keep in mind when examining the results from this study. First of all, the number of participants was small (four). Also, the study was completed under headphones. In the current study, the hearing-in-noise task was completed with speakers. And finally, none of the maskers used in this study were speech and when speech is used as a masker, most research has found that there is a spatial release from masking (SR).

Another study that addressed the effect of spatial separation of target and masker was conducted by Duquesnoy (1983). The purpose of the study was to determine if separation of the target and masker could positively influence the signal-to-noise ratio (SNR) required for understanding sentences in noise. One of the differences of this study compared to the Shinn-Cunningham and Wang (2008) study is that the participants were 20 elderly adults (age 75 – 88 years) with sensorineural hearing loss (SNHL). Ten young normal hearing participants were also included in this study (NH). Sentences created by

Plomp and Mimpen (1979) were recorded by a female talker and used as stimuli. There were five possible signal and masker locations: front-front (FF), front-right (FR), front-left (FL), right-front (RF), and left-front (LF). The target sentences were presented in quiet or with one of three masker types including noise, speech (lists of sentences by a male talker), and backward speech. The signal and masker were presented either to the right ear only, the left ear only, or binaurally. Results revealed a significant difference between the SNHL and NH groups for all conditions. Interestingly, separating the signal and masker lead to better speech intelligibility for the NH group but not for the SNHL group. There was no significant difference between forward and backward speech maskers. Also, the NH group performed significantly better when speech (forward or backward) was used as the masker, but the SNHL group did not. This study suggests that participants with SNHL (particularly those who are above age 75) might not benefit from spatial separation of the signal and masker or from speech used as a masker like other research has shown in participants with NH. The lack of spatial release from masking (SR) in the SNHL group could be due to a decrease in temporal and/or frequency resolution and possibly due to a decrease in spatial awareness. These results support that participants with SNHL might not benefit from spatial separation of target and masker and do not show a significant difference in performance when using different types of maskers. Based on results from other studies mentioned in this paper (Freyman et al., 2001; Arbogast et al., 2005), however, the current study used spatial separation of the target and masker, as well as speech as a masker, to maximize any spatial release from masking that might improve the participant's speech intelligibility in noise performance.

It is important to note that the participants in this study were age 75+ years so the results could have been confounded by decreased cognitive ability. In order to avoid this possibility, the current study included younger participants between the ages of 29 and 67 years.

Kidd, Arbogast, Mason, and Gallun (2005) studied the effect that an “a priori” knowledge of the location of the target signal and an “a priori” knowledge of which of three signals was the target sentence could affect speech intelligibility in noise. Four participants with normal hearing completed this study. The stimuli were Coordinate Response Measure (CRM) sentences recorded by four male talkers. As discussed before, an example of the CRM sentences is: “Ready [callsign] go to [color] [number] now” where the participant’s task is to correctly identify the color and number included in the target sentence. Sentences were randomly presented to three speakers at 0°, +60°, and -60° azimuth (re: the participant’s nose) at 60 dB SPL. There were different types of cues for the identification and the location of the target sentences. To assist identification of the target sentence, the callsign of the target sentence was either displayed on a screen before or after the three sentences were played. For location, the investigators provided the participant with the probabilities of the target sentence occurring at each of the three speakers. Results revealed that for both callsign (before or after) conditions, as uncertainty about the location of the target signal increased, performance decreased. The results suggest that knowing the location of the target signal can improve speech intelligibility in noise. The lower the uncertainty in the listening situation, the better the participants performed. Conversely, the higher the uncertainty, the poorer the participants performed. For the current study, the target signal was presented from a fixed location at 0° azimuth to minimize uncertainty about the location of the target signal and therefore minimize the effect this has on speech intelligibility in noise. Also, the investigator in the current study informed the participants about which signal-masker condition to expect before each run.

A 2003 article by Blumsack includes an overview of research on spatial hearing abilities in patients with hearing impairment. For most people, localization can be accomplished with only one ear but two is better than with one. Another point made in this article is that as background noise increases, localization ability decreases. In general, hearing impairment negatively affects the ability to localize. Vertical localization can be affected by a hearing loss in the high frequencies, and horizontal localization can be affected by a hearing loss in the mid to high frequencies. Predictably, an asymmetric hearing loss can decrease localization ability because it affects ITD and ILD cues. Regarding amplification, a bilateral hearing aid fitting can result in better horizontal localization when compared to a unilateral fitting. A behind-the-ear (BTE) style hearing aid can decrease pinna-related cues, making it more difficult to localize sounds in the vertical plane. Horizontal localization ability can be negatively affected by a closed earmold on a hearing aid. In the current research, the participants were fit with bilateral hearing aids with open earmolds to maximize localization ability with the hearing aids. Vertical localization was not tested in the proposed study so BTE style hearing aids (open-fit) were deemed appropriate because this style of hearing aid only affects vertical localization ability.

Another overview of the research about spatial awareness is included in an article by Darwin (2006). This article points out that in a speech-in-noise task, if the masker is a steady-state background noise, the target signal will be weaker than the background noise, so the patient must piece together the parts of the speech signal that are received. When speech is used as the masker, the patient must group together the frequency and temporal characteristics of each stream in order to focus on the target speech. If temporal and frequency cues are not present during a speech-in-noise situation, people rely more heavily on spatial separation cues. Patients with hearing loss might have a more difficult time using temporal and frequency cues because of the possibility of decreased temporal and frequency resolution in the cochlea. This could lead to the dominant signal being even more dominant than the weaker speech signal when compared to patients with normal hearing.

2.4.1 Spatial Separation, Hearing Impairment, and Hearing Aids

Regarding spatial separation and patients with hearing impairment who use hearing aids, Shinn-Cunningham (2009) explains that background sounds are “salient” to the new hearing aid user so these salient sounds typically “win” the battle for selective attention. Background sounds (either speech or noise) can overlap the target speech signal in frequency and time. In general, as the number of maskers increase, speech intelligibility decreases because the increasing number of maskers increases the amount of overlap of frequency and temporal information of the target speech signal, making it more difficult for the patient to spatially separate the different auditory "objects." When there is more than one talker in a conversation, localization is important especially if noise is present. This is because the listener must be able to quickly switch attention between the different talkers. Speech intelligibility can be improved if the listener can focus on the frequency, intensity, "voice quality," rhythm, and content of the target speech signal. As discussed before, understanding speech in noise can be especially difficult for patients with sensorineural hearing loss possibly due to a decrease in temporal and frequency specificity in the cochlea. Patients with hearing impairment have also been shown to have poorer gap detection, harmonicity and pitch detection, and localization ability when compared to patients with NH.

In order to address the decrease in speech intelligibility in patients with hearing impairment, Van den Bogaert, Doclo, Wouters, and Moonen (2009) investigated the effect of adaptive directional microphones (ADMs), multichannel Wiener filters (MWFs), and MWF with partial noise estimate (MWF-N). The MWF is a filtering technique that attempts to preserve binaural cues for speech and noise *and* maintain noise reduction performance. The MWF has mathematically been shown to preserve binaural cues of the speech component but not the binaural cues of the noise component (Doclo, Klasen, Van den Bogaert, Wouters, & Moonen, 2006). The preservation of binaural cues for the speech *and* noise components of the input signal is ideal so that the hearing aid user can maximize the spatial awareness of the signal and the noise. Another technique that attempts to preserve binaural cues and maintain noise reduction is the MWF with an "interaural transfer function" extension (MWF-ITF). This technique has been shown to maintain noise reduction performance *and* preserve binaural cues but only for *one* noise source (Van den Bogaert, Doclo, Moonen, & Wouters, 2007). A third technique that attempts to preserve binaural cues while maintaining noise reduction is the MWF with "partial noise estimate" (MWF-N). The purpose of the Van den Bogaert, Doclo, Wouters, and Moonen (2009) study was to compare hearing aids with ipsilateral microphones (monaural) to hearing aids with contralateral microphones that communicate with the ipsilateral hearing aid (binaural). The investigators used adaptive directional microphones (ADMs; monaural), microphones with MWF (binaural), and microphones with MWF-N (binaural). Ten participants with normal hearing participated. The study included three hearing-in-noise conditions (1) signal at 0° and noise at 60° (S_0-N_{60}), (2) S_{90}-N_{270}, and (3) S_0-$N_{90, 180, 270}$. These hearing conditions were tested in three different rooms: (1) a "realistic reverberant environment", (2) a semi-anechoic chamber, and (3) under headphones. The target stimuli were sentences presented by a male talker at 65 dB(A) and the masker was multi-talker babble. Results revealed that participants performed significantly better with the hearing aids with contralateral microphones (similar to hearing aids with binaural processing) than with the hearing aids with ipsilateral only microphones (similar to bilateral hearing aids). The purpose of adding the partial noise estimate to the MWF filter (MWF-N) is to enhance spatial awareness and localization. Adding the partial noise estimate only caused a slight decrease in speech intelligibility performance. The importance of this study is that by using contralateral microphones in hearing aids, speech intelligibility might improve. The results of this study cannot be generalized to patients with hearing loss because it was only tested on participants with normal hearing. This makes the current research more relevant because contralateral microphones have not been compared to ipsilateral microphones on participants with HI in a speech intelligibility in noise task. Can the hearing aids used in the current study improve speech intelligibility performance in patients with hearing impairment as well?

The aim of the current study was to determine whether hearing aids with binaural processing can help participants in a horizontal localization task and in a hearing-in-noise task. The hearing aids that were used in the proposed study are Oticon Epoq XW receiver-in-the-ear (RITE) hearing aids. Oticon published a white paper based on data collected from research using Epoq XW hearing aids with binaural processing (Schum, 2008). The white paper reviews many important points that pertain to the current study as well. The paper states that ITD cues are used at frequencies below 1500 Hz, ILD cues are used at frequencies greater than 1500 Hz, and vertical localization cues are used at frequencies greater than 5000 Hz. Patients with sensorineural hearing loss can use spatial separation to better understand speech in noise but not as well as those with normal hearing. The paper also discusses the way that the compression system in Epoq XW works. With traditional hearing aids, no matter where the sound originates in space, the compression system will allow less amplification at the near ear and more amplification at the far ear, resulting in virtually the same intensity at both ears. The traditional compression system disrupts the natural ILD cues used for horizontal localization. Epoq XWs, on the other hand, work together and apply different levels of compression to the different aids if the sound is coming from one side versus the other. ILD cues, in theory, are maintained with the binaural processing of Epoq XW hearing aids versus traditional (unlinked) hearing aids.

Another white paper published by Oticon includes a more detailed explanation about the binaural compression system (Oticon white paper). Epoq XW hearing aids can wirelessly communicate with one another and are thought to preserve spatial awareness. With a binaural compression system, the aids can maintain the difference between the levels of a sound at the two ears of the listener, preserving ILD cues. For example, when a sound originates from the side of the listener, the aid on the near ear will amplify the sound more than the aid on the far ear. Because the Epoq XW is available as an open-fit receiver-in-the-ear (RITE) style hearing aid, this can also help preserve ILD cues because the open mold allows low and mid frequencies to enter the ear canal without much change. If hearing aids with binaural processing can help preserve localization cues, they could help patients better understand speech in noise. With improved localization, the patient might be able to group sounds into objects more easily. If the patient can group the sounds into objects, then the brain can ignore unwanted sounds/objects and focus more easily on the object of interest. The Oticon white paper includes information from a study that was conducted with the Oticon Epoq XW (see Hansen, 2008). In this study, the participants filled out an abbreviated version of the Speech, Spatial, and Qualities (SSQ) questionnaire to assess if they perceived that the Epoq XW hearing aids improved their spatial awareness or if their own hearing aids improved their spatial awareness. The results revealed that the Epoq XW hearing aids lead to better spatial awareness (subjectively speaking). Neither spatial awareness or localization were tested objectively in this study, therefore, it cannot be concluded that the perception of improved spatial awareness is actually a phenomenon created by these hearing aids. Also, it cannot be concluded from this study that because the participants perceived an improvement in spatial awareness, that they could actually focus attention on a target speech signal and ignore unwanted signals; these objective measures were not completed in the study. This is another reason that the current study is relevant, because the participants with hearing impairment completed a localization task with the Oticon Epoq XW hearing aids to determine if the binaural processing of the aids can improve objective localization performance. And further, can the aids improve speech intelligibility in noise?

2.4.2 Spatial Awareness, Hearing in Noise, and Hearing Aids

Behrens (2008) presented a study about the Oticon Epoq XW hearing aids that included results from the Speech, Spatial, and Qualities of Hearing scale (SSQ). This study included 58 participants with mild to moderate hearing loss who were experienced users of high-end Oticon hearing aids. The participants were bilaterally fit with Epoq XW hearing aids and wore them for at least four weeks before testing. After their hearing aid trial period, the participants filled out an abbreviated version of the SSQ, once based on their experience with their own hearing aids, and another time based on wearing the Epoq XWs for approximately four weeks. The responses for the SSQ are based on a scale of 0 to 10 with 0 representing minimal ability and 10 representing complete ability. For the following seven situations, Epoq XW ranked on average one point higher than the participant’s own hearing aids: “Talk with one person in quiet,” “Locate speaker around a table,” “Ignore competing sounds,” “Ignore interfering voice,” “Sounds in expected location,” “Locate vehicle from pavement,” and “Judge distance form voice or footsteps.” These results suggest that for at least seven of the items included in the SSQ, the participants perceived benefit from the Epoq XWs when compared to their own hearing aids. There is no laboratory evidence thus far that confirms the perceived improvement in spatial awareness which was investigated in the current study.

Hansen (2008) presented the results from the same Epoq study mentioned above, but also included results from an objective hearing-in-noise test completed by the same 58 participants who were fit with Epoq XW hearing aids. The participants wore the Epoq XWs for at least four weeks prior to testing. For the hearing-in-noise test, the Epoq XW hearing aids were programmed as they were at the end of the trial period (if changes were made after the initial fitting, the changes remained for the hearing-in-noise study). The Danish sentence test called “Dantalle II” was used to assess hearing-in-noise ability. Speakers were located at 0°, 110°, 180°, and 250° azimuth (re: the participant’s nose). During testing, the level of the masker was held constant and the level of the signal (always presented at 0° azimuth) was varied to obtain the signal-to-noise ratio where the participant correctly repeated at least 50% of the sentences. Results revealed that there was improvement in hearing-in-noise performance with the Epoq XW hearing aids versus the participants’ own hearing aids. Another white paper written about the same Oticon Epoq XW study (Hansen, 2008) stated that the difference in hearing-in-noise performance between the participants’ own hearing aids and the Oticon Epoq XWs was significant. These objective results are consistent with the subjective results discussed in the Behrens (2008) article. Another result from this study is that the Epoq XW hearing aids were, in general, accepted within the first week of use. After the study was complete, the participants were asked if they would rather keep their own hearing aids or keep the hearing aids used in the study. The majority of participants preferred keeping the Epoq XWs over their own hearing aids. It is important to note that the results of this study only included 17 out of 50 items from the SSQ. There is no statement regarding whether the participants filled out the entire SSQ, and based on the results, the researchers chose only 17 of the total amount of items to better reflect benefit of the Epoq XW hearing aids over the participants' own hearing aids. In the current study, hearing-in-noise performance was tested with English sentences with maskers at different speaker locations which made it different from this Oticon study. In addition to hearing-in-noise testing, another objective test was completed in the current study that was not completed in the Oticon study: horizontal localization. Similar to this study, scoring for the hearing-in-noise testing for the current study involved calculation of the SNR where the participant correctly repeated the target sentences at least 50% of the time. Also like this study, the masker level was fixed during the hearing-in-noise testing, while the level of the signal was adapted to obtain the final SNR.

The main purpose of the current research was to determine if binaural hearing aids (BIN) can positively affect performance in a horizontal localization task or in a hearing-in-noise task when compared to no hearing aids (NO) or bilateral hearing aids (BIL). Was there a significant difference between listening conditions (NO, BIL, and

BIN) for the horizontal localization or hearing-in-noise tasks? If so, in what listening condition did the participants perform the best for the localization and the hearing-in-noise tasks? Also, was there a significant difference between the four masker conditions (S_0-N_{90}, S_0-N_{180}, S_0-N_{270}, and S_0-$N_{90, 180, 270}$) for the hearing-in-noise task?

Other questions answered in this research regarding horizontal localization are the following: (1) Was there a significant difference in performance when the half-circle speaker array was positioned to the right (participants 1 – 8) versus to the left (participants 9 – 16)? (2) Was there a difference in performance for “front” speakers (1 – 6) versus “back” speakers (7 – 11)? The current study was unique compared to the Oticon studies because the participants completed a horizontal localization task as well as a hearing-in-noise task and they were new hearing aid users.

III. METHODOLOGY

3.1 Participants

The study included 11 male and 5 female participants between the ages of 29 and 67 years. The maximum age in this study was limited to 67 years in order to minimize cognitive factors that could affect test results. The participants had bilateral mild to moderate essentially symmetrical high frequency sensorineural hearing loss (SNHL; except participant 07 who had a mild flat SNHL). For frequencies at and below 2000 Hz, the participant's audiometric thresholds ranged from normal to mild (0 – 40 dB HL). For frequencies above 2000 Hz, the participant's thresholds ranged from mild to moderate (25 – 65 dB HL) for at least three of the four frequencies. This hearing loss configuration is representative of the majority of patients seeking amplification. Refer to Tables 1 and 2 for right and left ear thresholds, respectively, along with age and gender. For this study, a symmetrical hearing loss is defined as no more than a 10 dB HL difference between ears for at least seven out of eight frequencies tested from 250 – 8000 Hz. One participant (09) had a slight asymmetry at 3000 Hz and another participant (05) had an asymmetry at 4000 Hz. Two participants (04 and 07) had an asymmetry at 8000 Hz. These differences were probably due to these participants' individual exposure to shooting guns. Sensorineural hearing loss was defined as an air-bone gap (ABG) of 10 dB or less at frequencies between 250 – 4000 Hz. All participants had normal Type A tympanograms, suggesting normal tympanic membrane movement. Type A tympanograms were defined as compliance of 0.3 – 1.7 and a peak between -150 and 50 daPa. Participants scored 90% or higher on word recognition testing at 30 dB sensation level (SL; re: SRT) using Northwestern University word lists. Participants had no prior hearing aid experience in order to reduce variability in the outcomes due to prior experience with different styles and technologies of hearing aids.

Table 1

Participant characteristics and thresholds (in dB HL) for the right ear.

Subject	Age	Gender	250 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
01	29	M	20	15	15	30	25	25	25	25
02	65	M	15	20	20	20	30	20	25	40
03	61	F	20	5	10	35	35	25	45	45
04	61	M	5	5	10	20	50	65	35	55
05	56	M	10	10	15	15	40	60	40	25
06	56	M	5	10	10	15	30	60	60	50
07	37	M	30	30	30	35	30	35	35	30
08	61	F	15	20	25	30	30	35	50	60
09	53	M	10	15	10	10	25	35	30	35
10	59	M	10	15	20	20	30	45	55	55
11	65	F	25	25	15	25	25	25	35	55
12	54	F	20	25	30	35	45	55	60	60
13	57	M	10	15	25	35	35	45	40	35
14	63	F	5	5	10	15	25	30	50	60
15	67	M	15	20	20	20	40	25	40	65
16	62	M	10	5	5	25	55	55	55	60

Table 2

Participant characteristics and thresholds (in dB HL) for the left ear.

Subject	Age	Gender	250 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
01	29	M	20	15	20	30	30	25	25	30
02	65	M	25	30	20	20	25	25	30	50
03	61	F	15	5	5	25	35	35	35	55
04	61	M	0	5	10	30	45	60	25	5
05	56	M	15	15	15	15	30	30	35	15
06	56	M	10	10	10	10	40	60	55	60
07	37	M	25	30	30	30	30	30	25	15
08	61	F	10	20	25	25	35	40	50	50
09	53	M	15	15	15	15	45	45	30	25
10	59	M	10	15	20	25	35	40	50	45
11	65	F	20	20	15	25	25	35	45	45
12	54	F	20	30	35	35	45	50	50	50
13	57	M	15	20	20	40	45	50	45	35
14	63	F	5	5	5	15	25	30	40	60
15	67	M	15	15	15	20	35	35	45	65
16	62	M	5	5	0	25	50	55	55	55

3.2 Equipment/Apparatus

The participant's hearing sensitivity was tested with a GSI 61 audiometer with E.A.R. insert earphones in a double-wall sound-treated audiometric booth. Acoustic immittance was completed using a TympStar immittance bridge. Both the localization and the hearing-in-noise tests were completed in an anechoic chamber with the following dimensions: 3.67 m long x 2.44 m wide x 2.21 m high. Stimuli were presented using Adobe Audition via a Dell Latitude D400 laptop, amplifier, and 11 Apple Pro speakers arranged in a half-circle either to the right (participants 1 – 8) or left (participants 9 – 16) side of the participant. The stimuli were routed from the laptop to the speakers via a MOTU 828mx11 USB 2.0 device, a Behringer Ultragain Pro 8 Digital 8-Channel A/D and D/A converter (Model ADA8000), and two Rane MA6 multichannel amplifiers. The speakers were positioned approximately one meter from the center of the participant's head, every 18° to complete a 180° half-circle arc. The speakers had a specified frequency range of 70 – 20,000 Hz. Each of the 11 speakers were clearly labeled with its respective speaker number, from numbers 1 – 11 (see Figure 1). For the localization task, the participants faced either speaker 1 (participants 1 – 8) or speaker 11 (participants 9 – 16). For participants 1 – 8, speaker 1 was located at 0° azimuth (re: the participant's nose) and speaker 11, at 180° azimuth. For participants 9 – 16, speaker 11 was at 0° azimuth and speaker 1 was at 180° azimuth. Refer to Figures 2 and 3 for a diagram of speaker setup. The participants were seated in a chair that could be adjusted in height so that the opening of the ear canal was approximately at the height of the speaker diaphragms. Once the participant was positioned in the center of the speaker array, a small headrest that was attached to a microphone stand was placed behind the participant to ensure proper head placement during testing. The headrest stand was adjusted to the approximate height of the participant's head while seated. The participant was instructed to make sure that the head was touching the headrest throughout testing. The investigator monitored the participant's head position and reminded the participant to keep the head touching the headrest as needed.

Figure 1. Photograph of speaker setup with number labels in anechoic chamber. Headrest and contralateral speaker 12 not included in this photo in order to highlight speaker numbering and placement.

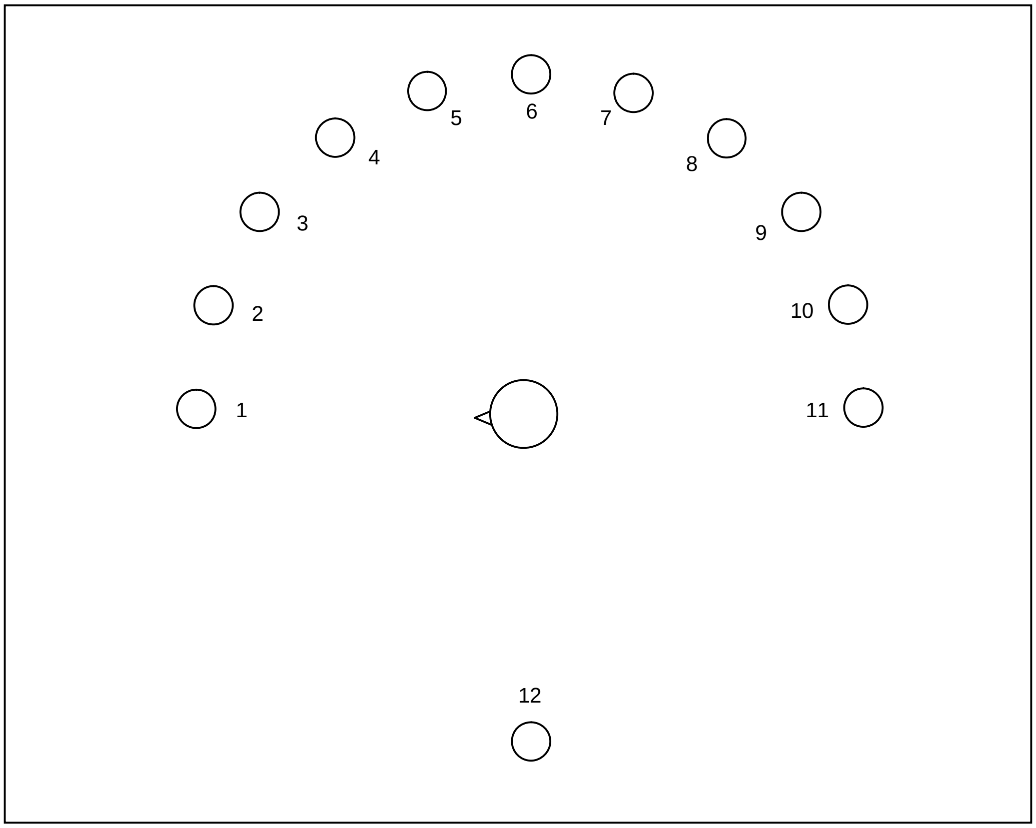

Figure 2. Schematic of speaker setup for localization testing for participants 1 – 8, facing speaker 1 and with speaker array on the right side.

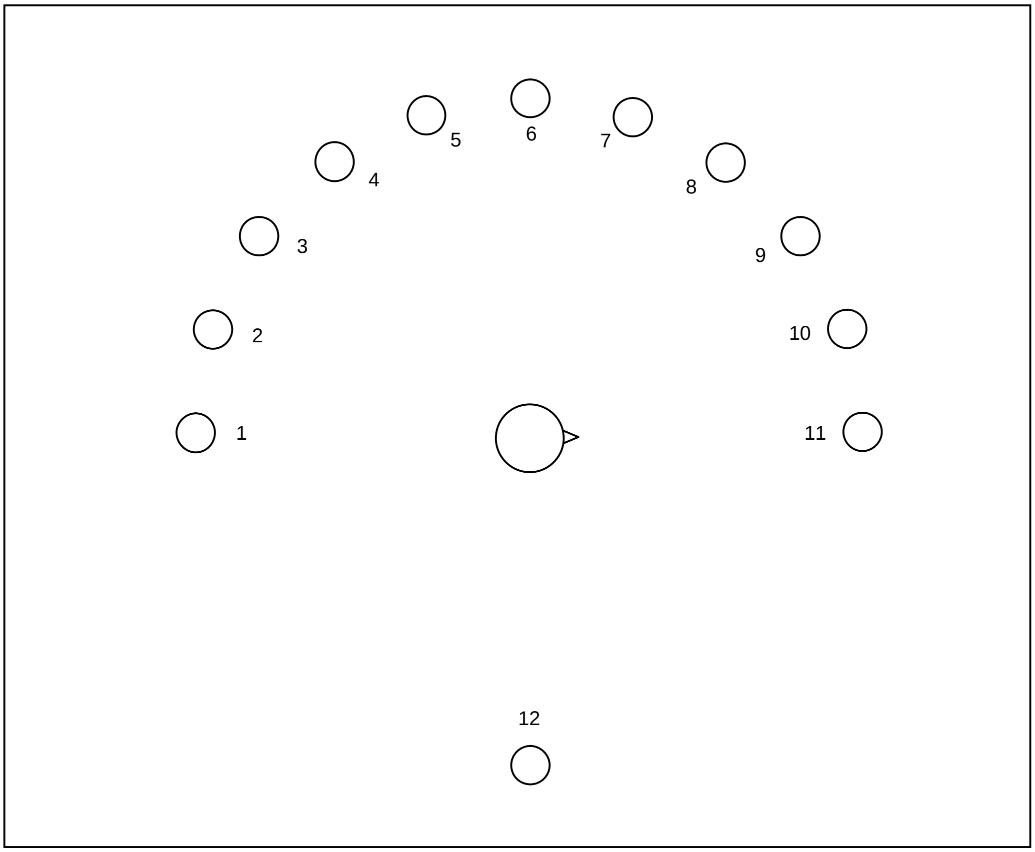

Figure 3. Schematic of speaker setup for localization testing for participants 9 – 16, facing speaker 11 and with speaker array on the left side.

For the hearing-in-noise test, all participants faced speaker 1 (0° azimuth). Three other speakers were used to present maskers: speaker 6 (to the right of the participant at 90° azimuth), speaker 11 (directly behind the participant at 180° azimuth), and speaker 12 (to the left of the participant at 270° azimuth; refer to Figure 4). The speakers were positioned approximately one meter from the center of the participant's head and in 90° increments. The participants were seated in the same chair that could be adjusted in height so that the ear was approximately at the height of the speaker diaphragms. Once the participant was positioned in the center of the speaker array, the small headrest was placed behind the participant at the level of the head to ensure proper head placement during testing. The participant was instructed to make sure that the head was touching the headrest throughout testing. The investigator monitored the participant’s head placement, and reminded the participant to keep the head touching the headrest as needed.

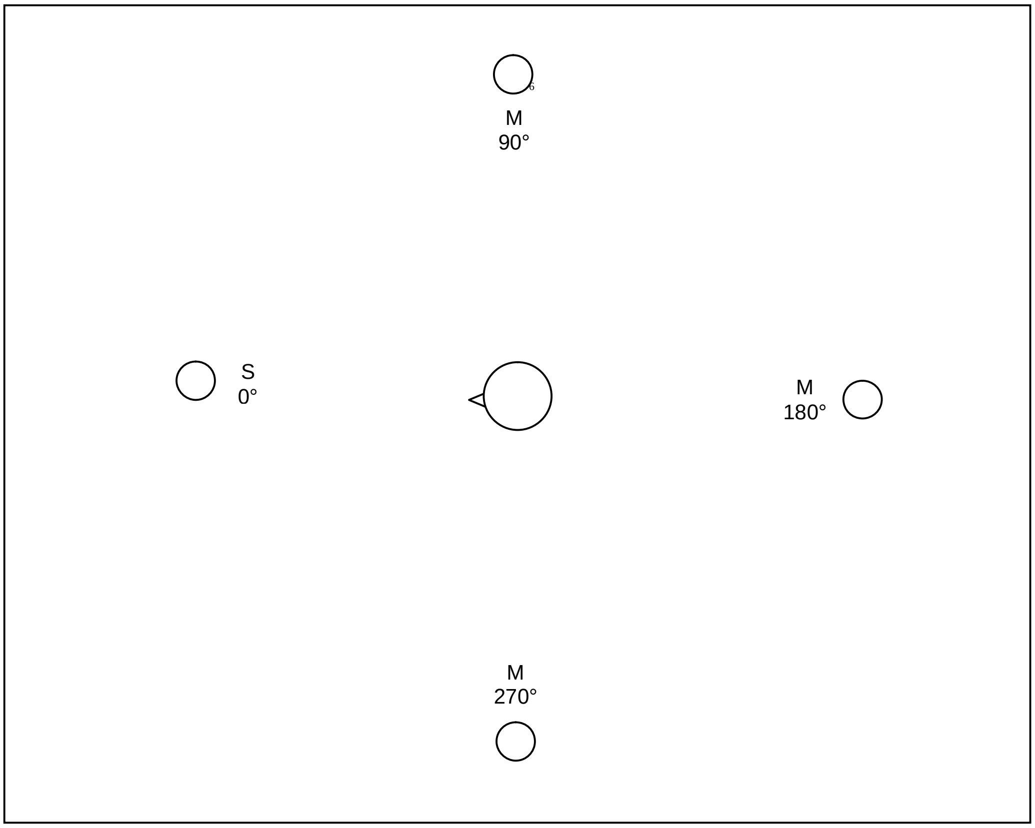

Figure 4. Schematic of speaker setup for hearing-in-noise testing. S=Signal, M=Masker. The four hearing-in-noise conditions included: (1) signal at 0° and masker at 90° (S_0-N_{90}), (2) signal at 0° and masker at 180° (S_0-N_{180}), (3) signal at 0° and masker at 270° (S_0-N_{270}), and (4) signal at 0° and maskers at 90°, 180°, and 270° (S_0-$N_{90,\ 180,\ 270}$).

3.3 Calibration

The positioning of the 11-speaker array and contralateral speaker 12 was initiated from a point in the center of the anechoic chamber. Each speaker was approximately 31.29 cm from the next one and 1 meter from the center point. A small weight was suspended from the ceiling with monofilament line at the center point of the speaker array to keep the center point consistent between test sessions. This plumb-bob device was secured near the top of the ceiling in the anechoic chamber and was attached to the line so that it could be lowered to measure the placement of the participant in the middle of the speaker array. Marking tape was placed on the base of each speaker stand and lined up with tape on the floor of the chamber to ensure proper placement of the speakers and stands between testing sessions. Before each testing session (localization and hearing-in-noise), the speakers were calibrated to the appropriate sound pressure level. A Quest 2700 sound level meter (SLM) was placed on a tripod in the center of the speaker array with the microphone at the height of the speaker diaphragms. The plumb-bob was lowered to just above the SLM microphone to ensure proper placement of the SLM. The stimulus used for the calibration for localization testing was the same pink noise that was used as the testing stimulus. For the localization testing, speakers 1 – 11 were calibrated to 75 dB SPL and speaker 12 was calibrated to 65 dB SPL. All levels were reached within ± .2 dB SPL of the target intensity and were measured using an A-weighted scale. The stimulus used to calibrate for the hearing-in-noise test was the pre-recorded cold-running speech of the three masker voices for speakers 6, 11, and 12 (refer to Figure 4). The level was calibrated to be, on average, 30 dB SL above the participant’s best/lowest speech recognition threshold (SRT; converted from HL to SPL). The HINT sentences were used to calibrate speaker 1 to 30 SL (re: SRT, converted to SPL).

3.4 Hearing Aids

Participants were fit with Oticon Epoq XW receiver-in-the-ear (RITE) hearing aids bilaterally. The hearing aids were programmed to the best-fit target based on Oticon's fitting algorithms. One of the listening conditions for this study was unaided. For a second listening condition, the hearing aids were programmed to work independently ("Binaural Broadband" off; BIL) and for the third condition, the aids were programmed to work together ("Binaural Broadband" on; BIN). The order of listening conditions was counterbalanced to minimize any learning effects (see Appendix A1). The features that were disabled when "binaural broadband" (BB; binaural processing) was turned off are as follows: Spatial Sound, My Voice, Binaural Dynamic Feedback Cancellation, and Binaural Coordination. Spatial Sound was the feature of interest for the proposed study and it is the term used by Oticon to describe the compression system that can wirelessly communicate between hearing aids and, in theory, preserve localization cues. Turning this feature off could affect localization and/or hearing-in-noise ability which is the purpose of the current study. The My Voice feature in the hearing aids recognizes when the patient is either talking or listening to another talker. When the patient goes from listening to another talker to talking, the hearing aids attempt to equalize the signal-to-noise ratios (SNRs) of the other talker and the surrounding noise and of the patient talking and the surrounding noise. Turning this feature off should not have affected results of the localization or hearing-in-noise tasks because the participant did not talk during stimulus presentation. Binaural Dynamic Feedback Cancellation

(DFC) is a feature that allows the hearing aids to better determine whether a tone originates from the patient's environment or in the hearing aid (feedback). If the tone originates from the environment, such as a music note or the beep from a microwave, this sound will reach *both* hearing aids. If both hearing aids detect this tone, they can communicate with each other that the sound occurred in the patient's environment. Because the tone is in both hearing aids, the hearing aids will not send an out-of-phase signal to cancel the sound as in the case of hearing aid feedback. On the other hand, if the sound is coming from the hearing aid, it is most likely feedback. The hearing aids can wirelessly communicate that the tone or squeal is only present in one hearing aid. The hearing aid on the affected ear will assume that the tone is feedback and will send a tone just out of phase form the feedback to cancel it out. Disabling this feature is not believed to affect localization or hearing-in-noise test results. Binaural Coordination is a feature that makes changing programs or changing volume easier for patients. If the hearing aid patient turns up the volume or changes the program of one aid then, via wireless communication, the volume or program changes in the opposite hearing aid. This should not have affected test results because participants did not change programs or adjust volume during testing.

Two sets of Oticon Epoq XW RITE hearing aids were used in the study. "Set 1" was programmed with BB turned off (BIL) and "Set 2" was programmed with BB turned on (BIN). An electroacoustic analysis (EA) was completed on each hearing aid before localization and hearing-in-noise testing for each participant. The hearing aids were connected to the appropriate receiver size for the participant and EA was measured to ensure that the hearing aids as well as the receivers were working to manufacturer's specs. Each hearing aid was connected to a coupling device that is used for verification measurements of open-fit hearing aids. Both ends of the coupling device were made of tubing. One side of the tubing was connected to a standard HA-2 (2-cc) coupler and the other side, connected to the hearing aid receiver. The EA was completed using the Automatic Gain Control (AGC) function of an AudioScan Verifit (Etymonic Design, Inc.). Both sets of hearing aids were programmed with two programs. Program one was programmed with omnidirectional microphone mode and noise reduction (NR) turned off for localization testing. NR was turned off because pink noise was used as the stimulus for localization testing. Program two was programmed to fixed directional microphone mode and NR turned on for the HIN task. This is the most realistic hearing aid setting for patients to use in a noisy situation, which is the situation that the hearing-in-noise test most closely resembled. Participants had no prior hearing aid experience.

3.5 Listening and Hearing Aid Conditions

The participants were tested with three listening conditions. For one condition, the participants were tested without hearing aids (NO) to establish a baseline. In a second condition, the two hearing aids were not linked (BIL), and in a third condition, the hearing aids were linked (BIN). The participants completed both tasks (localization and hearing-in-noise) with all three listening conditions: NO, BIL, and BIN. The order of listening conditions for each participant was counterbalanced to minimize the possibility of the learning effect (see Appendix A1). Performance could be affected by learning, because participants completed both tasks three times, hence the counterbalancing.

3.6 Stimuli

For the horizontal localization task, 1.5-second pink noise bursts were used as the target stimulus. The duration of the pink noise was chosen so that the compression system in the hearing aids had enough time to engage. Anything less than one second, according to the hearing aid manufacturer, would not be enough time to stimulate the compression system. A continuous pink noise was presented from speaker 12 (see Figures 2 and 3). According to the hearing aid manufacturer, the binaural compression system in the hearing aids will not engage unless the circuitry detects a difference in the acoustic environment. That is the reasoning for the constant pink noise presented to the contralateral side of the participant. When the target pink noise was presented at a higher intensity level and from a different location, in theory, the hearing aids should have recognized the different azimuths and altered the amount of amplification to each hearing aid based on the location of the “different” (target) stimulus. A two-second pause was programmed between each pink noise burst. The investigator was able to pause the string of pink noise bursts as needed to allow enough time for the participant to respond and for the response to be recorded. The constant pink noise on the contralateral side of the participant was presented at a fixed level of 65 dB SPL. The target pink noise bursts were presented at 75 dB SPL (10 dB SL, re: the constant pink noise). The target was presented at 75 dB SPL so that the participant would receive at least 5 – 10 dB SL at each octave frequency since the worst hearing threshold for any participant was 65 dB HL.

Sentences from the Hearing in Noise Test (HINT) were used as target stimuli for the hearing-in-noise task. The HINT normally consists of 25 lists of 10 sentences. For this study, lists were combined so that there were 12 lists of 20 sentences and one list of 10 sentences that was used as the practice run for each participant. Three different recordings were used as maskers during the hearing-in-noise testing. One of the recorded voices was a male voice (M1) and two of the voices were female (F1 and F2). Only one of the maskers was a male voice because the target sentences are spoken by a male voice. The masker voices were recorded using Adobe Audition 3.0 at a 16K Hz sampling rate in a sound-treated radio recording studio. Each masker voice read from a classic novel. M1 read from The Old Man and the Sea, F1 read from Alice in Wonderland, and F2 read from Lord of the Flies. The three maskers were instructed to read with the mouth approximately one-half inch from the microphone, and to attempt to read with equal effort/intensity, and with as few pauses as possible throughout the recording. The three recordings were equalized using the Group Waveform Normalize feature in Adobe Audition. Gaps of silence in the recordings that were greater than 0.5 seconds were deleted. The masker recordings were edited into small segments of audio material, individual to each HINT sentence. Each HINT sentence was matched up in Adobe Audition so that the onset of the target sentence and the onset of the masker were approximately equal. The length of the masker clip was at least equal to, if not longer than, the length of the target HINT sentence. For randomization, each HINT sentence was randomly assigned a masker from number one to three, one representing M1, two representing F1, and three representing F2. A random list of 20 numbers from one to three was generated for this randomization and was only accepted if each number was represented at least five times so that each masker voice was represented at least five times during each list of 20 sentences. Each sentence in all of the HINT sentence lists had one randomly assigned masker voice (M1, F1, or F2). These sentence lists with random maskers were used for all participants but the lists were randomly assigned for different conditions for each participant (see Appendix A2). Each target HINT sentence and its assigned masker (M1, F1, or F2) had the same onset time. The offset time of the masker was slightly later than the offset time of the target sentence to ensure that the masker fully overlapped the target sentence in duration.

3.7 Localization Procedure

For the localization experiment, participants 1 – 8 faced speaker 1 in the 11-speaker array and participants 9 – 16 faced speaker 11. The participants sat in a height-adjustable chair in the center of the speaker array. The investigator lowered the plumb-bob device to ensure that the center of the participant's head (between the ears) was in the center of the speaker array. Participant height was adjusted, as needed, using a story stick. Ongoing pink noise was presented from speaker 12 at 65 dB SPL. The target pink noise bursts were presented at 75 dB SPL and were 1.5 seconds in duration. The target stimuli were randomly presented to each speaker two times (two trials per speaker) for the practice run. If the participant struggled during the practice run, the investigator provided feedback to the participant. If the participant got the speaker location wrong, the correct answer was given, and the stimulus was presented from that speaker location again. The actual testing consisted of five random presentations from each speaker (five trials per speaker), making up five total runs per speaker for each listening condition (NO, BIL, and BIN).   No feedback was given during the test runs.

Number labels were posted under each speaker, from numbers 1 – 11 (see Figure 1). Participants 1 – 8 had the speaker array to the right side and participants 9 – 16 had the speaker array to the left side. An 8.5 x 11 in. schematic of the speaker array with corresponding speaker numbers was provided to each participant for reference. In order to minimize head movement, a headrest was placed behind the participant at head level. Participants were encouraged to make sure that the back of the head touched the headrest during the presentation of the stimulus. Another way that head movement was minimized was having the investigator in the anechoic chamber during testing to monitor the participant’s head movement and to reinstruct as needed. The investigator was seated in the anechoic chamber at approximately 315° azimuth (re: the participant’s nose facing speaker 1) during testing (see Figure 5). After the presentation of each target stimulus, the participant was allowed to turn in the chair to look toward the speaker where they thought the stimulus originated. Participants identified which speaker number they perceived the sound was coming from, and the investigator recorded the responses. No feedback was given to the participants during the test runs.

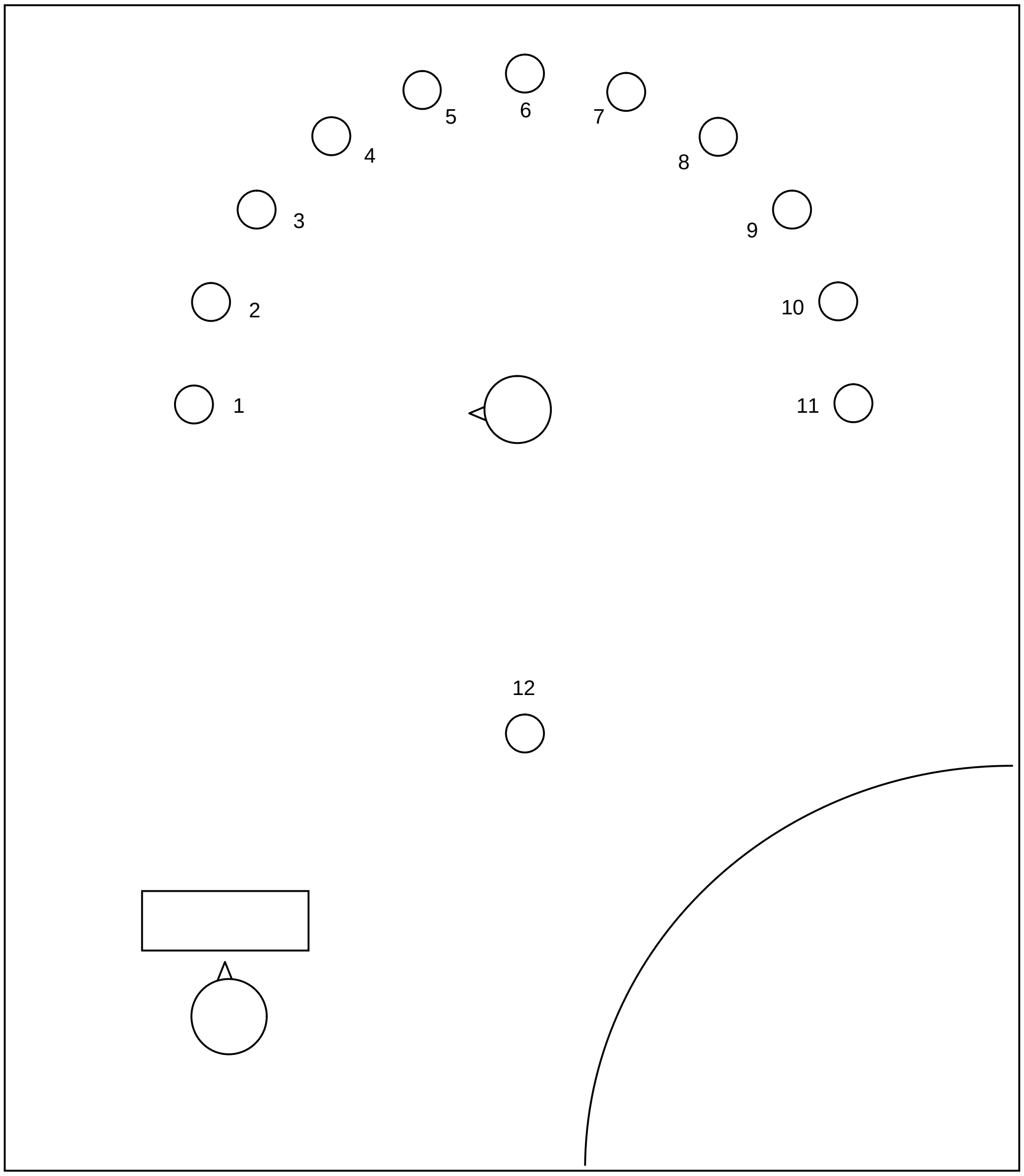

Figure 5. Schematic of speaker setup, chamber door, and investigator’s desk within the chamber.

3.8 Hearing in Noise Procedure

Hearing in Noise Test (HINT) sentences were presented simultaneously with the pre-recorded maskers. Target sentences were presented from speaker 1 at 0° azimuth (re: the participant's nose). Participants responded by repeating the target sentence presented from speaker 1. There were four different target and masker conditions: (1) signal at 0° and masker at 90° (S_0-N_{90}), (2) signal at 0° and masker at 180° (S_0-N_{180}), (3) signal at 0° and masker at 270° (S_0-N_{270}), and (4) signal at 0° and maskers at 90°, 180°, and 270° (S_0-$N_{90, 180, 270}$). Refer to Figure 4 for a diagram of the speaker setup for each condition. Before the target and masker conditions were completed, a quiet condition was completed with a 10-sentence HINT list. This was considered a practice run to familiarize the participants with the target voice for the hearing-in-noise testing. The practice run was completed without hearing aids. All of the target and masker conditions were completed with three listening conditions (NO, BIL, and BIN). The listening conditions were counterbalanced (refer to Appendix A1). For example, participant one completed the hearing-in-noise testing with listening condition one, then two, then three. Participant two completed listening condition three, then one, then two. The participants were tested for all four of the masker conditions for each listening condition. The order of masker condition was randomized for each participant. For each listening condition (counterbalanced) and masker condition (randomized), a HINT sentence list was randomly assigned (see Appendix A2).

The target sentences were presented from a fixed level, 30 dB SL (re: the participant's best unaided SRT). The SRT was tested unaided, in quiet, and with insert earphones as part of the hearing test. The dB HL level of the lowest SRT was converted to dB SPL and the target was presented 30 dB SPL above that level. Table 3 includes the SRT (in dB HL) for each participant for each ear and the corresponding presentation level for HIN testing (in dB SPL). For six of the participants, this level would have been 55 – 60 dB SPL. For these participants, the intensity of the target speech signal was adjusted to 65 dB SPL to ensure activation of the compression system in the hearing aids. For the first sentence of each list, the signal-to-noise ratio (SNR) started at 0 dB SNR. Participants repeated the target sentences as they heard them. If the participant responded incorrectly, then the SNR was increased by 4 dB (+4 dB SNR). If the sentence was correctly repeated, then the SNR was decreased by 4 dB (-4 dB SNR), and the next sentence was presented. For the first sentence, if the participant responded incorrectly, the SNR was increased until the participant provided a correct response, and that SNR was recorded for the first sentence. For the first four sentences, the SNR was *increased* by 4 dB if the participant responded *incorrectly*, or the SNR was *decreased* by 4 dB if the participant responded *correctly*. For the remaining 16 sentences, the SNR was increased by 2 dB if the participant responded incorrectly, or decreased by 2 dB if the participant responded correctly. The final SNR was calculated using a similar method as discussed in the HINT manual (HINT, 2003): the sum of the SNR for sentences 5 – 20 and the level at which sentence 21 would have been presented, divided by 17. Table 4 is an adaptation of a table in the HINT manual that details the calculation of the SNR score. The investigator was present in the anechoic chamber during the hearing-in-noise testing to remind the participant to minimize head movement. No feedback was given to the participants.

Table 3

SRTs (dB HL) and HIN Presentation Level (dB(A))

Subject	R_SRT	L_SRT	Presentation Level
01	15	15	65
02	20	25	70
03	15	15	65
04	10	10	**65**
05	15	15	65
06	10	10	**65**
07	25	20	70
08	20	20	70
09	5	10	**65**
10	10	10	**65**
11	15	15	65
12	25	25	75
13	15	15	65
14	10	10	**65**
15	20	10	65
16	5	5	**65**

Note. SRTs are in dB HL and presentation levels are in dB SPL. Presentation levels in boldface were slightly greater than 30 dB SL (re: SRT) to ensure activation of the compression system in the hearing aids.

Table 4

Method for Calculating SNR for HIN Testing

Sentence Number	Stimulus Level	Masker Level	SNR	Correct Response?
1	65	65	0	Yes
2	61	65	-4	Yes
3	57	65	-8	Yes
4	53	65	-12	Yes
5	51	65	-14	Yes
6	49	65	-16	Yes
7	47	65	-18	No
8	49	65	-16	Yes
9	47	65	-18	Yes
10	45	65	-20	No
11	47	65	-18	Yes
12	45	65	-20	No
13	47	65	-18	No
14	49	65	-16	Yes
15	47	65	-18	Yes
16	45	65	-20	No
17	47	65	-18	Yes
18	45	65	-20	No
19	47	65	-18	No
20	49	65	-16	Yes
[21]	47	65	-18	

Note. Signal-to-noise ratio (SNR) for hearing-in-noise (HIN) testing.

3.9 Schedule

The total time for testing sessions was approximately 3.5 hours. Breaks were taken as needed during the localization and hearing-in-noise testing. Two of the participants in this study finished all testing (hearing test, localization testing, and hearing-in-noise testing) in one day. Eight participants completed testing over two sessions (hearing test on one day and localization and hearing-in-noise testing during a second session). The average amount of time between the hearing test and localization testing was seven days. Six participants completed testing over three sessions with the average length of time between hearing test and localization testing being seven days, and between the localization and hearing-in-noise testing, five days.

3.10 Scoring

The root mean square (RMS) error was calculated for each speaker and a total score was calculated for all of the speakers for the localization task. The RMS for each speaker was calculated by taking the square root of the following: the square of the difference between perceived location and actual location, divided by the total number of presentations for that speaker. The total RMS for each listening condition (NO, BIL, and BIN) was calculated by taking the square root of: the square of the difference between perceived location and actual location for each speaker, added together, then divided by the total number of speakers. The total RMS in degrees was computed by multiplying the total RMS by the distance between speakers. A low RMS score represents better localization performance and higher RMS indicates poorer performance. A perfect score for RMS in degrees would be 0°.

For participants 1 – 8, the speaker array was on the right side; speaker 1 was located at 0° (re: the participant’s nose), speaker 6 was located at 90° azimuth, speaker 11 was located at 180° azimuth, and so on. For participants 9 – 16, the speaker array was on the left side, with speaker 1 at 0° azimuth, speaker 6 at 90° azimuth, speaker 11 at 180° azimuth, and so on. The data were entered into a database as speaker number, then converted in another file to degrees azimuth. The data for participants 1 – 8 were entered as 1 – 11, representing 0 - 180° azimuth. For participants 9 – 16, speaker 11 was at 0° azimuth and 1 was at 180°, so this data was entered as the opposite speaker in the array from the actual participant response. For example, if the stimulus was presented from speaker 7 (actual location at 108°), and the participant's response was speaker 7, the value entered into the data sheet was speaker 4 (corresponding to a response of 108° for participants 1 – 8). This was done so that the response (in degrees azimuth) for participants 1 – 8 corresponded to the responses from participants 9 – 16. Also, most mistakes during localization tasks were made at speaker locations behind the participant. If responses for speakers 1 – 11 were entered for participants 1 – 8 and 9 – 16 the same, then any difference between front versus back orientation would have been cancelled out. That is why for participants 1 – 8, the responses were coded as speaker 1 – 11, but for participants 9 – 16 (facing speaker 11), the responses were coded the opposite, to represent the location of the speaker (front/back/side, in degrees azimuth), not just by the speaker number. This was done to minimize the chance of the mistakes for participants 1 – 8 (generally higher for speakers 7 – 11) and the mistakes of participants 9 – 16 (generally higher for speakers 1 – 5) canceling each other out.

Some participants in the present study had front/back confusions. Because all of the participants had high frequency hearing loss above 4000 Hz, front/back confusions (responding with speaker number 11 when the stimulus was presented from speaker 1 and vice-versa) were entered as the opposite of the participant’s actual response (e.g. if the target stimulus was presented from speaker 1, and the participant responded with speaker 11, exactly 180° off, the response was coded as speaker 1).

The SNR performance for the hearing-in-noise task is the sum of the SNR for sentences 5 – 20 and the SNR at which sentence 21 would have been presented, divided by 17 (refer to Table 4). The more negative the SNR, the better the hearing-in-noise performance, while the closer to zero or the more positive the SNR, the poorer the performance. For the target HINT sentences, participants had to repeat the entire target sentence correctly. According to the HINT manual (HINT, 2003), only mistakes such as a/the, is/was, has/had, and are/were were accepted as correct. If any other word in the target sentence was repeated incorrectly, the entire sentence was considered incorrect.

IV. RESULTS

4.1 Localization

For the horizontal localization task, the dependent variable was the total root mean square (RMS) difference between actual and perceived speaker location for each speaker. The independent within-subject variables were the listening conditions (NO, BIL, and BIN), run (1 – 5), and location of each speaker (front versus back). The independent between-subjects variable included the orientation of the speaker array (to the right for participants 1 – 8 and to the left for participants 9 – 16). The specific aim was to determine which of the listening conditions resulted in the best/lowest RMS score and if this score was significantly better than the other scores. The null hypothesis for the localization test was that there was no significant difference between the NO, BIL, and the BIN listening conditions. The alternative hypothesis was that there was a significant difference between NO, BIL, and/or BIN.

A repeated-measures analysis of variance (ANOVA) was computed for the localization data to determine if there was a significant difference between the following within-subject variables: listening condition (NO, BIL, and BIN), speaker (1 – 11), and run (1 – 5 for each listening condition). The run factor was not significant so this variable was collapsed for the remainder of the analyses. A second ANOVA was completed to determine if there was a significant difference for the within-subject variables of listening condition and speaker and for the between-subjects variable of speaker array orientation (speaker array to the right versus left). The orientation of speakers was not significant so this variable was collapsed. A third ANOVA included the within-subject variables of listening condition and location of speaker (front versus back). The dependent variable in all of these analyses was the total RMS error for each speaker. Significance in this study was defined with an alpha level of $p < .05$.

4.1.1 Listening Condition, Speaker, and Run

The first ANOVA included the within-subjects variables of listening condition (3), speaker (11), and run (5). The between-subjects variable (speaker array orientation) was not included in this analysis. The goal of this ANOVA was to determine if there was an overall difference for listening condition, speaker, and run across all of the participants. Mauchly's test of sphericity revealed a significant departure from sphericity ($p < .05$) with the Epsilon value for Greenhouse-Geisser equal to 0.27. Because the Epsilon value for the sources was less than 0.75, the Greenhouse-Geisser (G-G) correction was used throughout the analysis when looking for significance.

The only significant finding in this analysis was for speaker $F(2.32, 32.41) = 11.58$, $p < .05$. The effect size of this difference was 0.45 (large) and the power was 0.99. The complete results from this analysis are included in Table 5. A pair-wise comparison was completed to determine where there was a significant difference (see Figure 6). The speaker comparisons with significance values and standard errors can be found in Appendix B. Generally speaking, speaker 2 was not significantly different from any other speakers, and speaker 11 was only significantly different from speaker 10. All other speakers were significantly different from at least four other speakers. Refer to Figure 7 for a graph of the overall RMS error (y-axis) averaged across listening conditions for each speaker (x-axis). There were no other significant main effects or interaction effects in this analysis. The run variable was collapsed for the remainder of the analyses.

Table 5

ANOVA Results for Listening Condition (Listen), Run, and Speaker

Source	df	F	ŋ	p
Listen	1.88	1.5	0.31	0.24
Run	2.78	1.53	0.32	0.22
Speaker	2.32	11.58	0.67	0.00**
Listen x Run	3.94	2.35	0.37	0.07
Listen x Speaker	4.65	1.94	0.35	0.11
Run x Speaker	5.33	1.14	0.28	0.35
Listen x Run x Speaker	6	1.08	0.26	0.38

Note. ** denotes *p* < .01.

Speaker Number

Speaker Number	1	2	3	4	5	6	7	8	9	10	11
1							*	*	*	**	
2											
3							**	**	**	**	
4							*	**	**	**	
5						*	*	*	*	**	
6							**	**	**	**	
7										*	
8											
9											
10											**
11											

Figure 6. Significant differences between speakers averaged across listening conditions. Note. * denotes *p* < .05 and ** denotes *p* < .01.

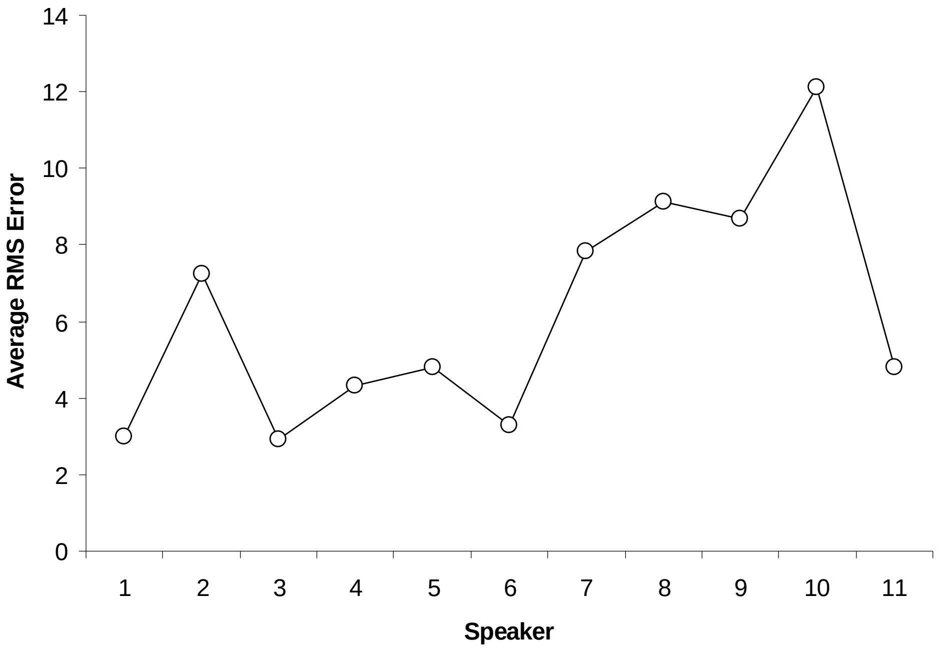

Figure 7. Average RMS error in degrees (y-axis) for each speaker (x-axis) averaged across listening conditions.

4.1.2 Listening Condition, Speaker, and Orientation of Speakers (Right vs. Left)

A second ANOVA was completed with listening condition (3) and speaker (11) as within-subject variables and orientation of speakers (2, right versus left) as a between-subjects variable. Orientation of speakers refers to where the speaker array was located (to the right side for participants 1 – 8 and to the left side for participants 9 – 16). The goal of this analysis was to determine if there was a significant difference between results for participants with the speaker array to the right and results for participants with the speaker array to the left. Was there a significant difference between the listening conditions for the two different groups when the between-subjects variable of orientation of speakers was included? Mauchly's test of sphericity revealed a significant departure from sphericity ($p < .05$) for at least one variable, so the Greenhouse-Geisser correction was used. For this analysis, the main effects of listening condition $F(1.84, 25.69) = 4.48$, $p < .05$ and speaker $F(2.74, 38.37) = 3.91$, $p < .05$, were significant. The effect sizes for these sources were large (0.24 and 0.22, respectively). The power for these sources was 0.69 and 0.76, respectively. A significant interaction was found for listening condition by orientation of speakers $F(1.84, 25.69) = 4.89$, $p < .05$. The effect size of this interaction was 0.26 which is considered large and the power of this interaction was 0.73. Refer to Table 6 for a summary of this analysis.

Table 6

ANOVA Results for Listening Condition, Speaker, Speaker Array Orientation (Orient)

Source	df	F	ŋ	p
Between subjects				
Listening x Orient	1.84	4.89*	0.51	0.02
Speaker x Orient	2.74	1.34	0.3	0.31
Listening x Speaker x Orient	4.87	1.89	0.35	0.11
Within Subjects				
Listening	1.84	4.48*	0.49	0.02
Speaker	2.74	3.91*	0.47	0.02
Listening x Speaker	4.87	1.66	0.33	0.16

Note. * denotes *p* < .05.

A pair-wise comparison with speaker array orientation as a between-subjects variable was completed to determine if there was a significant difference between speaker array to the right versus speaker array to the left for any of the listening conditions. This analysis revealed that there was no significant difference between the two groups for any of the listening conditions. Because of this lack of significance between the speaker array to the right versus speaker array to the left groups, this variable was collapsed for the remainder of the analyses.

When listening condition (3) and speaker (11) were included in the ANOVA, and speaker array orientation was excluded, a significant main effect was found for listening condition. A pair-wise comparison was completed to determine where the differences existed between listening conditions for this analysis. It is important to note that the overall RMS for all participants for each listening condition was used. Overall, participants performed the best with the NO condition, followed by the BIL condition, and the worst performance was with the BIN condition. The comparison revealed that there was a significant difference between NO and BIL ($p < .05$) and between NO and BIN ($p < .05$). There was no significant difference between BIL and BIN ($p = .31$). Refer to Figure 8.

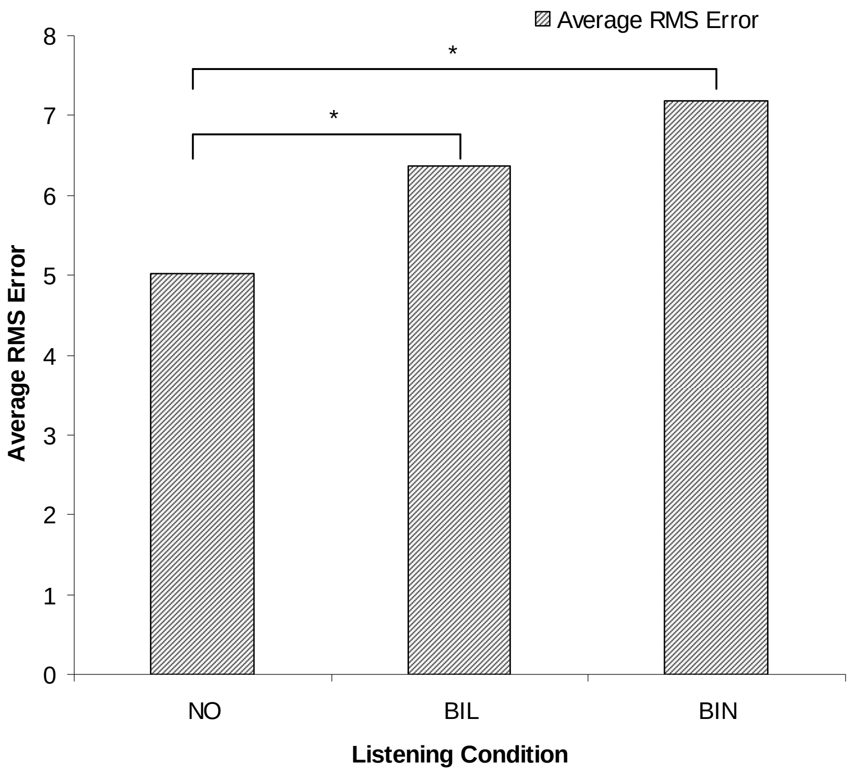

Figure 8. Average RMS error in degrees (y-axis) for all participants for each listening condition (x-axis). * $p < .05$.

4.1.3 Listening Condition and Location of Speaker (Front vs. Back)

A third ANOVA was completed with listening condition (3) and location of speaker (2; front versus back) as within-subject variables. The front speakers were defined as speakers 1 – 6 and the back speakers were defined as speakers 7 – 11. The goal of this analysis was to determine if there was a significant difference between RMS error for front speakers (1 – 6) and back speakers (7 – 11) for each listening condition. Mauchly's test of sphericity revealed no significant departure from sphericity, so "sphericity assumed" values were used throughout this analysis. Results revealed a significant main effect for listening condition $F(2, 30) = 3.64$, $p < .05$, and for speaker location $F(1, 15) = 15.59$, $p < .05$. The effect sizes for these variables were 0.20 and 0.51, respectively, which are both considered large effect sizes. The power of these effects were 0.63 and 0.96, respectively. There was no significant interaction effect for listening condition by speaker location $F(2, 30) = 2.56$, $p = .09$. Refer to Table 7 for results from this analysis.

Table 7

Listening Condition and Speaker Location (Front vs. Back)

Source	df	F	ŋ	p
Listening Condition	2.00	3.64*	0.44	0.04
Speaker Location	1.00	15.59**	0.71	0.001
Listening x Location	2.00	2.56	0.38	0.09

Note. * denotes $p < .05$. ** $p <$ 01.

A pair-wise comparison for listening condition and speaker location was completed to determine where the significant differences presented. The comparison for listening condition revealed that there was a significant difference between the NO and BIL listening conditions ($p < .05$) and between the NO and BIN listening conditions. There was no significant difference between the BIL and BIN listening conditions ($p = .45$). These results were the same as the second ANOVA. The pair-wise comparison for speaker location revealed a significant difference between front versus back speaker locations ($p < .01$). The participants performed significantly better (lower RMS error) for the front speakers (1 – 6) than for the back speakers (7 – 11). Refer to Figure 9.

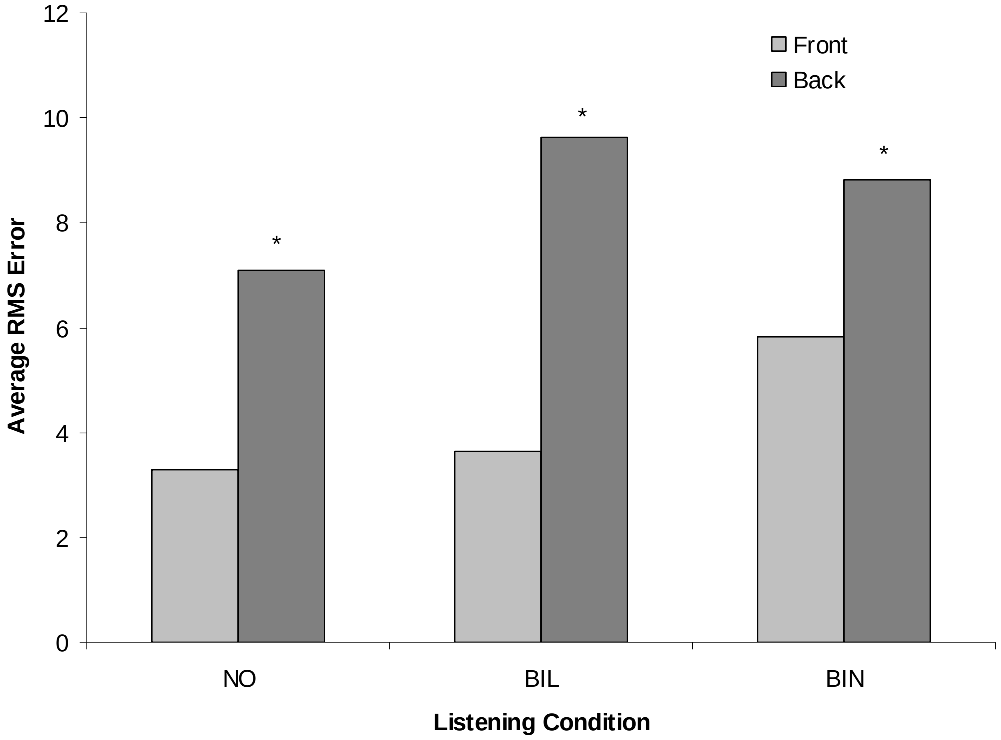

Figure 9. Average RMS error in degrees (y-axis) for the three listening conditions (x-axis). Light gray bars represent front speakers (1 – 6) and dark gray bars represent back speakers (7 – 11). * $p < .05$.

4.2 Hearing in Noise

For the hearing-in-noise task, the dependent variable was the signal-to-noise ratio (SNR) that was required for at least 50% correct sentence repetition. The lower the SNR value (i.e. -10 dB SNR), the better the performance, and conversely, the higher the SNR value (i.e. +5 dB SNR), the worse the hearing-in-noise performance. The independent variables for this task were the NO, BIL, and BIN listening conditions and the target and masker conditions (S_0-N_{90}, S_0-N_{180}, S_0-N_{270}, and S_0-$N_{90, 180, 270}$). The specific aim was to evaluate whether participants performed better in noise for the NO, BIL, or BIN listening conditions and for which of the target and masker conditions (S_0-N_{90}, S_0-N_{180}, S_0-N_{270}, and S_0-$N_{90, 180, 270}$). The null hypothesis for the hearing-in-noise test was that there was no significant difference between the NO, BIL, and BIN listening conditions and that there was no significant difference between the masker conditions. The alternative hypothesis was that there was a significant difference between the NO, BIL, and BIN listening conditions and that there was a significant difference between S_0-N_{90}, S_0-N_{180}, S_0-N_{270}, and/or S_0-$N_{90, 180, 270}$.

A repeated-measures analysis of variance (ANOVA) was computed for the hearing-in-noise data to determine if there was a significant difference between the listening conditions (NO, BIL, and BIN) and the masker conditions (S_0-N_{90}, S_0-N_{180}, S_0-N_{270}, and S_0-$N_{90, 180, 270}$). A second ANOVA was completed to determine if there was a significant difference between the listening conditions when considering the one-masker conditions (S_0-N_{90}, S_0-N_{180}, and S_0-N_{270},) only.

4.2.1 Listening Condition and Masker Condition

A repeated-measures analysis of variance (ANOVA) was calculated for the hearing in noise data to determine whether there was a significant difference between the three listening conditions (NO, BIL, and BIN) and/or between the four masker conditions

(S_0-N_{90}, S_0-N_{180}, S_0-N_{270}, and S_0-$N_{90, 180, 270}$). Mauchly's test of sphericity revealed that there was no significance for sphericity, so "sphericity assumed" values were used when looking for significance.

The ANOVA revealed no significant difference between any of the listening conditions $F(2, 30) = 2.85$, $p = .07$. The effect size for this variable was 0.16 (large) and the power was 0.52. There was, however, a significant difference between masker conditions $F(3, 45) = 550.78$, $p < .05$. Refer to Figure 10 for an illustration of this analysis. No significant interaction was found for listening condition by masker condition $F(6, 90) = .88$, $p = .51$.

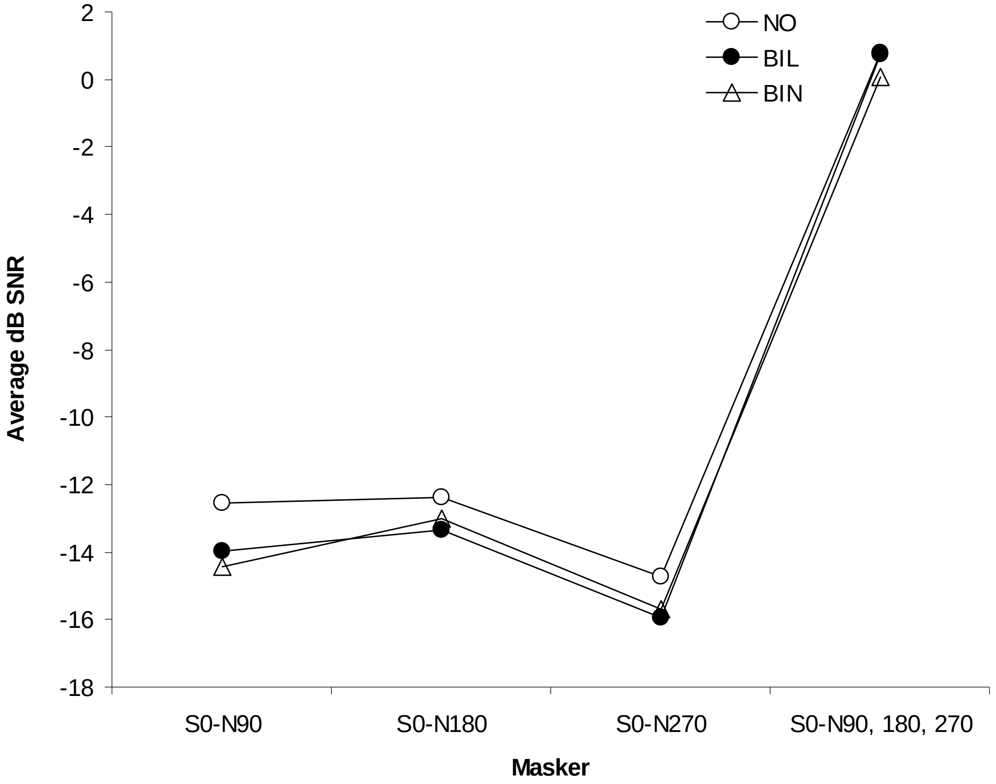

Figure 10. HIN performance as dB SNR (y-axis) for each of the masker conditions (x-axis). The NO listening condition is represented with open circles, BIL with closed circles, and BIN with open triangles.

A pair-wise comparison for masker condition revealed that there was a significant difference between S_0-N_{90} and S_0-N_{270} ($p < .05$), S_0-N_{90} and S_0-$N_{90,\,180,\,270}$ ($p < .05$), S_0-N_{180} and S_0-N_{270} ($p < .05$), S_0-N_{180} and S_0-$N_{90,\,180,\,270}$ ($p < .05$), and S_0-N_{270} and S_0-$N_{90,\,180,\,270}$ ($p < .05$). The mean values reveal that the participants performed the best in the S_0-N_{270} masker condition, followed by S_0-N_{90}, then by S_0-N_{180}, and finally, the poorest performance for the S_0-$N_{90, 180, 270}$ masker condition. Table 8 reveals the mean dB SNR for each masker condition averaged across listening conditions and Table 9 shows the mean dB SNR for each listening condition pooled across the four masker conditions. There was no significant difference between S_0-N_{90} and S_0-N_{180}. Figure 11 illustrates these comparisons.

Table 8

Mean dB SNR for each masker condition averaged across listening conditions.

Masker Condition	Mean
S_0-N_{90}	-13.66
S_0-N_{180}	-12.91
S_0-N_{270}	-15.46
S_0-$N_{90, 180, 270}$	0.53

Table 9

Mean dB SNR for each listening condition averaged across masker conditions.

Listening Condition	Mean
NO	-9.729
BIL	-10.621
BIN	-10.776

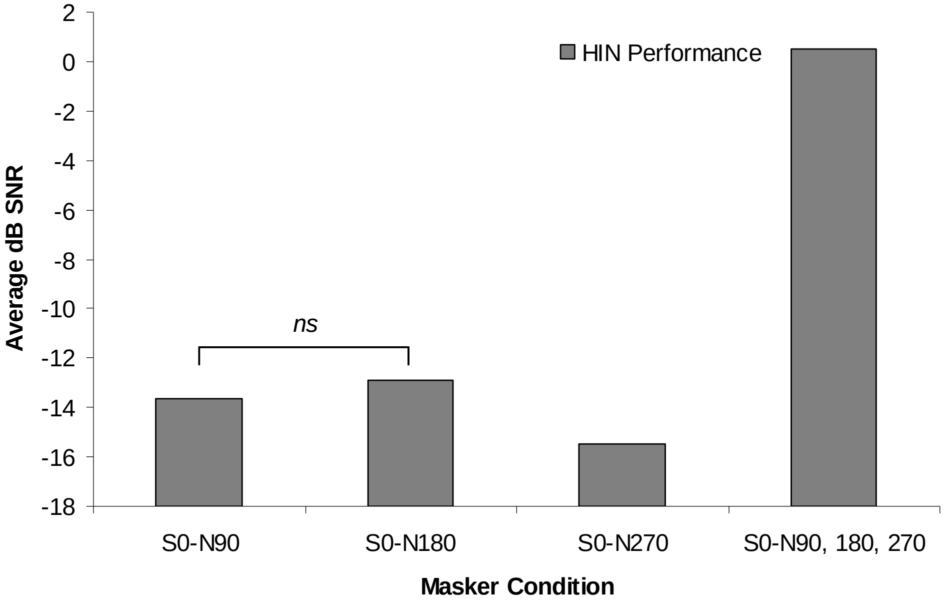

Figure 11. Average dB SNR (y-axis) for each masker condition (x-axis). Graph shows non-significant difference; all other comparisons are significant (*p* < .05).

4.2.2 Listening Condition and One-Masker Conditions

Another ANOVA was computed that excluded the three-masker condition (S_0-$N_{90,\ 180,\ 270}$). This ANOVA included the one-masker conditions (S_0-N_{90}, S_0-N_{180}, and S_0-N_{270}) only. The goal of this ANOVA was to determine if there was a significant difference between listening conditions for the masker conditions that only included one masker at a time. Mauchly’s test of sphericity revealed that there was no significant departure from sphericity, so sphericity assumed values were used for this analysis.

Results revealed that there was a significant difference for listening condition *F*(2, 30) = 3.49, $p < .05$. The effect size of this variable was 0.19 (large) and the power was 0.61. The estimated marginal means revealed that the participants performed best in the BIL condition, followed by BIN, then the NO listening condition (see Table 10). A pair-wise comparison for listening condition revealed that there was a significant difference between NO and BIL ($p < .05$) and NO and BIN ($p < .05$). There was no significant difference between BIL and BIN ($p = .96$). Refer to Figure 12.

Table 10

Mean dB SNR for each listening condition across the one-masker conditions.

Listening Condition	Mean
NO	-13.228
BIL	-14.413
BIN	-14.387

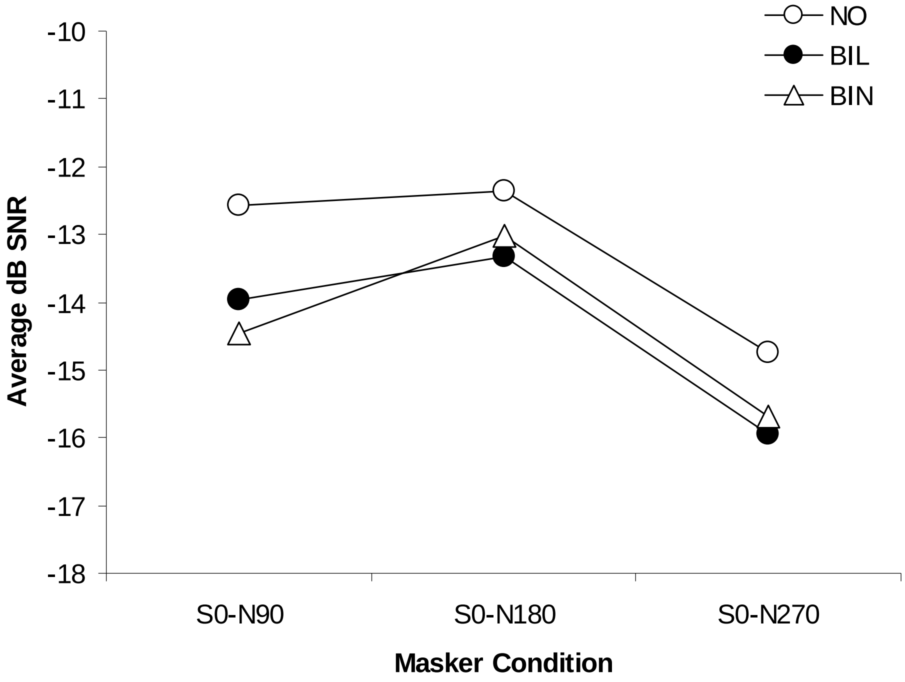

Figure 12. HIN performance as dB SNR (y-axis) for each of the one-masker conditions (x-axis). The NO listening condition is represented with open circles, BIL with closed circles, and BIN with open triangles.

The ANOVA also revealed that there was a significant main effect for masker condition $F(2, 30) = 19.08$, $p < .05$. The effect size was 0.56 (large) and the power was 1.00. A pair-wise comparison of the masker conditions revealed that there was a significant difference between S_0-N_{90} and S_0-N_{270} ($p < .05$) and S_0-N_{180} and S_0-N_{270} ($p < .05$). There was no significant difference between S_0-N_{90} and S_0-N_{180}, ($p = .17$). The estimated marginal means revealed that the participants performed best in the S_0-N_{270} (masker left) condition, followed by the S_0-N_{90} condition (masker right), and worst in the

S_0-N_{180} (masker behind) condition. Refer to Table 7. The ANOVA revealed that there was no significant interaction effect for listening condition by masker condition (*p* = .73).

V. DISCUSSION

5.1 Localization

Eleven of the 16 participants in the present study had front/back confusions (when the stimulus was presented from speaker 1, the participant responded with speaker 11 and vice-versa). The only participants that did not have front/back confusions were 01, 02, 07, 08, and 13. The maximum hearing loss for these five participants ranged from 30 – 60 dB HL, so degree of hearing loss did not seem to play a role in this small group that did not have front/back confusions. Because all participants had some degree of high frequency hearing loss, front/back confusions were accepted as correct and entered as the opposite of the participant's actual response (e.g. if the target stimulus was presented from speaker 1, and the participant responded with speaker 11, exactly 180° off, the response was coded as speaker 1). This was only done for speakers 1 and 11 because they were the only speakers that were exactly 180° different. The reason for recoding these mistakes is that at 0° azimuth (speaker 1), the sound is likely perceived the same at both ears, and likely the same for 180° azimuth (speaker 11) as well.

Random guessing for this task was ruled out by examining the data and seeing no obvious outliers. Because the scores were RMS error in degrees and not percentage scores, random guessing could not be measured as a percentage. Once the data was analyzed, however, it was clear that there were no outliers, suggesting that no participants randomly guessed.

5.1.1 Listening Condition, Speaker, and Run

For this analysis, there was only a significant difference for speakers. Figure 7 illustrates the average performance (y-axis) for each speaker (x-axis) averaged across the listening conditions. This graph illustrates that the worst performance (highest RMS error) was for speaker 10. This could have been due to the fact that some participants confused speaker 10 with speaker 2. These confusions were not considered true front/back confusions, so were not recoded because speaker 2 is 144° different from speaker 10, not 180° different. As a review, if the stimulus was presented from speaker 1 and the participant perceived it as coming from speaker 11 (and vice-versa), these responses were entered as correct instead of incorrect, because the stimulus presented from speaker 1 or speaker 11 are likely perceived to be the same at the ear level (same ITD and ILD at the ears). Speakers 2 and 10, however, were 144° apart, so if they were confused, it could not be considered a true front/back confusion. Therefore, these responses were entered exactly as the participant responded. That may be one possible explanation why there is a spike in RMS error for speaker 10.

This analysis confirmed a significant difference between speakers. A pair-wise comparison was completed to determine where there was a significant difference. The comparisons can be seen in Figure 6, and the significance values and standard errors can be found in Appendix B. Generally speaking, speaker 2 was not significantly different from any other speakers, and speaker 11 was only significantly different from speaker 10. The latter comparison makes sense because these speakers were close in proximity and they were both “back” speakers and apparently harder to differentiate when compared to, for example, speaker 1 versus speaker 2. All other speakers were significantly different from at least four other speakers.

5.1.2 Listening Condition, Speaker, and Orientation of Speakers (Right vs. Left)

The listening condition, speaker, and array orientation analysis revealed that there was no significant difference between listening conditions for the speaker array to the right (participants 1 – 8) versus speaker array to the left (9 – 16). Overall, participants performed best in the NO condition, followed by BIL, then BIN. As a reminder, the speaker array was on one side of the participants because, in theory, for the hearing aids to sense a change in the acoustic environment (and engage the binaural compression system), there had to be a noise to the contralateral side of the speaker array to stabilize the compression system. That is why the speaker array orientation to the side of the participants was chosen. To examine if there was a difference between speaker array orientation to the right or the left side, half of the participants were tested with the speaker array on the right side, and the other half, with the speaker array on the left side. It was hypothesized that there would be no significant difference between speaker array orientation to the right versus speaker array orientation to the left. One of the reasons for this hypothesis is because the hearing loss for each participant was essentially symmetrical. If the participants had asymmetrical hearing loss, they would likely reveal better localization to the side of the better ear. The between-subjects variable was included in this analysis to test the hypothesis that the orientation of the speaker array would not make a significant difference between groups for localization performance. Results revealed that there was no significant difference in localization performance between speaker array orientations.

Participants performed best in the NO condition, followed by BIL, then BIN. This was the opposite of the anticipated results for the listening conditions. This could have been due to the fact that the participants in the current study had no hearing aid experience. This was chosen as part of the inclusion criteria in order to avoid the variable of type and amount of hearing aid experience. Different hearing aid experience among participants was expected to add in a variable that could not be controlled for. Including participants with no hearing aid experience, on the other hand, was to avoid the variable of years and type of experience that could have possibly influenced the results.

In the current study, participants were tested unaided (NO), with un-linked hearing aids (BIL), and with linked hearing aids (BIN) in a counterbalanced order. It was expected that the participants could automatically perform better during the localization task with hearing aids because of better access to high frequency information. It was expected that the participants would perform even better with the linked hearing aids because of preservation of ILD cues provided by the linked hearing aids. However, one must take into account that these participants had no prior hearing aid experience. Most of them have had a hearing loss for 20 or more years, and their brains are likely “wired” to that hearing loss. To place a pair of hearing aids on these participants and to expect their brains to know what to do with the new input might not be reasonable. This might have been why the participants performed better without hearing aids. They had become accustomed to their hearing loss and did not know what to do with the new input from the hearing aids.

One might wonder if the participants would have performed better had they been new hearing aid users that wore the test hearing aids for a month or two and then were tested in the localization task. An interesting future study would be to include participants in a similar design, but to test them in a localization task at initial fitting and then one or two months after wearing the hearing aids regularly. Might the results be different a month or two after wearing the hearing aids under investigation? There was a trade-off in this study of including participants with no prior hearing aid experience.

5.1.3 Listening Condition and Location of Speaker (Front vs. Back)

The listening condition and speaker location analysis revealed a significant difference between listening conditions and speaker location. The significant differences between NO and BIL and NO and BIN confirm the results from the previous analysis. Overall, the participants performed the best in the NO condition, followed by BIL, then BIN.

Speaker locations were divided into “front” speakers (1 – 6) and “back” speakers (7 – 11). Localization performance was significantly better for the front speakers versus the back speakers. This has been illustrated in numerous studies (Makous &

Middlebrooks, 1990; Butler, 1986; Byrne, Sinclair, & Noble, 1998; Keidser et al., 2006). Results from Van den Bogaert et al. (2006) suggested that when using a half-circle speaker array to the front, there was poorer performance for speakers to the side versus to the front. The findings from the present study confirm that, even with SNHL, participants tend to perform better in the frontal horizontal plane versus the back. This analysis suggests that localizing to the back, in general, is significantly more difficult than localizing to the front.

Looking at individual data, some participants did perform better with BIN versus the NO listening condition. The ANOVA did not show any significant difference in performance with the BIN condition being better than the NO condition, but the raw data does show this trend for a few participants. See Table 11 for the actual scores of four participants who had the best localization performance for the BIN listening condition.

Table 11

RMS Error for each Listening Condition

Subject	NO	BIL	BIN
04	1.64	1.7	1.31
05	1.99	3.32	1.03
09	2.54	2.22	1.57
13	1.09	1.09	0.98

Note. Participants included in this table performed better in the BIN versus the NO listening condition. A lower number corresponds to a better score.

Another factor that could have affected localization results is the fact that the participants were tested in an anechoic chamber, which is a best-case scenario acoustic environment because there are no reflected sound waves to cause interference. An interesting future study would be to test localization performance in a reverberant environment that would more closely approximate a real-world acoustical environment. To test the other extreme, it might be worthwhile to conduct the same localization study in a reverberation chamber.

During the localization task, participants were encouraged to keep their heads against the headrest during each stimulus presentation. Once the stimulus stopped playing, the participants were allowed to look around the speaker array to find the speaker number where they perceived the stimulus to come from. One of the reasons that the participants were not allowed to hone in on the target stimulus while it was playing is because the slight movement of the speaker diaphragms would have given the participants a visual cue. In this way, the participants would not have relied on auditory cues alone. A future study would involve either (1) using speakers with diaphragms that are covered or (2) covering up the speaker array with a screen so that the movement of the speaker diaphragms would not be visible. In this way, the participants could be allowed to hone in on the target stimulus which might lead to better localization performance.

According to the hearing aid manufacturer, a 1 – 2 second stimulus was expected to be long enough in duration to allow the binaural compression systems in the hearing aids to be activated. In the current study, the participants performed the best in the NO listening condition, followed by BIL then BIN. One can assume that if a shorter stimulus was used in the study, the results would have remained the same or been poorer for the BIN condition. If a longer stimulus presentation was used, might the compression system in the hearing aids have more time to engage and maintain interaural cues? Would this longer duration signal have improved localization performance in the BIN condition? If a longer stimulus did improve localization performance, is that a realistic amount of time for hearing aids to take to stabilize and engage the proper compression algorithm? If a longer stimulus did improve localization performance in the BIN condition, then the hearing aid manufacturer would have a starting point to improve an algorithm that promises faster engagement of the compression system to be more useful in real-world situations.

5.2 Hearing in Noise

5.2.1 Listening Condition and Masker Condition

The ANOVA for the HIN task revealed no significant difference between listening conditions. On average, participants performed relatively the same during the hearing-in-noise testing with each listening condition (no hearing aids, non-linked hearing aids, and linked hearing aids). This is different from the localization results where participants performed significantly better in the NO versus BIL and the NO versus BIN listening conditions.

A significant difference was found for masker condition, however. Participants performed significantly better in the S_0-N_{270} condition (masker to the left) than for the S_0-N_{90} condition (masker to the right). The next best performance was for the S_0-N_{180} condition (masker behind), followed by the poorest performance in the S_0-$N_{90, 180, 270}$ condition (maskers to the right, back, and left). The poorest performance was for the noisiest condition, S_0-$N_{90, 180, 270}$. The large difference between performance for the S_0-$N_{90, 180, 270}$ condition and all of the other masker conditions (refer to Figure 10) can partly be explained by an increase in intensity of three maskers at once versus only one masker at once, or energetic masking. Adding a second masker likely increased the intensity of the masker by approximately 3 dB SPL and the third masker, by approximately 3 dB SPL more, for a total increase of approximately 6 dB SPL. Figure 10 reveals that the difference in dB SNR between the one-masker conditions and the three-masker condition was much greater than 6 dB SNR. The minimum difference in dB SNR between S_0-$N_{90, 180, 270}$ and the other masker conditions was 13.1 dB SNR and the maximum difference was 16.7 dB SNR. Adding up the intensities of the three maskers does not fully explain the 13.1 – 16.7 dB SNR difference. Another factor could have been informational masking. Because speech was used as a masker, there were peaks and valleys in the maskers. During the valleys or gaps in the speech masker, the participant was likely better able to understand the target sentence. However, when there were three speech maskers at once (S_0-$N_{90, 180, 270}$), the gaps or valleys in one masker were likely covered up by the peaks in another masker. With the three-masker condition, there were fewer valleys present because they were filled in with peaks of one of the other two maskers.

This is informational masking. The difference between the one-masker and three-masker conditions could not be due to energetic masking alone. There was also informational masking involved, making it more difficult for the participants to understand the target sentence, hence the large difference in dB SNR between the one-masker and three-masker conditions.

It is also worth mentioning that the target in the current study was at a fixed location (0° azimuth). Even with the different masker locations, this setup most closely resembles a one-on-one conversation in a noisy environment. It does not necessarily simulate a group conversation in noise where the listener must switch attention back and forth between talkers. In this study, the participant always knew from what direction the talker would come from. The task might have been more difficult, but more realistic for a group conversation in noise, if the location of the signal was not always at 0° azimuth. Also, different masker locations were used in this study, but the investigator let the participants know where the masker would be located for the upcoming list of sentences. The participants, in turn, could prepare themselves for what was coming up (e.g. the other talker would be to the right, to the left, behind, or all around). A future study with a similar design could use random order of the masker conditions to see if this would affect performance. Results from Kidd, Arbogast, Mason, and Gallun (2005) revealed that knowing the location of the target signal can improve speech intelligibility in noise. In their study, the lower the uncertainty in the listening situation, the better the participants performed. Conversely, the higher the uncertainty, the poorer the participants performed.

If the proposed study is completed, however, the method used for adjusting the SNR during testing would be difficult because the masker location would always be changing.

Looking at individual data, some participants did perform better with hearing aids compared to without hearing aids. The data used here are averages of the SNRs across masker conditions. Nine of the 16 participants had the best hearing-in-noise performance for the BIN condition, followed by the BIL condition, and the poorest performance for the NO condition (see Table 12). The statistical analysis might not have proved any significance between listening conditions, but over 50% of the participants in the study did perform better in the BIN condition. The difference between the NO versus BIL and BIN for these participants might have been due to the fact that the hearing aids were in directional microphone mode for the HIN testing, making it easier to ignore the unwanted talker to the sides and/or back and better understand the target sentence at 0° azimuth. Hornsby and Ricketts (2007) found that participants performed significantly better with hearing aids with directional microphones versus omnidirectional microphones for two of the noise conditions used in their study (NC1: speech front and noise surround, NC2: noise front, noise both sides). This does not necessarily explain the improved performance from the BIL to the BIN condition for these participants. It might be that for these nine participants, the linked hearing aids did in fact help them to better understand speech in noise. It is also important to note that, according to the HINT manual (HINT, 2003), an improvement in dB SNR as little as 1 dB can improve speech intelligibility by up to 8.9%. The dB SNR values for each listening condition might not have been statistically different, but practically significant. If the participant’s performance improved by 1 or 2 dB SNR, this could mean better speech intelligibility in noise of 8.9 – 17.8% which could make a significant difference in real-world situations.

Table 12

Total dB SNR for each listening condition

Subject	NO	BIL	BIN
01	-7.84	-9.32	-9.45
03	-11.68	-12.41	-14.30
05	-11.15	-12.82	-14.53
06	-7.35	-8.18	-10.12
07	-7.18	-10.94	-10.94
08	-13.50	-13.53	-14.53
09	-10.59	-10.30	-11.47
11	-8.88	-12.00	-12.85
12	-8.89	-9.77	-11.00

Note. Participants included in this table performed best in the BIN condition. The more negative the number, the better the performance.

5.2.2 Listening Condition and One-Masker Conditions

Because of the difference of up to 16.7 dB SNR between the one-masker conditions and the three-masker condition, an ANOVA was completed that excluded the three-masker condition (S_0-$N_{90, 180, 270}$). The results from this analysis revealed a significant difference between listening conditions, unlike the analysis that included all of the masker conditions. The participants performed best in the BIL condition, followed by BIN, then NO. When all of the masker conditions were considered, the participants performed best in the BIN condition, followed by BIL, then NO. But, there was no significant difference between listening conditions for that analysis. For this analysis that excluded the three-masker condition, there was a significant difference between NO and BIL and NO and BIN. The participants performed the best for the BIL condition for the one-masker conditions, but this was not statistically different than performance in the BIN condition. For the analysis that included the three-masker condition, the slight improvement in performance for the BIN versus BIL condition suggests that the hearing aids with binaural processing did help some of the participants in the most challenging environment. The hearing aids with binaural processing might have provided spatial awareness and allowed the participant to better focus on the target signal.

Regarding the masker conditions, the participants performed best for the S_0-N_{270} (masker left) condition, followed by S_0-N_{90} (masker right), then S_0-N_{180} (masker behind). There was a significant difference between S_0-N_{90} and S_0-N_{270} and S_0-N_{180} and S_0-N_{270}. For the significantly poorer performance for the S_0-N_{90} (masker right) compared to the S_0-N_{270} (masker left) condition, it is possible that the participants were better able to inhibit or tune out the masker when it was on the left side of the participant versus on the right side of the participant. It might have been more difficult for the participants to ignore the masker on the right side, and it might have been easier to ignore the masker to the left side. Interestingly, performance for the S_0-N_{180} condition (masker behind the head) was poorer than when the maskers were to either side of the head. One might hypothesize that the participants would have done better with the masker behind the head versus to the sides of the head because of maximal spatial separation. Arbogast, Mason, and Kidd (2005) investigated spatial release from masking (SR) in their study with normal hearing (NH) participants and hearing impaired participants (HI). The NH and the HI groups in their study benefited from spatial release from masking when the target and masker were speech, and when the target and masker were separated by at least 90°. The current study revealed no additional spatial release from masking when the masker was located at 180° versus 90° or 270°.

5.3 Conclusions

For the horizontal localization task, the best performance was without hearing aids (NO), followed by unlinked hearing aids (BIL), and the worst performance was for linked hearing aids (BIN) across all participants. There was a significant difference between the NO and BIL and the NO and BIN listening conditions. The results also revealed that overall, participants had significantly lower RMS error scores (better localization) for the front speakers 1 – 6 than for the back speakers 7 – 11. This suggests that localizing to the front was more accurate than localizing to the back. For the hearing-in-noise task, there was no significant difference between listening conditions (NO, BIL, and BIN) when all masker conditions were included. When only the one-masker conditions were considered, there was a significant difference between the NO and BIL and the NO and BIN listening conditions with the best performance for the BIL condition, followed by BIN, then NO. Results also revealed a significant difference between masker conditions. The participants in this study performed the best when the speech masker was to the left (S_0-N_{270}), next best when the masker was to the right (S_0-N_{90}), followed by the masker to the back (S_0-N_{180}), and the performance was much worse when the masker was presented from all three locations (S_0-$N_{90,\ 180,\ 270}$).

VI. Appendices

Appendix A1

Order of Listening Conditions for Each Participant (continued on next page).

Part. No.	HIN	Local
1	1	3
	2	1
	3	2
2	3	2
	1	3
	2	1
3	2	3
	3	2
	1	1
4	3	1
	2	3
	1	2
5	1	2
	3	1
	2	3
6	2	1
	1	2
	3	3
7	1	3
	2	1
	3	2
8	3	2
	1	3
	2	1
9	2	3
	3	2
	1	1
10	3	1
	2	3
	1	2
11	1	2
	3	1
	2	3
12	2	1
	1	2
	3	3

Note. Order of Conditions for Hearing in Noise (HIN) Testing and Localization (Local) Testing. 1=No Hearing Aids (NO), 2=Bilateral Hearing Aids (BIL), and 3=Binaural Hearing Aids (BIN).

Appendix A1 (cont'd)

Order of Listening Conditions for Each Participant.

Part. No.	HIN	Local
13	1	3
	2	1
	3	2
14	3	2
	1	3
	2	1
15	2	3
	3	2
	1	1
16	3	1
	2	3
	1	2

Note. Order of Conditions for Hearing in Noise (HIN) Testing and Localization (Local) Testing. 1=No Hearing Aids (NO), 2=Bilateral Hearing Aids (BIL), and 3=Binaural Hearing Aids (BIN).

Appendix A2

Order of Hearing Aid, Masker, and Sentence List Conditions for HIN Testing (continued on next 5 pages)

Part.	Listen. Cond.	Masker Cond.	Sent. List
1	1	4	12
	1	1	6
	1	3	11
	1	2	1
	2	1	7
	2	4	10
	2	2	8
	2	3	4
	3	4	3
	3	2	9
	3	3	5
	3	1	2
2	3	4	12
	3	3	1
	3	1	2
	3	2	8
	1	3	4
	1	2	9
	1	1	5
	1	4	3
	2	3	6
	2	2	10
	2	4	11
	2	1	7
3	2	3	8
	2	2	9
	2	1	2
	2	4	10
	3	3	5
	3	4	12
	3	2	7
	3	1	11
	1	3	1
	1	1	4
	1	4	6
	1	2	3

Note. For listening condition, 1=no hearing aids (NO), 2=bilateral hearing aids (BIL), and 3=binaural hearing aids (BIN). For Masker Condition, 1=S_0N_{90}, 2=S_0N_{180}, 3=S_0N_{270}, and 4=$S_0N_{90,\ 180,\ 180}$.

Appendix A2 (cont'd)

Order of Hearing Aid, Masker, and Sentence List Conditions for HIN Testing (continued on next 4 pages)

Part.	Listen. Cond.	Masker Cond.	Sent. List
4	3	4	7
	3	3	10
	3	1	1
	3	2	9
	2	2	3
	2	3	6
	2	4	4
	2	1	2
	1	4	11
	1	2	12
	1	3	8
	1	1	5
5	1	4	5
	1	1	10
	1	3	8
	1	2	4
	3	2	3
	3	4	2
	3	3	9
	3	1	1
	2	3	7
	2	1	12
	2	4	6
	2	2	1
6	2	2	9
	2	3	4
	2	1	6
	2	4	1
	1	4	8
	1	1	10
	1	2	3
	1	3	11
	3	3	12
	3	2	5
	3	1	7
	3	4	2

Note. For listening condition, 1=no hearing aids (NO), 2=bilateral hearing aids (BIL), and 3=binaural hearing aids (BIN). For Masker Condition, 1=S_0N_{90}, 2=S_0N_{180}, 3=S_0N_{270}, and 4=$S_0N_{90,\ 180,\ 180}$.

Appendix A2 (cont'd)

Order of Hearing Aid, Masker, and Sentence List Conditions for HIN Testing (continued on next 3 pages)

Part.	Listen. Cond.	Masker Cond.	Sent. List
7	1	1	8
	1	4	7
	1	3	12
	1	2	11
	2	2	9
	2	1	5
	2	3	1
	2	4	4
	3	4	3
	3	3	10
	3	1	6
	3	2	2
8	3	2	5
	3	1	12
	3	3	2
	3	4	11
	1	2	8
	1	3	7
	1	1	1
	1	4	10
	2	4	4
	2	1	6
	2	3	3
	2	2	9
9	2	2	11
	2	4	7
	2	3	9
	2	1	6
	3	4	2
	3	2	12
	3	3	8
	3	1	4
	1	3	10
	1	4	1
	1	1	5
	1	2	3

Note. For listening condition, 1=no hearing aids (NO), 2=bilateral hearing aids (BIL), and 3=binaural hearing aids (BIN). For Masker Condition, 1=S_0N_{90}, 2=S_0N_{180}, 3=S_0N_{270}, and 4=$S_0N_{90,\,180,\,180}$.

Appendix A2 (cont'd)

Order of Hearing Aid, Masker, and Sentence List Conditions for HIN Testing (continued on next 2 pages)

Part.	Listen. Cond.	Masker Cond.	Sent. List
10	3	2	10
	3	4	8
	3	1	4
	3	3	6
	2	4	3
	2	3	11
	2	1	5
	2	2	9
	1	1	2
	1	2	7
	1	4	1
	1	3	12
11	1	3	3
	1	2	5
	1	1	2
	1	4	9
	3	3	4
	3	2	12
	3	1	8
	3	4	11
	2	1	6
	2	3	10
	2	2	7
	2	4	1
12	2	1	10
	2	4	4
	2	2	7
	2	3	2
	1	2	1
	1	1	6
	1	4	12
	1	3	9
	3	2	3
	3	4	11
	3	3	5
	3	1	8

Note. For listening condition, 1=no hearing aids (NO), 2=bilateral hearing aids (BIL), and 3=binaural hearing aids (BIN). For Masker Condition, 1=S_0N_{90}, 2=S_0N_{180}, 3=S_0N_{270}, and 4=$S_0N_{90,\ 180,\ 180}$.

Appendix A2 (cont'd)

Order of Hearing Aid, Masker, and Sentence List Conditions for HIN Testing (continued on next page)

Part.	Listen. Cond.	Masker Cond.	Sent. List
13	1	4	10
	1	2	2
	1	3	11
	1	1	6
	2	3	1
	2	4	3
	2	2	8
	2	1	7
	3	4	4
	3	2	5
	3	1	12
	3	3	9
14	3	2	4
	3	4	8
	3	1	7
	3	3	6
	1	1	11
	1	3	2
	1	2	1
	1	4	12
	2	4	5
	2	3	10
	2	1	3
	2	2	9
15	2	4	2
	2	3	6
	2	2	12
	2	1	10
	3	2	1
	3	3	3
	3	1	4
	3	4	11
	1	3	5
	1	4	7
	1	2	8
	1	1	9

Note. For listening condition, 1=no hearing aids (NO), 2=bilateral hearing aids (BIL), and 3=binaural hearing aids (BIN). For Masker Condition, 1=S_0N_{90}, 2=S_0N_{180}, 3=S_0N_{270}, and 4=$S_0N_{90,\,180,\,180}$.

Appendix A2 (cont'd)

Order of Hearing Aid, Masker, and Sentence List Conditions for HIN Testing

Part.	Listen. Cond.	Masker Cond.	Sent. List
16	3	1	8
	3	2	9
	3	3	4
	3	4	5
	2	1	1
	2	4	3
	2	2	11
	2	3	10
	1	1	2
	1	4	12
	1	2	6
	1	3	7

Note. For listening condition, 1=no hearing aids (NO), 2=bilateral hearing aids (BIL), and 3=binaural hearing aids (BIN). For Masker Condition, 1=S_0N_{90}, 2=S_0N_{180}, 3=S_0N_{270}, and 4=$S_0N_{90,\,180,\,180}$.

Appendix B

Pair-wise comparison results for each speaker (continued on next 3 pages).

Speaker	Speaker	Standard Error	p
1	2	4.159	0.33
	3	2.403	0.97
	4	2.204	0.55
	5	1.72	0.31
	6	1.656	0.87
	7	1.807	0.02*
	8	2.522	0.03*
	9	2.538	0.04*
	10	2.657	0.00**
	11	2.462	0.48
2	1	4.159	0.33
	3	2.834	0.15
	4	3.08	0.36
	5	3.567	0.50
	6	3.489	0.27
	7	3.264	0.86
	8	2.654	0.49
	9	2.576	0.58
	10	3.062	0.13
	11	4.481	0.60
3	1	2.403	0.97
	2	2.834	0.15
	4	1.238	0.27
	5	1.443	0.21
	6	1.329	0.79
	7	1.026	0.00**
	8	0.99	0.00**
	9	1.214	0.00**
	10	2.074	0.00**
	11	2.647	0.49

Appendix B

Pair-wise comparison results for each speaker (continued on next 2 pages).

Speaker	Speaker	Standard Error	p
4	1	2.204	0.55
	2	3.08	0.36
	3	1.238	0.27
	5	0.806	0.58
	6	0.887	0.25
	7	1.052	0.01*
	8	1.01	0.00**
	9	1.243	0.00**
	10	2.018	0.00**
	11	2.481	0.85
5	1	1.72	0.31
	2	3.567	0.50
	3	1.443	0.21
	4	0.806	0.58
	6	0.515	0.01*
	7	0.937	0.01*
	8	1.425	0.01*
	9	1.551	0.03*
	10	2.072	0.00**
	11	2.241	1.00
6	1	1.656	0.87
	2	3.489	0.27
	3	1.329	0.79
	4	0.887	0.25
	5	0.515	0.01*
	7	0.77	0.00**
	8	1.309	0.00**
	9	1.431	0.00**
	10	1.921	0.00**
	11	2.047	0.47

Appendix B

Pair-wise comparison results for each speaker (continued on next page).

Speaker	Speaker	Standard Error	p
7	1	1.807	0.02*
	2	3.264	0.86
	3	1.026	0.00**
	4	1.052	0.01*
	5	0.937	0.01*
	6	0.77	0.00**
	8	1.07	0.25
	9	1.431	0.56
	10	1.662	0.02*
	11	1.999	0.15
8	1	2.522	0.03*
	2	2.654	0.49
	3	0.99	0.00**
	4	1.01	0.00**
	5	1.425	0.01*
	6	1.309	0.00**
	7	1.07	0.25
	9	0.85	0.61
	10	1.628	0.09
	11	2.392	0.09
9	1	2.538	0.04*
	2	2.576	0.58
	3	1.214	0.00**
	4	1.243	0.00**
	5	1.551	0.03*
	6	1.431	0.00**
	7	1.431	0.56
	8	0.85	0.61
	10	1.899	0.09
	11	2.591	0.16

Appendix B

Pair-wise comparison results for each speaker.

Speaker	Speaker	Standard Error	p
10	1	2.657	0.00**
	2	3.062	0.13
	3	2.074	0.00**
	4	2.018	0.00**
	5	2.072	0.00**
	6	1.921	0.00**
	7	1.662	0.02*
	8	1.628	0.09
	9	1.899	0.09
	11	1.887	0.00**
11	1	2.462	0.48
	2	4.481	0.60
	3	2.647	0.49
	4	2.481	0.85
	5	2.241	1.00
	6	2.047	0.47
	7	1.999	0.15
	8	2.392	0.09
	9	2.591	0.16
	10	1.887	0.00**

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