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Impact of Hearing Aid Technology on Outcomes in Daily Life III: Localization

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Abstract

Objective—Compared to basic-feature hearing aids, premium-feature hearing aids have more advanced technologies and sophisticated features. The objective of this study was to explore the difference between premium-feature and basic-feature hearing aids in horizontal sound localization in both laboratory and daily life environments. We hypothesized that premium-feature hearing aids would yield better localization performance than basic-feature hearing aids.

Design—Exemplars of premium-feature and basic-feature hearing aids from two major manufacturers were evaluated. Forty-five older adults (mean age 70.3 years) with essentially symmetrical mild-to-moderate sensorineural hearing loss were bilaterally fitted with each of the four pairs of hearing aids. Each pair of hearing aids was worn during a 4-week field trial and then evaluated using laboratory localization tests and a standardized questionnaire. Laboratory localization tests were conducted in a sound treated room with a 360°, 24-loudspeaker array. Test stimuli were high-frequency and low-frequency filtered short sentences. The localization test in quiet was designed to assess the accuracy of front/back localization, while the localization test in noise was designed to assess the accuracy of locating sound-sources throughout a 360° azimuth in the horizontal plane.

Results—Laboratory data showed that unaided localization was not significantly different from aided localization when all hearing aids were combined. Questionnaire data showed that aided localization was significantly better than unaided localization in everyday situations. Regarding the difference between premium-feature and basic-feature hearing aids, laboratory data showed that, overall, the premium-feature hearing aids yielded more accurate localization than the basic-feature hearing aids when high frequency stimuli were used and the listening environment was quiet. Otherwise, the premium-feature and basic-feature hearing aids yielded essentially the same performance in other laboratory tests and in daily life. The findings were consistent for both manufacturers.

Conclusions—Laboratory tests for two of six major manufacturers showed that premium-feature hearing aids yielded better localization performance than basic-feature hearing aids in one out of four laboratory conditions. There was no difference between the two feature levels in self-

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reported everyday localization. Effectiveness research with different hearing aid technologies is necessary and more research with other manufacturer's products is needed. Furthermore, these results confirm previous observations that research findings in laboratory conditions might not translate to everyday life.

Keywords

Hearing aids; Localization; Front/back localization; Self-report measure

Introduction

This is the third paper of a series on the impact of hearing aid technology on outcomes in daily life. This paper focuses on horizontal sound localization with premium-feature and basic-feature hearing aids.

Being able to accurately localize sounds is a fundamental and important function of hearing. This function not only is important for safety but also might help a listener to improve speech understanding and communication in an adverse listening environment (Best et al. 2010). Poor sound localization ability can be a major contributor to auditory handicap (Noble et al. 1998). Although sound localization exploits a variety of acoustical cues, three cues are generally described as most salient. They are: interaural time difference (ITD), interaural level difference (ILD), and monaural spectra. ITD cues are primarily used for localizing low frequency sounds (below 1500Hz). ILD cues are primarily used for localizing high frequency sounds (above 1500Hz). Monaural spectral cues are coded in high frequencies (above 5000Hz) and are used for locating sounds in the front/back dimension as well as vertically. Further details of these cues as well as others that have been studied can be found in Blauert (1997, 2005).

Using hearing aids, especially behind-the-ear (BTE) style hearing aids, is known to alter the abovementioned cues relative to unaided listening (Byrne et al. 1998). Previous laboratory research showed that using hearing aids either made localization performance poorer compared to without hearing aids or had no effect on localization (e.g., Byrne et al. 1992; Byrne et al. 1995; Kobler et al. 2002; Markides 1977; Noble et al. 1990; Van den Bogaert et al. 2006). For example, Van den Bogaert et al. (2006) found that aided horizontal localization performance was poorer than unaided performance when test stimuli were audible for both aided and unaided conditions. In contrast, Nobel and Byrne (1990) evaluated localization performance with three hearing aid styles (behind-the-ear [BTE], in-the-ear [ITE], and in-the-canal [ITC]), which were known to have different impacts on localization cues. They found that the participants' localization performance with the hearing aid style that they were accustomed to wearing was not significantly different from unaided performance, suggesting that the disrupted localization cues could be reestablished after sufficient acclimatization. This observation was corroborated by Drennan et al. (2005). In the past two decades, modern digital hearing aid technologies have made considerable advances in both hearing aid design and fitting. A number of technologies or features that are intended to improve sound localization have been developed. They can be categorized either as adaptive directional microphone (DM) or binaural synchronization technologies.

Adaptive directional microphones

Adaptive DMs are designed to be more sensitive to sounds from a desired direction and less sensitive to sounds (e.g., noises) emitted from other directions. Although DMs are not typically designed to improve localization, the improvement of signal-to-noise ratio could increase audibility of desired sounds. This could potentially improve the ability to locate these sounds. Laboratory measurements have shown that DMs with cardioid, hypercardioid, and supercardioid polar patterns improve hearing-impaired listeners' localization performance compared to omnidirectional microphones (Chung et al. 2008). Adaptive DMs can be categorized as single-channel adaptive DMs and multi-channel adaptive DMs. Single-channel adaptive DMs generate only one broadband polar pattern at a time regardless of the number or spectra of noise sources present. The polar pattern is determined by the location of the most intense noise source. In contrast, multi-channel adaptive DMs can generate one directional polar pattern for each of several frequency channels to de-emphasize noises with different frequencies that are emitted from different directions. Therefore, if there is only one noise source in an environment, no differences in performance between these two types of DMs are anticipated. However, differences in performance between the two types of DMs are expected in the presence of concurrent spatially-separated noises with different frequency emphasis. In this situation, multi-channel adaptive DMs should be more effective in improving signal-to-noise ratio compared to single-channel DMs. Given the fact that multi-channel adaptive DMs have been in wide use in digital hearing aids for several years, there is surprisingly little independent evidence regarding their improved effectiveness compared with single-channel adaptive DMs for any type of outcome.

Pinna effect simulation (PES) is a special application of a multi-channel adaptive DM intended to restore the effect of a pinna for BTE style hearing aids. When using a BTE style hearing aid (including receiver-in-the-canal [RIC] hearing aids), incoming sounds are picked up by the hearing aid microphone without filtering by the pinna. As a consequence, monaural spectral cues provided by the pinna are missing, resulting in poorer front/back discrimination performance with BTEs compared to hearing aid styles with microphone locations in the ear (e.g., Best, et al., 2010; Jensen et al. 2013; Van den Bogaert et al. 2011). Furthermore, acoustical evidence has shown substantial binaural directivity advantages at frequencies above 1000Hz when the microphone is located at the entrance of the ear canal compared to above the pinna (Sivonen 2011).

PES digitally simulates the directivity advantages provided by a pinna by manipulating the polar patterns of BTE hearing aids' multi-channel DMs. Typically, the polar patterns for low frequency channels are set to an omnidirectional mode while the polar patterns for high frequency channels (usually above 1000Hz) are set to a front-facing directional mode (e.g., hypercardioid). By using this type of processing, higher frequency sounds arriving from the back are attenuated and lower frequency sounds are left intact. Previous independent research has shown that, compared to an omnidirectional microphone, PES can yield a substantial reduction in front/back localization errors in a laboratory setting when test stimuli have sufficient high frequency components. These laboratory advantages were not replicated in self-reported localization with PES in daily life (Keidser et al. 2009).

Bilateral synchronization

Bilateral synchronization is another technology that has been described as having the potential for improving sound localization. With this feature, the left and the right hearing aids are linked using wireless transmission technology. Thus, functions such as volume control, hearing aid program, noise reduction, DM mode, and compression settings theoretically could be coordinated for the two hearing aids. As a consequence, ITD and ILD cues might be preserved, potentially optimizing localization performance. Independent studies have yielded inconsistent findings concerning the potential improvements in localization that might be achieved with bilateral synchronization. Two published independent studies examined the potential advantages of bilateral synchronization of DM modes for horizontal localization (Keidser et al., 2006; Van den Bogaert et al, 2006). Both concluded that independently operating DMs have an adverse effect on scores in a laboratory setting. This suggests that bilaterally synchronized DM modes might improve localization. Keidser et al. (2006) and Ibrahim et al. (2013) explored potential localization benefits of bilaterally synchronized compression modes but reported inconsistent results, with Keidser et al. reporting no benefit and Ibrahim et al. seeing improvements for some stimuli. Drennan et al. (2005) determined that localization worsened when ITD and ILD cues were distorted, but after three weeks of acclimatization to the new cue patterns, localization ability returned to the original level.

Premium-feature versus basic-feature hearing aids

Despite the fact that the abovementioned technologies for improving sound localization performance are available in the hearing aid market, they are not available in every hearing aid model. At the time when this research was undertaken, basic-feature hearing aids had single-channel adaptive DMs and a basic synchronization function that provided bilateral volume and program control. In contrast, the premium-feature hearing aids used in the research had multi-channel adaptive DMs, PES, and an advanced synchronization function that allowed not only binaural volume and program control, but also coordination of noise reduction, and directionality settings between the two devices. However, compression settings were not synchronized. In addition, the premium-feature hearing aids had other more-advanced versions of features compared to basic-feature hearing aids, including more compression channels, more advanced feedback cancellation, and more advanced noise reduction algorithms. Given these advanced capabilities, it might be presumed that premium-feature hearing aids would outperform basic-feature hearing aids in terms of sound localization. However, there is limited independent evidence to support this notion, and what evidence there is tends to have been conducted in laboratory conditions with other features disabled. Therefore, it is of considerable interest and importance to compare localization outcomes with premium-feature hearing aids to those with basic-feature hearing aids when both types of models are used as they are in daily life, with all sound processing features simultaneously active.

The goal of this research was to explore sound localization performance with premium-feature and basic-feature hearing aids in both laboratory and daily life environments. We hypothesized that premium-feature hearing aids would yield better localization performance than basic-feature hearing aids. Four specific research questions were answered:

1. Is aided localization performance better than unaided localization performance?
2. Do premium-feature hearing aids yield better localization performance than basic-feature hearing aids in a laboratory setting?
3. Do premium-feature hearing aids yield better localization performance than basic-feature hearing aids in everyday life?
4. Are answers to the second and the third questions the same for hearing aids from two of the six major hearing aid manufacturers?

Methods

This study was a single-blinded double crossover trial. Specifics about the research design, participants, and hearing aid fitting have been described in detail in the first paper of this series (Cox, Johnson, & Xu, 2016) and are described briefly here. Study procedures were reviewed and approved by the University of Memphis Institutional Review Board.

Participants

Forty-five adults (30 males and 15 females) with essentially symmetrical, non-fluctuating, mild to moderate, sensorineural hearing loss were included in this study. Mean hearing thresholds are shown in Figure 1. Age range of these participants was from 61 to 81 (M = 70.3, SD = 5.5). Nineteen participants were experienced hearing aids users. All participants were native English speakers. They were recruited from the University of Memphis Hearing Aid Research Laboratory subject database, as well as through word-of-mouth referral.

Hearing Aids

Exemplars of two premium-feature and two basic-feature mini BTE hearing aids with thin tubing were used. These hearing aids were from two major manufacturers (referred to as brand A and brand B in this article) and released to the market in 2011. Each participant was bilaterally fitted, following best practice guidelines, with each of the four pairs of hearing aids. An appropriate coupling strategy was used for each participant: 25 were fitted with custom vented earmolds, 3 with custom occluded earmolds, and 17 with open non-custom domes. Real Ear Aided Response was used to match ear canal levels to prescription targets based on the National Acoustics Laboratory Non-Linear 2 protocol (Keidser et al. 2011). Each hearing aid's feature settings were adjusted in accordance with the brand's recommendations for that participant's hearing loss. Three manually selectable programs were provided: (1) an automatic program (the default setting); (2) the strongest fixed front-facing directional program (manually selectable); and (3) the program with the most effective technology for detecting speech signals originating from different directions (manually selectable)[1]. Further details of these three programs can be found in Cox et al. (2016). For each pair of hearing aids, a remote control was provided to allow for adjustments of volume and program as needed. A self-learning function was available for the premium-

[1]The terms "strongest" and "most effective" reflect the judgement of the researchers after measuring the performance of the devices (or reviewing published information in cases when measurements were not feasible). They are not manufacturer terms. Each manufacturer can use different terms to describe essentially similar features.

feature hearing aids and was turned on. Each participant wore a pair of hearing aids for four weeks in daily life before evaluation. The order of hearing aid brand and the order of using premium-feature and basic-feature hearing aids within each brand were counterbalanced.

Laboratory Localization Performance

Each participant's localization performance was evaluated in a quiet situation (localization in quiet test) and in a situation with continuous interfering noises (localization in noise test) under unaided and four aided conditions. The localization in quiet test was designed to assess the accuracy of localizing sounds from front or back, while the localization in noise test was designed to assess the accuracy of localizing sounds from 360° directions in the horizontal plane when there were interfering noises.

Table 1 describes the features of the automatic program for the four research hearing aids. This program setting was used for laboratory testing. Most of the electroacoustic aspects of these features were verified. However, some features, such as multi-channel vs single-channel DMs, can only be verified in specialized laboratories and these were not verified. The first two features entered in Table 1 are of particular interest for this article.

Instrumentation and Test stimuli

All localization tests were conducted in a double-wall sound treated room (2.7 × 2.1× 2.0 meters) with reverberation times measured in 1/3-octave bands (0.25 to 8.0 kHz) from 56 to 27 msec. Twenty-four SoundTube SM31-EZ-T single cone full-range loudspeakers (SoundTube Entertainment, Park City, UT) were used. Each of the loudspeakers was mounted on a loudspeaker stand with the center of the cone at ear level (1.14 meters from the floor). The loudspeakers were positioned 15° apart on a 360° horizontal circle with an inside diameter of 2 meters. The loudspeakers were numbered clockwise from 1 to 24, starting at 0° azimuth. Only the 12 odd number loudspeakers were used to deliver test stimuli, but this was not disclosed to the participants. A diagram of the loudspeaker setup is shown in Figure 2. Frequency responses of the 12 connected loudspeakers were within ±3 dB from 100 Hz to 2000Hz, and ±4.5 dB from 2000Hz to 10000Hz. Test stimulus presentation via these loudspeakers was controlled using Tucker-Davis Technologies (TDT) System 3 devices. The test stimulus was delivered from a personal computer to a TDT RP2.1 real-time processor. The signal was then set to the desired level by a programmable attenuator (TDT PA5) and a stereo amplifier (TDT SA1). The amplified signal was delivered to the target loudspeaker using a multiplexer (TDT PM2R). A MATLAB program developed by the second author was used for test administration and data collection.

The test stimuli were short sentences from the Speech Pattern Contrast (SPAC) test materials (Boothroyd 1984) recorded and described by Cox et al. (1987). There were 128 test sentences (32 for localization in quiet and 96 for localization in noise) and 12 practice sentences. Half of the test and practice sentences were spoken by a male talker (talker 5 in Cox et al. 1987) and the other half of the sentences were spoken by a female talker (talker 6). These two talkers were selected because they had similar long-term average speech spectra. The rationale for including male and female talkers was to increase ecological validity of the tests. Among the total 140 sentences, half of them were acoustically filtered to select the low frequency (LF) components and the other half were filtered to select the high frequency (HF) components. The purpose of including both LF and HF stimuli was to consider the potential effect of speech frequency emphasis on a listener's localization performance when using premium and basic hearing aid features. To produce these stimuli, the original full spectrum sentences were filtered by a LF (200–600Hz) or a HF (1500–4500Hz) 30th-order Butterworth band-pass filter. Durations of the filtered sentences were between 1.30 and 1.40 sec with a mean of 1.33 sec.

The presentation levels of the filtered sentences were based on a presentation level of the full spectrum sentences at 75 dB SPL. Thus, the nominal presentation levels of the LF and HF stimuli were 72 dB SPL and 61 dB SPL, respectively. Pilot measurements showed that with these levels, audibility of both LF and HF stimuli was maintained for individuals with mild-to-moderate sensorineural hearing loss when tested in the unaided condition (this also was confirmed during data collection of the present study). It has been demonstrated that level roving can minimize the risk of using overall stimulus level as a cue to locate sounds during a laboratory localization test (e.g., Keidser et al. 2006). In the present study, roving was automatically achieved because the test stimuli were filtered sentences and they were already slightly different in digital RMS levels. A roving range was calculated according to the difference between the minimum and maximum digital RMS levels for each type of filtered sentences. The mean roving range across the two types of stimuli was ±3.3 dB. This is similar to the roving range of ±3 dB used in Keidser et al. (2006).

Localization in Quiet

To provide optimal conditions for pinna effects (real or simulated) to be observed, this testing was performed without masking noises. To estimate the PES created by the premium-feature devices, the characteristics of realistic pinna effects were assessed in a double-walled sound-treated room, using a KEMAR manikin. Hearing aids were programmed using the average participant audiogram for this project. Comparable pinna effects were measured with each hearing aid mounted on the manikin and coupled to the ear canal cavity using a closed dome. All measurements were made at the manikin's simulated tympanic membrane (TM) using a passage of speech at conversational level integrated over one minute. In each of the five conditions (unaided and four aided), the passage was presented first from the front and then the same distance to the ears from the back of the KEMAR. The pinna effect was computed by subtracting the spectrum of the signal observed from the back from that observed from the front.

The results of these measures are depicted in Figure 3. The top panel shows the unaided effect. The level received at the TM was different depending on whether the stimulus emanated from the front or the back. Overall, the difference was a boost of 3–5 dB from about 1 kHz to 12 kHz for speech from the front. The middle panel depicts the comparable results for the basic and premium-feature devices from brand A. The difference between the two curves shows that the PES was seen from about 3 to 12 kHz with the maximum effect of about 10 dB centered at about 7 kHz. The bottom panel depicts the comparable results for the basic-feature and premium-feature devices from brand B. In this brand, the difference between the two curves shows that the PES was seen in a broad boost from about 1.5 kHz to

6 kHz with the maximum effect of about 10 dB across the range of roughly 2–5 kHz. Overall, both premium-feature devices provided a simulated pinna effect of greater magnitude than seen in the unaided ear (top panel) and the brand B PES was more exaggerated than that of the brand A device.

Localization in Noise

To engage the premium-feature and basic-feature DMs and allow for differentiation of the benefit afforded by the bilateral synchronization of directionality and noise reduction in the premium-feature devices, a simple setup was implemented using two noises with different frequency emphasis and source locations. Both were one-octave steady-state noises that were band-pass filtered from a white noise sample. The LF noise was centered at 500Hz, and the HF noise was centered at 3000Hz. Because many directional polar patterns are designed to maintain high sensitivity for sounds from the front and reduce sensitivity for sounds from the back, the two noises were presented from the back of the listener. Two additional loudspeakers (Realistic Minimus-7) were placed at 165° azimuth and 225° azimuth at ear level for presentation of the LF and HF noises, respectively (Figure 2). These two azimuths were selected to prevent the noises being located at two least-sensitive directions (nulls) of one regular polar pattern (e.g., cardioid, hypercardioid, super-cardioid, or bidirectional). With a single-channel adaptive DM, the broadband polar pattern was expected to default to one front-facing directional polar pattern that would attenuate both noises simultaneously as well as possible (Dillon 2012). In contrast, with a multi-channel adaptive DM, two separate polar patterns in two frequency channels would theoretically work independently to attenuate the two noises. The LF and HF noises were stored on the two channels of a CD, amplified separately, and delivered to the two loudspeakers. They were presented simultaneously and continuously during the localization in noise test. The LF noise was presented at 55 dB SPL and the HF noise was presented at 65 dB SPL. Presentation levels were determined based on the levels that would be present in a 70 dB SPL white noise. Since the masking noises were continuously on during the testing, it was anticipated that each pair of hearing aids would be adjusted by the automatic program according to the strategy employed for noisy environments without speech between stimulus presentations. The directional performance of the four research hearing aids in the presence of the noises was roughly estimated using measures made with an AudioScan Verifit instrument equipped with software version 3.12. Broad-band test sounds were presented from front and back loudspeakers in the test space and directional pattern was noted. When the test involved speech (front) and pink noise (rear), all devices produced roughly 10–15 dB suppression of the rear noise for both LF and HF frequency regions. When the test involved pink noise from both front and back, three devices produced essentially the same pattern as seen for speech in noise. However the Premium B hearing aids, while continuing to suppress rear noise in the high-frequency region, showed no directional suppression in the low frequency region.

Procedure

For each of the unaided and aided conditions, the localization in quiet and localization in noise tests were administered in one session. During the tests, the participant sat in the middle of the 24-loudspeaker array and faced loudspeaker 1 at 0° azimuth. For each of the four aided conditions, the participant's hearing aids were set to the automatic program with the preferred volume level used during the field trial. From then on, no adjustment to the hearing aids was allowed during the tests. The participants were instructed to identify the voice location and to respond by saying the number of the loudspeaker. No feedback of performance was given. The participants were required to face towards loudspeaker 1 before each sentence presentation. To improve the ecological validity of the localization tests, the participants were allowed to turn their heads somewhat from side to side during sentence presentation, if desired. However, they were instructed that their shoulders must remain facing forwards at all times. To help the participants give their responses when stimuli were presented from the back, a diagram showing locations of the 24 loudspeakers was provided. If they could not determine the direction of a presentation, they were allowed to say "I don't know." That answer was coded as "no response" for this presentation and it was excluded from analyses. A test administrator sat outside the sound room to control stimulus presentation and record responses from the participant using the MATLAB test administration program.

For the localization in quiet test, 4 loudspeakers were used. They were loudspeakers 3, 11, 15, and 23, and corresponded to 30°, 150°, 210°, and 330° azimuths, respectively (Figure 2). In contrast, for the localization in noise test, all 12 active loudspeakers were used. In both localization tests, 4 LF (2 female and 2 male) and 4 HF (2 female and 2 male) test stimuli were presented from each active loudspeaker in random order. The participant was not told which loudspeakers were active in any given test.

A practice sequence with 12 filtered sentences was given prior to each of the two localization tests to familiarize the participant with the task. Participants heard one practice sentence from each of the 12 active loudspeakers in random order at levels identical to those of the test stimuli.

Everyday Life Localization Self-report Test

In addition to the laboratory-based evaluation, unaided and aided sound localization performance also was assessed in everyday listening conditions using the Speech, Spatial, and Qualities of Hearing Scale (SSQ; Gatehouse & Noble 2004). Items in this questionnaire cover a variety of aspects of hearing in many complex situations representative of everyday life. The scoring scale for unaided listening is from 0 (complete inability or complete absence of a quality) to 10 (complete ability or complete presence of a quality). Prior to completion of the SSQ, all of the experienced hearing aid users were asked if they felt that they were able to recall accurately their day-to-day hearing abilities without wearing hearing aids. One full-time user was not able to recall his unaided data. This user agreed to go unaided for a few days before completing the questionnaire about his unaided experiences.

Benefits of using hearing aids compared to without hearing aids was measured using a different version of the SSQ, referred to as the SSQ-B (Jensen et al. 2009). The SSQ-B comprises the same items as the SSQ and yields scores for the same subscales, but employs a modified response scale to measure the benefit (or deficit) of using amplification. The response scale used in the SSQ-B extends from −5 (much worse compared to no hearing aids) to +5 (Much better compared to no hearing aids). Participants completed the SSQ-B at the end of each 1-month hearing aid trial.

The standard instructions were used for both the SSQ and the SSQ-B. Based on a review of item content, scores for items for two subscales, 1- localization (Spatial items 1–6) and 2- distance and movement (Spatial items 7–13, 15, and 16), were averaged into a single composite score to evaluate localization performance (Gatehouse & Akeroyd 2006).

Statistical Analysis

It was decided in the planning phase that a medium effect size (effect size *Cohen's d* = 0.5, see [Cohen 1988]) would be the minimum interesting difference in laboratory or self-report outcomes between premium-feature and basic-feature hearing aids. The rationale for choosing this effect size has been discussed in Cox et al. (2016). With 45 participants, this research had greater than 98% power to detect a medium effect favoring premium-feature hearing aids (computed using G*power 3 [Faul et al. 2007]).

All statistical data analyses were performed using Statistical Package for the Social Sciences (SPSS) Version 21 software. A General Linear Model (GLM) within-subjects repeated measures analysis of variance (ANOVA) with planned contrasts was used. This analysis strategy has the advantage of increased statistical power while controlling the experiment-wise error rate (Rosenthal 1985). In each GLM analyses there was one dependent variable (listening condition), with 5 levels (unaided, basic A, basic B, premium A, and premium B). No interaction effects were tested. Following the research questions, 4 contrasts were explored:

1. Unaided versus Aided
2. Premium versus Basic (Both brands combined)
3. Premium versus Basic for brand A
4. Premium versus Basic for brand B

Contrasts 1 and 2 were mutually orthogonal and they were tested at a significance level of .05. Contrasts 3 and 4 were not orthogonal to the other 2 contrasts and they were tested at a corrected significance level of .025.

Results

Scoring

Because an assessment of talker effect was not a goal of this research and the two talkers had similar long-term speech spectra, scores for the two talkers were combined for all analyses.

The performance measure for both localization in quiet and localization in noise was root-mean-square (RMS) error. This calculation provides a measure of the absolute difference between the angle of the stimulus presentation and the angle of the indicated response. As a result, the maximum possible RMS error is 180°. As described in Van den Bogaert et al. (2011), RMS error is calculated according to the following equation:

$$RMS\,(degree) = \sqrt{\frac{\sum_{i=1}^{n}(Presentation_i - Response_i)^2}{n}}$$

where n is the number of presentation-response pairs for a given test condition. In the present study, RMS errors were calculated for the HF stimuli condition and the LF stimuli condition for both localization in quiet and localization in noise. Thus, n equaled 16 for localization in quiet and 48 for localization in noise. The calculated RMS errors for the five listening conditions were used for statistical analyses.

Localization in Quiet

Localization error patterns for the aided conditions are presented for the quiet test environment in Figures 4 and 5. For these figures, the x-axis represents the azimuth where the stimuli originated (12 possible), and the y-axis represents the azimuth that participants indicated they perceived the stimuli to have originated (24 possible). The circles represent stimulus-response pairs. The size of each circle indicates the relative number of responses for a given stimulus; hence, a larger circle represents more responses. Data have been combined for the two brands of basic devices and for the two brands of premium devices. In interpreting these figures, it might be helpful to envision a diagonal line rising from the bottom left corner to the top right corner of each plot. This diagonal line represents perfect performance. For reference, a plot showing a series of large circles rising along the theoretical diagonal line would indicate perfect performance by all participants. Figure 4 shows localization patterns in quiet for the basic (filled circles) and premium devices (open circles) when listening to HF stimuli. Figure 5 shows corresponding localization patterns in quiet when listening to LF stimuli.

For Figure 4, when listeners used premium devices (open circles) and stimuli were presented from 30° azimuth (from the front and right of the listener), responses were mostly accurate. This is demonstrated by the largest open circle for the 30° presentation azimuth occurring at the 30° response azimuth. Most confusions for HF stimuli originating from 30° were perceived to arise from a location within the correct quadrant when premium devices were used: varying slightly in location, but still originating from the front and right of the listener. This is demonstrated by the presence of smaller open circles representing response azimuths between 0° and 90°, and few open circles at azimuths greater than 90°. In contrast, when listeners used basic devices (represented in Figure 4 by filled circles), stimuli originating from 30° were not only perceived to be from locations from the front/right of the listener (0 – 90°), but also were perceived as originating from the front/left of the listener (demonstrated by filled circles for response azimuths between 270 – 345°). Far fewer open or filled circles are present for response azimuths between 110 – 255°. This indicates that listeners rarely mistook HF stimuli originating from 30° as arising from behind when using either premium or basic devices. These same response patterns were observed for HF stimuli presented from 330° (from the front and left of the listener), except reversed for right and left. When HF stimuli were presented from 150° (from behind and to the right of the listener) and listeners were using premium devices, there were more frequent errors, and errors were more evenly distributed across response locations on the right side of the listener. This is demonstrated by the similarly sized open circles present for all response azimuths from 0 – 150°. It can be observed that the open circles are slightly larger for response azimuths between 0 and 45°. This type of back-to-front error, which preserves the azimuth angle off of the acoustic midline, is a common type of spatial processing error, especially for hearing impaired listeners (Byrne & Noble 1998) and BTE hearing aid wearers (Van den Bogaert et al. 2006). Examination of the filled circles for the 150° presentation azimuth shows that the larger filled circles are between 0–45° and 300–345°, with fewer and smaller filled circles at other response azimuths. This indicates that when listeners used basic devices, sounds originating from 150° mostly were perceived as arising from the front/right and front/left of the listener: suggesting right-to-left confusions in addition to back-to-front errors. These same response patterns were observed for HF stimuli presented from 210° (from the rear and left of the listener), except were reversed for right and left.

Figure 5 demonstrates localization patterns in response to LF stimuli in a quiet environment. As with HF stimuli, fewer errors occurred when stimuli were presented from the front (30° and 330°) than from the rear (150° and 210°). In contrast to HF stimuli, there were fewer errors overall and response patterns were nearly identical with the two technology levels.

The top panel of Figure 6 summarizes localization performance in quiet for each of the five listening conditions (N=45) in terms of mean RMS error scores. RMS error scores for HF test stimuli are on the left, and scores for LF test stimuli are on the right. Keep in mind that greater RMS error values correspond to poorer localization performance. It can be seen From Figure 6 that the mean RMS error values among the unaided and four aided conditions differ within 12 ~~of 180~~ degrees, for both HF and LF test stimuli. Statistical analyses of RMS error values were analyzed separately for data obtained with HF and LF test stimuli. Distributions of scores obtained in quiet with HF stimuli were moderately negatively skewed for all five conditions. Variables were transformed using the square-root transformation. Analyses of results obtained in quiet with HF stimuli were based on these transformed normally-distributed data. Distributions of scores obtained with LF stimuli were consistent with a normal distribution.

Statistical results for HF stimuli in quiet showed a significant main effect of Condition ($F[4,176] = 6.369$, $p < .001$). Contrast 1 (unaided versus all aided combined) revealed that there was not a statistically significant difference between performance with and without hearing aids ($F[1,44]=.39$, $p=.534$). Contrast 2 (both premium vs. both basic) yielded a significant effect ($F[1,44]=4.98$, $p=.031$), indicating that, overall, the participants made significantly smaller errors with premium-feature hearing aids than with basic-feature hearing aids. The computed effect size (Cohen’s d) for this significant finding (premium vs. basic) shows a small effect of −.19 with a 95% confidence interval (CI) from −.39 to .02. Contrasts 3 (premium A vs. basic A) and 4 (premium B vs. basic B), tested each brand individually. For brand A, there was not a significant difference in errors between premium-feature and basic-feature hearing aids ($F[1,44]=.77$, $p=.39$; however, there were significantly smaller errors with brand B’s premium hearing aid compared to the basic hearing aid ($F[1,44]=7.05$, $p=.01$). This contrast demonstrated a medium effect size ($d = -.31$) and a

95% CI from −.61 to −.01. With LF stimuli, the main effect of Condition was not statistically significant (F[3.028,133.248][2] =.669, p=.574), indicating that the participants' localization errors were not significantly different across the five listening conditions. None of the planned contrasts yielded significant differences between basic-feature and premium-feature devices.

The above analysis of RMS error scores comprised all errors in quiet, including errors in which the designated response was a speaker within the same hemisphere as the target (e.g., target speaker was #3 and response was #4). Recall, however, that a central question in this research concerned the effects of the PES feature which was included in the premium-feature devices but not the basic-feature devices (see Figure 3). The PES feature is intended to promote accuracy in localization of front-originating versus back-originating sounds. To explore this topic from a different perspective, an additional analysis was performed. The localization errors in quiet were partitioned into four categories designated FB, BF, FF, and BB. A FB (front/back) error occurred when the target sound was from one of the front loudspeakers (3 or 23) and the response was given as one of the loudspeakers in the back hemisphere (8 through 18); a BF (back/front) error occurred when the target sound was from one of the back loudspeakers (11 or 15) and the response was given as one of the loudspeakers in the front hemisphere (1 through 6 or 20 through 24); a FF (front/front) error occurred when the target sound was from one of the front loudspeakers (3 or 23) and the response was given as a different loudspeaker in the front hemisphere (1 through 7 or 19 through 24); a BB (back/back) error occurred when the target sound was from one of the back loudspeakers (11 or 15) and the response was given as a different loudspeaker in the back hemisphere (7 through 19). The maximum possible number of errors per participant was 16 (4 speakers × 2 talkers × 2 stimuli).

The mean (N=45) number of errors in each category is depicted for the five listening conditions and for HF (black circles) and LF stimuli (grey circles) in Figure 7. A larger circle is indicative of more errors. For reference purposes, the largest circle (HF-premium A-BF) represents a mean value of 5.6 errors. Several points are noteworthy in this figure. The category with the most errors is BF (back-front) and the category with the fewest errors is FB (front-back). There were more FF errors for HF stimuli than for LF stimuli, whereas there were more BB errors for LF stimuli than for HF stimuli. There is no obvious pattern within any error category for the basic-feature devices to produce more errors than the premium-feature devices.

The HF and LF data represented in Figure 7 were separately explored statistically using repeated measures ANOVA with planned contrasts as described earlier. Our main interest was the result of contrast 2 (both premium versus both basic). Before analysis, the data distributions were examined and almost all of the 40 distributions (5 listening conditions × 2 stimuli × 4 error types) were found to be significantly non-normal in terms of skewness and/or kurtosis. Application of log 10 and inverse transformations did not improve the normality of all distributions and did not change the results of the analyses. ANOVA has been demonstrated to be robust against departures from normality (e.g., Donaldson 1968;

[2]Degrees of freedom have been corrected using Greenhouse-Geisser estimates of sphericity

Glass et al. 1972). Outcomes for the untransformed data are reported here for these reasons and to preserve clarity of interpretation of the empirical data.

The analyses returned results that were consistent with a visual examination of Figure 7: errors with premium-feature devices were not statistically significantly different from those with basic-feature devices for any of the four error types.

Localization in Noise

Localization error patterns for the aided conditions are presented for the noisy test environment in Figures 8 and 9. These figures should be interpreted as described for Figures 4 and 5 above. Again, in interpreting these figures it might be useful to envision a diagonal line representing perfect performance rising from the bottom left to the top right of each plot. Figure 8 shows localization error patterns for the two aided conditions when using HF stimuli (both brands combined). From examination of this figure, it can be seen that there are minimal differences in error patterns when comparing responses with basic (filled circles) and premium devices (open circles). Stimuli originating from in front of the listeners mostly were perceived accurately when listening with both levels of technology. This is demonstrated by the largest circles clustering around the theoretical rising diagonal line for presentation azimuths from 0–60° and 300–330°. Stimuli originating from behind the listeners were frequently perceived as arising from azimuths forward of their actual location, as is demonstrated by the largest circles for presentation azimuths from 120–240° occurring at response azimuths from 0–110° and 255–345°. These patterns demonstrate that the majority of localization errors for HF stimuli in noise were back-to-front reversals, together with some left-to-right confusions. Figure 9 shows localization error patterns for the two aided conditions when using LF stimuli in background noise (both brands combined). Again, it can be seen that there are minimal differences in error patterns when comparing responses with the basic and premium devices, and that smaller errors were observed when test stimuli were presented from the front compared with stimuli from the back. When contrasting Figures 8 and 9, it is apparent that localization was more accurate when stimuli were LF.

As with localization in quiet, a mean RMS value was computed for each listening condition by averaging individual values across all the participants. These are shown in the lower panel of Figure 6. From this figure it can be seen that mean RMS errors for the five listening conditions were similar for the HF stimuli (within 3 degrees) and also for the LF stimuli (within 4 degrees). Some distributions of scores obtained in noise (4 of 5 HF variables; 2 of 5 LF variables) were moderately negatively skewed. Influential outlying data points (10 of 450 data points) were adjusted following the recommendations of Tabachnick et al. (2006) described above. Analyses reported in this section are based on data after outlier adjustment.

Separate within-subjects repeated measures ANOVA were conducted on results obtained with HF stimuli and LF stimuli. The main effect of Condition was not significant for HF stimuli (F[4,176] =.753, p=.557) or LF stimuli (F[3.163,139.178][3] =1.195, p=.315). None of the planned contrasts for the two types of test stimuli yielded significant results. These

[3]Degrees of freedom have been corrected using Greenhouse-Geisser estimates of sphericity

findings indicated that the participants' horizontal localization performance in noise was not significantly different across the five listening conditions with HF or LF stimuli.

Localization in Daily Life

In each listening condition, a composite score was computed for each participant and each listening condition by averaging the rating scores across the questionnaire items for spatial hearing. These included spatial items 1–13, 15, and 16. Note that the SSQ composite scores for the four aided conditions were benefit scores relative to unaided performance. For the total 225 composite score data points (5 listening conditions × 45 participants), one outlier was identified and adjusted according to the recommendations described in Tabachnick et al. (2006). All figures and analyses reported in this section were based on the data after the outlier adjustment.

Individual SSQ composite scores with unaided versus each aided condition are plotted in Figure 10. In each panel, unaided SSQ scores are plotted on the x-axis, while SSQ benefit scores are plotted on the y-axis. The panel on the left shows data for hearing aids from brand A. The panel on the right shows data for hearing aids from brand B. A horizontal line is drawn at the 0 SSQ benefit score for each panel. Data points located above this line represent the participants who reported receiving benefits in sound localization with hearing aids. Data points located below this line represent the participants who reported poorer sound localization performance with hearing aids than without. It can be seen from Figure 10 that a large majority of the participants (92.2% of the total data points) reported positive localization benefits from using hearing aids.

The mean unaided SSQ composite score was 5.8 (SD=2.19) on a scale of 0 to 10. The four mean composite SSQ localization benefit scores for aided conditions were 1.68 (SD=1.54) for Basic A, 1.96 (SD=1.48) for Basic B, 1.80 (SD=1.50) for Premium A, and 1.99 (SD=1.36) for Premium B on a scale of −5 to +5. Because unaided and aided performance were evaluated using different scales, they could not be compared directly in the same analysis. To test the effectiveness of using the research hearing aids, the four SSQ localization benefit scores for the aided conditions were averaged for each participant. The resulting scores (M=1.86, SD=1.30) were compared to 0 (no benefit) using a one-sample t-test. The result showed that self-report localization performance was significantly improved when using the research hearing aids ($t(44)=9.59$, $p<.001$, Cohen's d = 1.43, 95% CI=[1.01, 1.84]). To test contrasts 2 through 4, a GLM within-subjects repeated measures ANOVA was performed on the SSQ benefit scores for the four aided conditions. Results revealed no significant effect of hearing aid Condition ($F[1.585,69.736]$[4] =1.475, p=.236). Further, none of the tested contrasts yielded significant results.

We speculated that the participants who reported poorer unaided localization performance might receive more localization benefit from using hearing aids. That is to say, we hypothesized that lower unaided SSQ scores would associate with higher SSQ benefit scores. Correlation analyses between unaided SSQ scores and each of the four aided SSQ benefit scores were performed to test this hypothesis. Three of the four correlation

[4]Degrees of freedom have been corrected using Greenhouse-Geisser estimates of sphericity

coefficients were negative, indicating a trend supporting our hypothesis. However, correlations were weak (r_{basicA} = .012, $r_{premiumA}$ = −.114, r_{basicB} = −.213, and $r_{premiumB}$ = −.245) and none was statistically significant.

Figure 11 depicts the relationship between SSQ scores for the premium-feature and basic-feature hearing aids for each brand. In each panel, the x-axis shows SSQ benefit scores with basic-feature hearing aids and the y-axis shows SSQ benefit scores for premium-feature hearing aids. Data points that fall above the rising diagonal line indicate better localization benefit with premium-feature devices. In each panel, the majority of the data points were close to the main diagonal line, indicating similar self-reported localization benefits with premium-feature and basic-feature hearing aids.

Discussion

We explored the difference between premium-feature and basic-feature hearing aids in assisting sound localization in laboratory and everyday situations. All research hearing aids were fitted following best-practice guidelines and participants were blinded about the devices they were wearing. Our findings demonstrated that, compared to the basic-feature hearing aids, premium-feature hearing aids resulted in better localization performance in one of four laboratory test conditions. In everyday life, the premium-feature and the basic-feature hearing aids were reported as being equally helpful in terms of sound localization.

Was aided localization better than unaided?

When using hearing aids, acoustic cues for locating sounds can be altered by hearing aid signal processing, which could disrupt localization ability. Some previous research has shown that aided laboratory localization performance is poorer than unaided performance (e.g., Byrne et al. 1992; Markides 1977; Van den Bogaert et al. 2006). However, other studies show that aided laboratory localization performance was equal to unaided performance (e.g., Byrne et al. 1995; Kobler et al. 2002; Noble et al. 1990). Differences in these findings might be due to variations in research methodology, hearing loss, and hearing aid configuration, etc. (Simon 2005). For example, as previously noted, at least two studies have shown that diminished aided localization ability can return to an unaided baseline after a period of acclimatization. Consistent with this observation, we found that, after one month of daily use, unaided and aided localization performance were not significantly different in any of the four laboratory test conditions. In contrast to the laboratory data, self-report data describing everyday listening showed that aided localization was reported to be significantly better than unaided localization in daily life. This finding was in line with previous research on self-reported localization (e.g., Gatehouse, Akeroyd 2006; Noble et al. 1995). It is reasonable to speculate that differences in laboratory and everyday localization benefit might be attributed to differences in audibility between unaided and aided listening in these two environments. In everyday environments, amplified sounds are generally more audible than unaided sounds. As a result, hearing aid users might perceive that it is easier to locate the more audible amplified sounds. However, in a laboratory environment, test sounds were presented at an audible level for both unaided and aided conditions. Under these conditions differences in audibility would not be a primary contributor to differences in unaided and aided localization performance.

Did premium-feature hearing aids yield better localization performance?

The premium-feature hearing aids used for this research implemented a feature designed to simulate the high-frequency information provided by the pinna. This information is lost when hearing aids, like those used in this research, have microphone locations above the pinna. We examined the impact of this pinna effect simulation (PES) in the laboratory using two scoring approaches: computation of RMS error for each subject (Figure 6) and examination of error categories for each subject (Figure 7).

RMS error scores indicated that the primary-feature devices yielded a small advantage in localization in a quiet environment, and when high-frequency stimuli were presented from close to the center line from either front or back. In this analysis, premium-feature hearing aids returned significantly better RMS error scores than basic-feature hearing aids when data from the two premium-feature devices were combined and compared to the combined data from the two basic-feature devices. When the effects for both brands of devices were combined, the premium-feature hearing aids outperformed the basic-feature hearing aids with a computed effect size of −.19. The lower end of the 95% CI for this computed effect size approached a medium effect (−.39), suggesting a slight possibility for future studies to approach the medium effect size that we chose as a minimum practically important difference between premium-feature and basic-feature devices. However, the upper end of the 95% CI was .02. This would indicate a slight potential for future studies to observe essentially equivalent performance between the two conditions.

When localization errors were categorized as in Figure 7, the small advantage for premium features seen with RMS error scoring could not be visually detected nor elicited with statistical analysis. In addition to front/back or back/front confusion, it appears that a sizable proportion of the errors involved incorrect localization within the same hemisphere (front or back) when target sounds were presented in quiet.

Pinna effect simulation is designed to improve front/back localization, and was only available in the premium-feature hearing aids. Therefore, it is reasonable to speculate that the better localization performance with the premium-feature hearing aids in the present study relates to the PES feature. Our finding with RMS error scoring was consistent with that of Keidser et al. (2009), who reported better front/back localization performance with PES over an omnidirectional microphone in a quiet laboratory environment with high frequency stimuli (3000Hz octave band filtered pink noise and cockatoo noise). The effect sizes for the 3000Hz octave band filtered pink noise and the cockatoo noise were −1.51 (95%CI=[−2.13, −.87]) and −2.13 (95%CI=[−2.9, −1.34]), respectively. Clearly, Keidser and colleagues obtained much larger performance effects than the present study. This might have resulted from some noteworthy differences between the two studies. For example: some features of the hearing aids used in Keidser's study, such as digital noise reduction, adaptive directionality, and sound environment classification, were deactivated during measurements, whereas all features were activated in our research; different test stimuli and data collection/analysis approaches were used; and, in the present study, the basic-feature hearing aids employed single channel adaptive microphones in contrast to the omnidirectional ones in the Keidser et al. work. These differences could contribute to the larger effects observed in Keidser's study.

Advantages of using a binaural synchronization function to improve front/back localization have been demonstrated compared to no binaural synchronization (Ibrahim et al. 2013). In the present study both the premium-feature and the basic-feature hearing aids had binaural synchronization capabilities. It is unclear whether the more advanced versions of this function found in the premium-feature hearing aids also might have contributed to the observed performance difference in front/back localization in quiet between the two types of hearing aids.

The experimental design for the localization in noise test (i.e., using spatially and spectrally separated noises) was intended to engage the single-channel and multi-channel adaptive DMs according to their optimal capabilities. In contrast to the results in the quiet laboratory environment, there were no significant overall differences between premium-feature and basic-feature hearing aids when the laboratory environment included interfering noises. These findings suggest that localization in noise was independent of the kind of adaptive DM implemented in the device. It also appears that more advanced binaural synchronization in the premium-feature devices was not helpful in localization in noise during this research. However, it also should be noted that the synchronization update rates for all experimental hearing aids (Table 1) were at least 1 second. Thus, it could be argued that the brevity of our stimuli (about 1.3 seconds) minimized the likelihood that any environmental adaptations could have assisted localization. Either longer external stimuli or faster device adaptation might change this outcome, if this processing is practicable in daily life.

Our findings are consistent with the reports of Drennen et al. (2005) and Nobel and Byrne (1990) who showed that listeners could adapt to new localization cues produced by hearing aid processing (i.e., ITD, ILD, and monaural cues). In the present study, for each participant, localization cues probably were altered differently by the premium-feature and the basic-feature devices due to differences in signal processing. However, after four weeks of acclimatization, each participant could have adapted to the new acoustic cues, resulting in similar localization performance in noise with different hearing aid technologies.

The results of the self-report measure showed that the premium-feature hearing aids did not yield significantly different localization benefit in daily life situations compared to basic-feature hearing aids. The advantages observed with the premium-feature hearing aids in the quiet laboratory were not reported in daily life. The different findings between laboratory and self-report measures might be attributed to acoustic differences in these listening environments. The laboratory environment was a carefully controlled listening situation designed to allow the hearing aids to function both optimally and authentically, with all features engaged as in daily life. In contrast, daily life listening situations are complex and unpredictable. There are situations with interfering sounds, substantial reverberation, and excessive noises, etc. All of these could compromise the performance of some hearing aid features to some extent, resulting in distorted or ambiguous localization cues. Any differences in hearing aid technologies might be overridden by the complexity of everyday listening environments. Therefore, it is plausible that the small laboratory effect ($d = -.2$) obtained in the present study was simply too slight to observe in everyday situations. Further, in routine listening, people are continually moving their heads and torsos. Brimijoin and Akeroyd (2012) demonstrated that continuous head and torso movement reduced front/back confusions in the real world. In the present study, although the participants were allowed to turn their heads during the laboratory tests, they only had a small range for head turning and had to keep their shoulders facing forward. Thus, the absence of the significant advantages of using premium-feature hearing aids for localization in the real world might be due in part to normal head and torso movements.

Were the results of comparisons between premium-feature and basic-feature hearing aids consistent across the two brands?

When the data from the two brands were analyzed separately, trends were not different than when the two brands were combined. According to RMS errors, the premium-feature hearing aids tended to outperform the basic-feature hearing aids for localization performance in quiet with high frequency stimuli for both brands. However, when analyzed separately for each brand, these trends were only robust enough to be statistically significant for brand B's devices. For this contrast, brand B's premium-feature hearing aids outperformed their basic-feature hearing aids with a small-to-medium effect size of $d = -.31$. The lower end of the 95% CI for this computed effect size reached a −.61, suggesting a slight possibility for future studies to obtain a practically important improvement in localization under these conditions with premium-feature devices. However, the upper end of the 95% CI was −.01. This would indicate a slight potential for future studies to observe essentially equivalent performance between the two conditions.

In all other laboratory and conditions and in self-report of everyday experiences, the premium-feature and basic-feature hearing aids of each brand yielded similar localization performance on average.

Although it was not originally a research question, we observed what appeared to be systematic differences between localization with the brand A devices (both basic and premium) and the brand B devices in localization errors in quiet. From Figure 6 (RMS error scores), it can be seen that the brand B devices yielded better localization performance in quiet than the brand A devices when using high frequency test stimuli. To test whether these differences were significant, a contrast of brand A's devices (basic and premium together) and brand B's devices (basic and premium together) was performed. This contrast was statistically significant ($F[1,44]=16.16$, $p<.001$), with a medium effect of −.5 and a 95% CI from −.8 to −.18. Despite this significant finding, there was no localization difference between the two brands in any other laboratory or self-report measures. Although it is unclear what characteristics in the devices from brand B contributed to this systematic advantage, it is consistent with the more exaggerated acoustical PES of brand B that is evident in Figure 3. This observation supports the potential for manufacturer-wise differences in terms of engineering design to process acoustic signals to achieve a specific hearing aid feature.

Potential limitations

The presence of non-occluding coupling of the hearing aid to the ear canal in most of our participants might have influenced the results, although this type of fitting was appropriate given our participants' mild-to moderate hearing losses. It could be argued that presence of unprocessed sounds in the ear canal might overwhelm any potential benefits ensuing from processed sounds yielded by synchronized features. To explore this possibility, this type of research should be carried out with listeners having more severe impairments who require fully occluding coupling strategies.

Most previous localization research has maximized experimental control by not allowing subjects to rotate their heads at all during the tests. While such control certainly has advantages, it does not represent conditions experienced by people in daily life. We compromised on this variable by allowing some head movement to make the test conditions more ecologically valid. Note however, that the amount of allowed head movement was limited and the stimuli were brief. This would be somewhat akin to a condition in the outdoors where someone shouts "Hey mister". The small allowed head movement made our test more realistic.

It is possible that participants were unable to recall instances when the hearing aids did or did not help them localize in their daily lives when they responded to a questionnaire at the end of a one-month field trial. More ecologically valid measures, such as momentary assessment, might reveal real-world differences that are not detectable using traditional self-assessment methods.

It is important to stress that the findings of the current research were based on the data obtained from hearing aids made by two of the six major manufacturers and using 2011 technologies. Could these findings apply to hearing aids from other manufacturers and future hearing aids? The answer is uncertain. Different manufacturers might use different acoustic processing for improving localization performance. Also, new features and technologies that attempt to improve localization will continue to evolve. However, technological advancements over the past two decades have been incremental for both premium-feature and basic-feature hearing aids. To compete, manufacturers release new hearing aids fairly frequently, employing technologies based on the latest research and innovations. This competitive marketplace increases the technological similarities among the hearing aids that are available from different manufacturers at a given time. On the other hand, our findings suggest that some differences in hearing aid processing between manufacturers' might affect laboratory localization performance. We cannot assert that the conclusions reached from this research will, or will not, apply to hearing aids from other manufacturers or future hearing aids. Research is needed that directly addresses these questions for additional hearing aid technologies.

Conclusions

A family of hearing aids usually includes several devices with different levels of technological sophistication. Hearing aids possessing the most advanced (premium) versions of features might be presumed to yield better overall outcomes than basic-feature hearing aids. The present study examined this presumption as it applied to horizontal localization of sound. Our findings showed that the premium-feature hearing aids yielded better localization performance than the basic-feature hearing aids in one specific laboratory condition (high frequency stimuli tested in quiet), but not in other laboratory tests. Further, in self-reports from everyday life, the premium-feature and basic-feature hearing aids yielded essentially the same improved localization performance. This reminds us that in hearing aids research, laboratory findings do not always predict everyday performance. Audiologists and hearing aid users require not only laboratory evidence, but also daily life evidence, to make evidence-based decisions when choosing hearing aid technology levels. Outcome data from the present study were collected from adult listeners with mild-to-moderate hearing loss using BTE style hearing aids. A recent survey by Hearing Industries Association showed that in 2016 about 81% of the hearing aids sold in the United States were BTE style (including RIC). This makes the findings of the present study of continuing relevance for hearing aid provision. Future research of this kind is needed when new hearing aids are introduced as well as with hearing aid wearers having more severe hearing loss and in different age ranges.

In summary, the findings of the present study of hearing aids from two of the six major manufacturers suggest that everyday aided localization will improve when amplification is used, but is unlikely to be noticeably further improved with more advanced technologies used in premium-feature hearing aids, at least for listeners like our research participants. For those who experience difficulty in locating amplified sounds in everyday situations, localization training programs might be an option. Training programs have been developed and shown to be useful in improving hearing aid users' everyday localization performance (Kuk et al. 2014; Tyler et al. 2010). Therefore, aural rehabilitation, including localization training, might be considered for hearing aid users who need more help with localization.

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Short Summary

Compared to basic-feature hearing aids, premium-feature hearing aids have more advanced technologies and state-of-the-art functioning. This study tested the hypothesis that premium-feature hearing aids can yield better horizontal localization performance than basic-feature hearing aids. Exemplars of premium-feature and basic-feature hearing aids from two of the six major manufacturers were evaluated. Post field trial evaluations included laboratory localization tests and self-report measures. Findings revealed that better performance with premium-feature hearing aids was observed in one of four laboratory conditions. The premium-feature and basic-feature hearing aids yielded essentially equal performance in other laboratory conditions and in daily life.

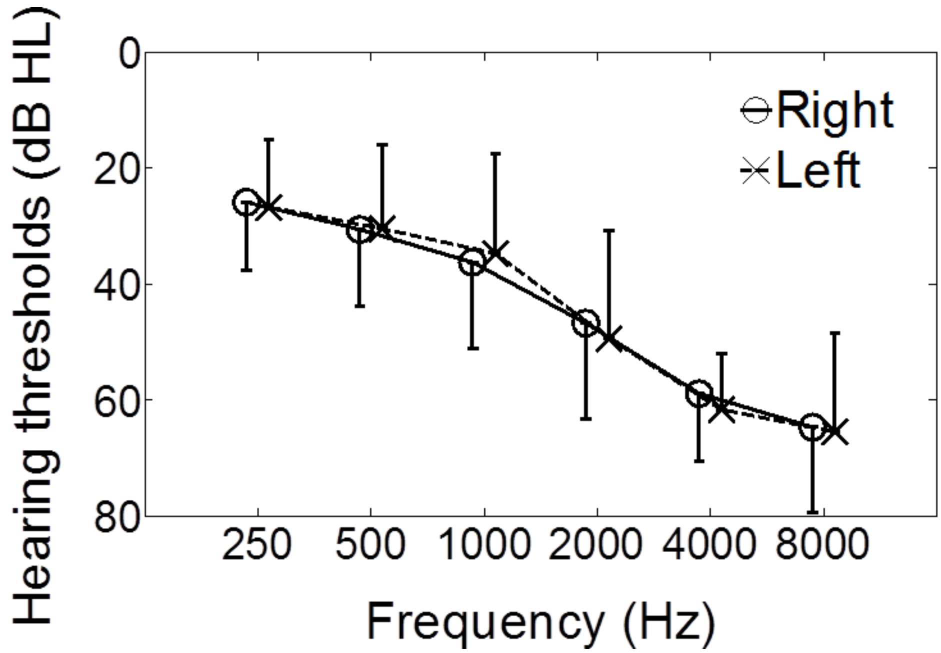

Figure 1.
Mean audiograms for all participants (N=45). Error bars show 1 standard deviation.

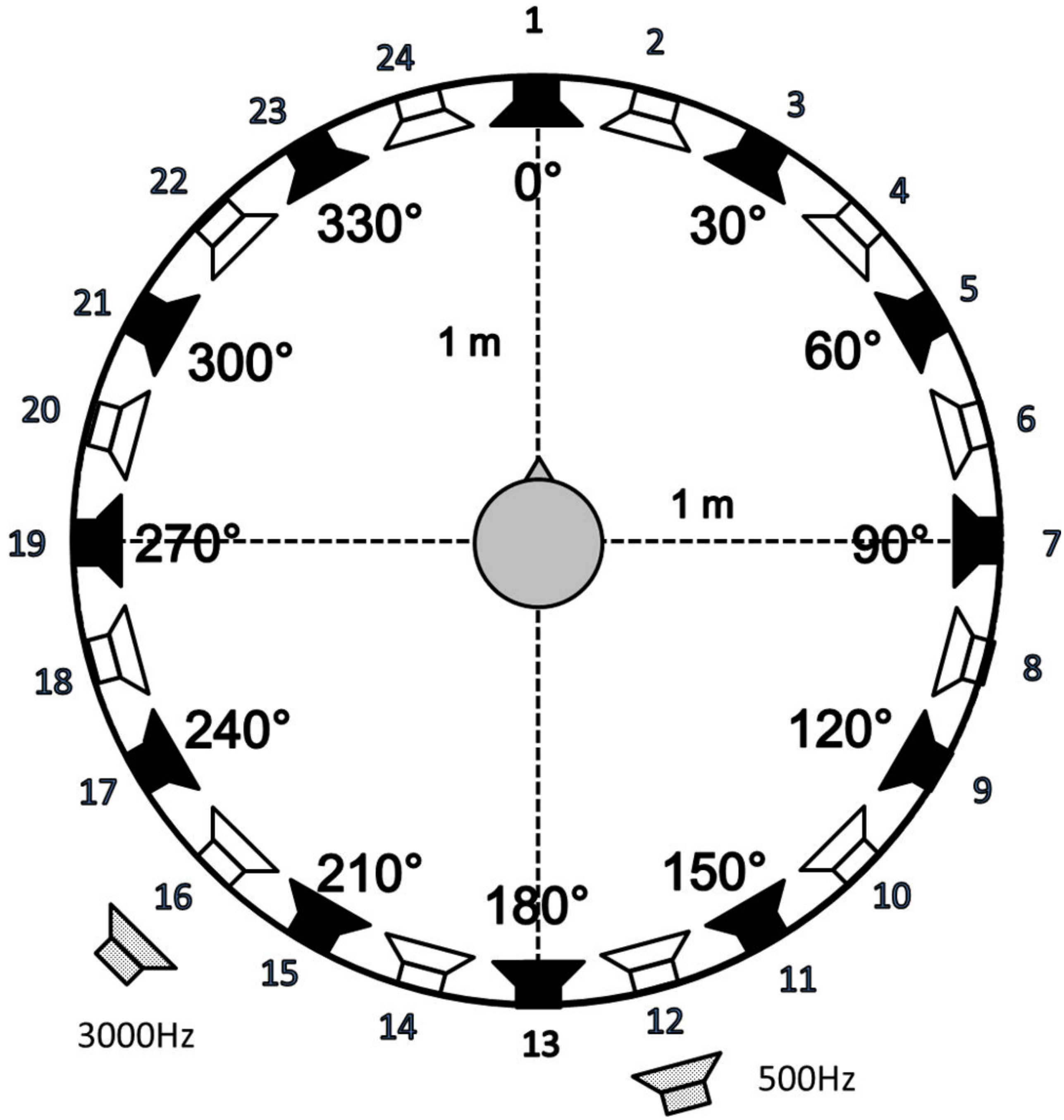

Figure 2.
Loudspeaker array for laboratory localization tests. Twenty-four loudspeakers were placed 15° apart. Only the odd number loudspeakers were active (the 12 solid filled loudspeakers). Two additional loudspeakers located outside the 24-loudspeaker circle were used for presentation of 500Hz and 3000Hz narrowband noises for the localization in noise test.

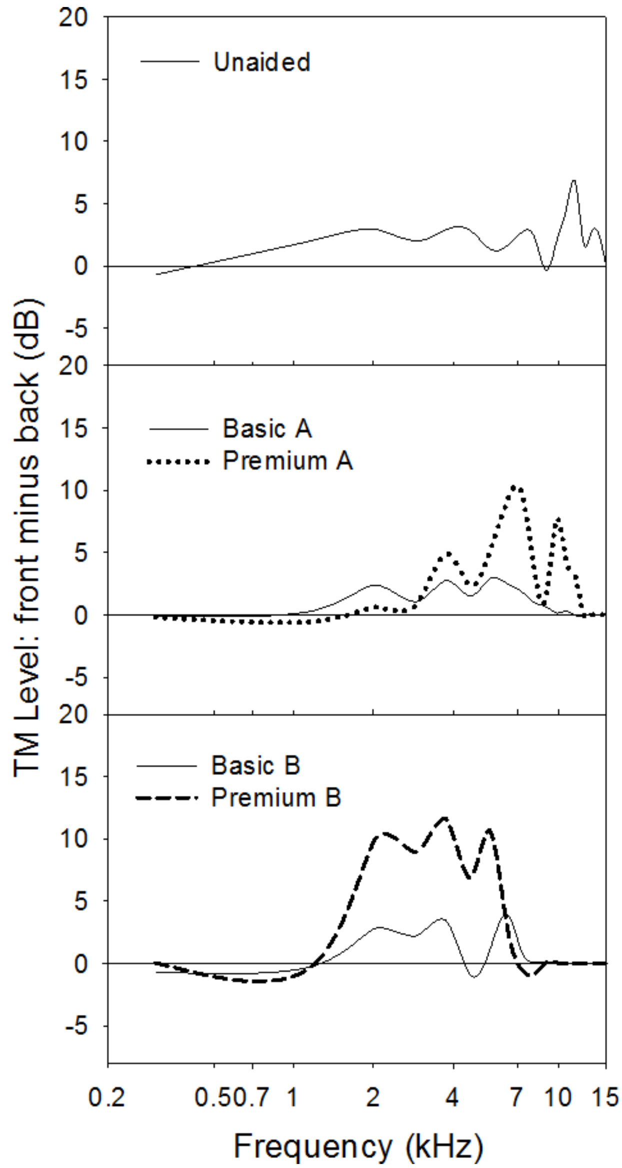

Figure 3.

Comparisons of the difference in TM levels observed when sound produced from the front of a manikin was compared with the same sound coming from the back. In all measurements, the manikin was equipped with realistic pinnas. The top panel depicts the acoustic boost provided by the "unaided" manikin's pinna. The middle panel shows corresponding data when brand A basic-feature and premium-feature hearing aids were worn by the manikin and coupled to the ear with a closed dome. The bottom panel shows corresponding data when brand B basic-feature and premium-feature hearing aids were worn by the manikin and coupled to the ear with a closed dome.

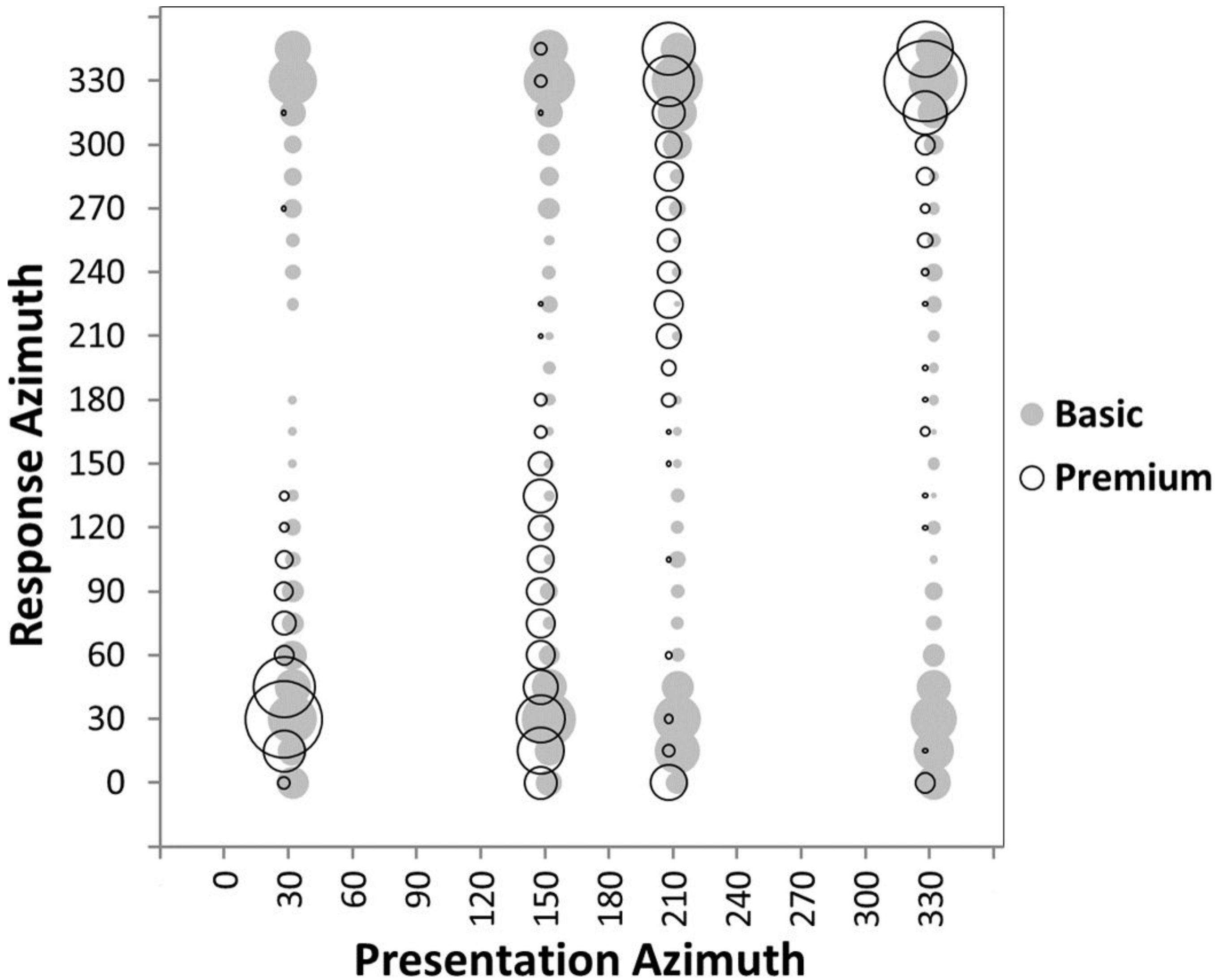

Figure 4.

Localization in quiet performance pattern with HF stimuli. Performance with premium and basic devices were with brands A and B combined. The size of each bubble is proportional to the number of presentation-response pairs.

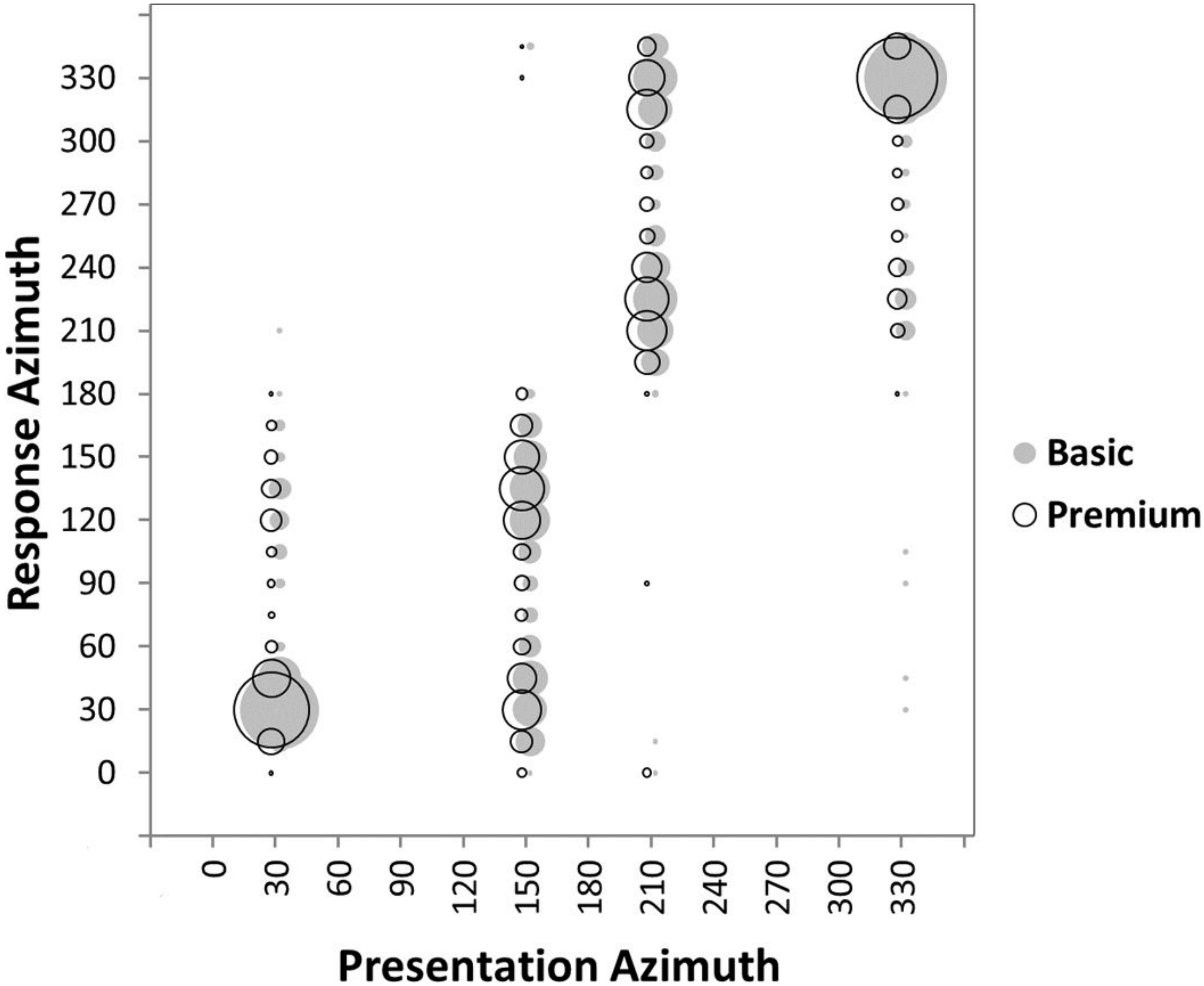

Figure 5.
Localization in quiet performance pattern with LF stimuli. Performance with premium and basic devices were with brands A and B combined. The size of each bubble is proportional to the number of presentation-response pairs.

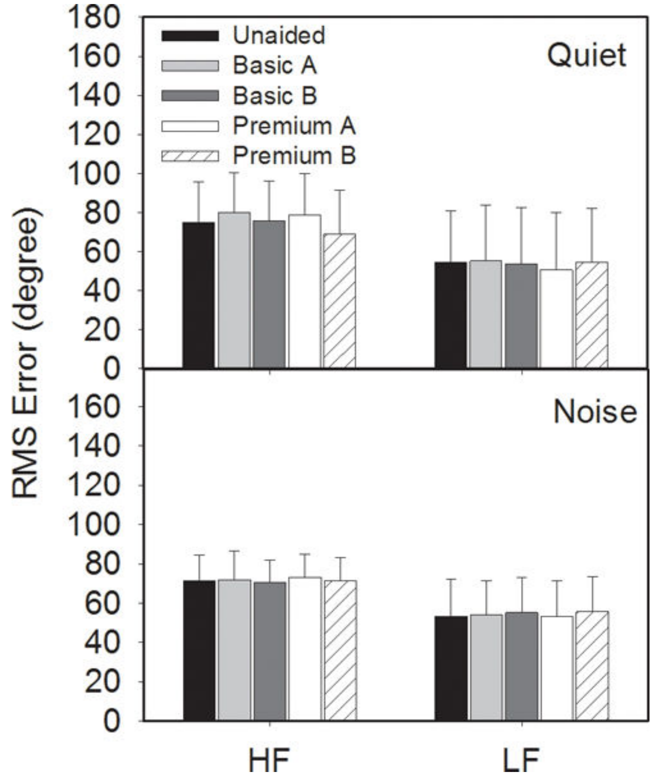

Figure 6.

Mean RMS error values for the unaided and the 4 aided conditions when tested in both quiet and noisy conditions. In each panel, the group of bars on the left shows mean RMS error values with HF stimuli and the group of bars on the right shows mean RMS error values with LF stimuli.

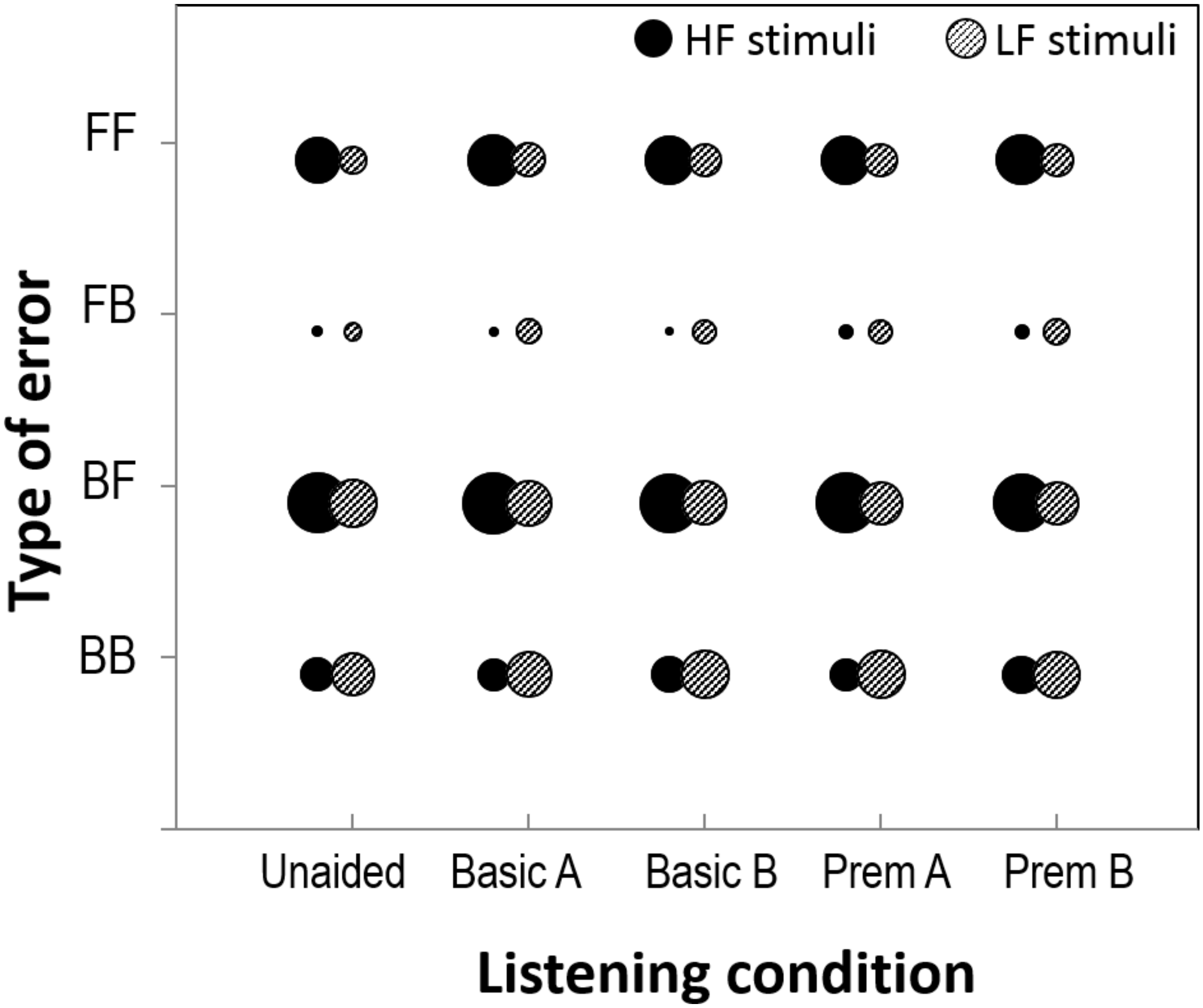

Figure 7.
Types of localization errors when unaided and when using each hearing aid. The size of each bubble is proportional to the mean error score. BB=back-back, BF=back-front, FB=front-back, FF=front-front. Black circles= HF stimuli, grey circles=LF stimuli.

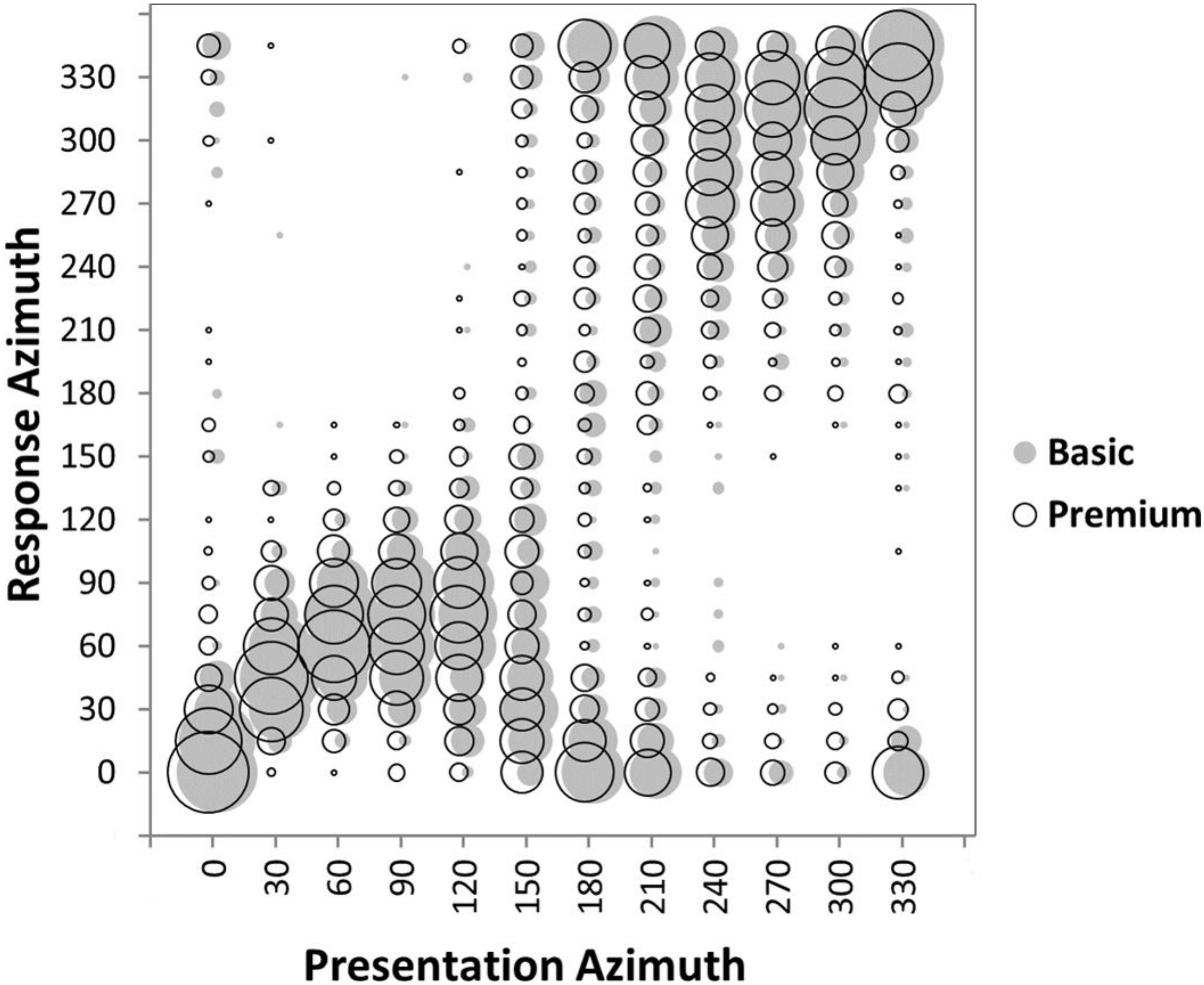

Figure 8.

Localization in noise performance pattern with HF stimuli. Performance with premium devices were with premium A and B combined. Performance with basic devices were with basic A and B combined. The size of each bubble is proportional to the number of presentation-response pairs.

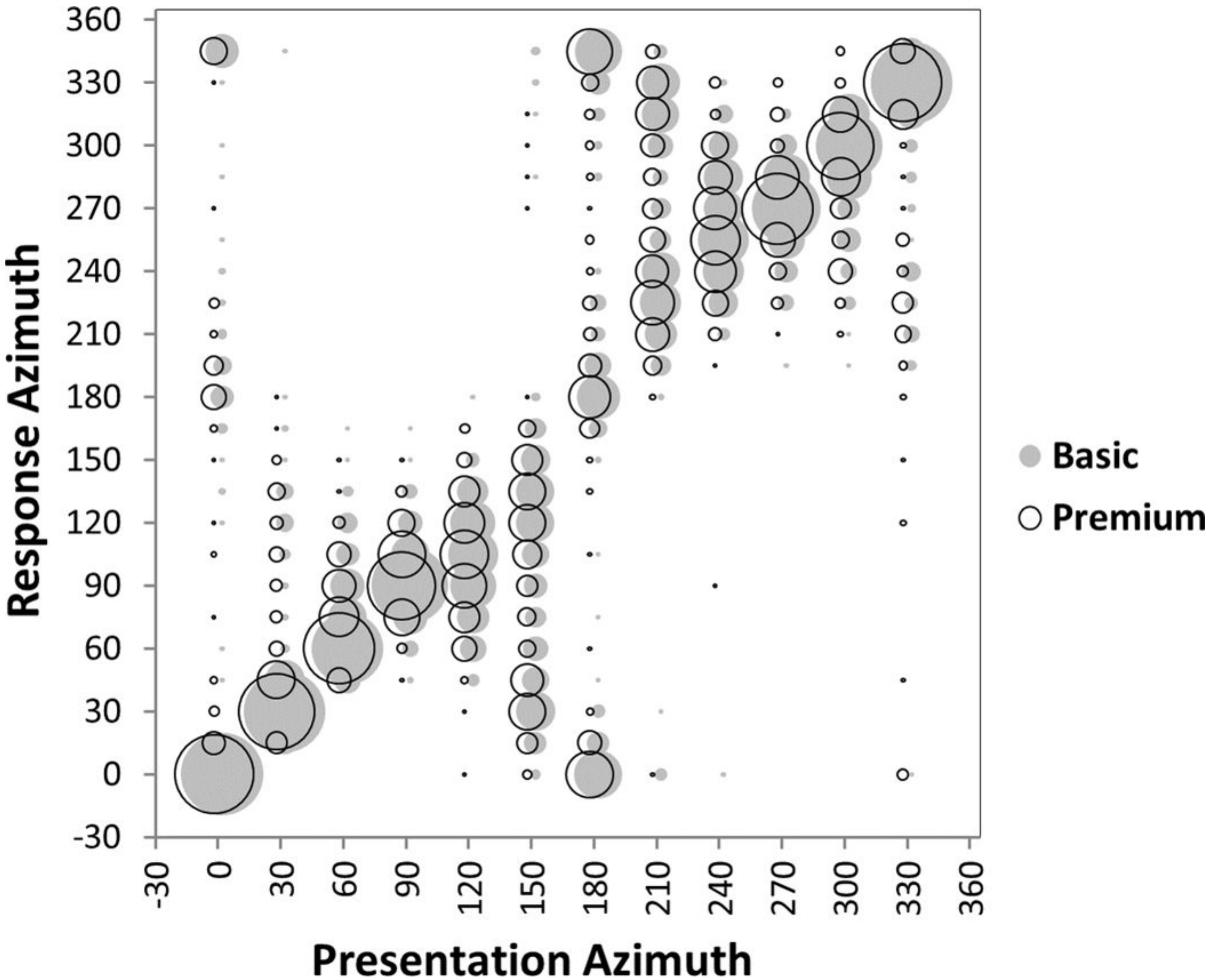

Figure 9.

Localization in noise performance pattern with LF stimuli. Performance with premium devices were with premium A and B combined. Performance with basic devices were with basic A and B combined. The size of each bubble is proportional to the number of presentation-response pairs.

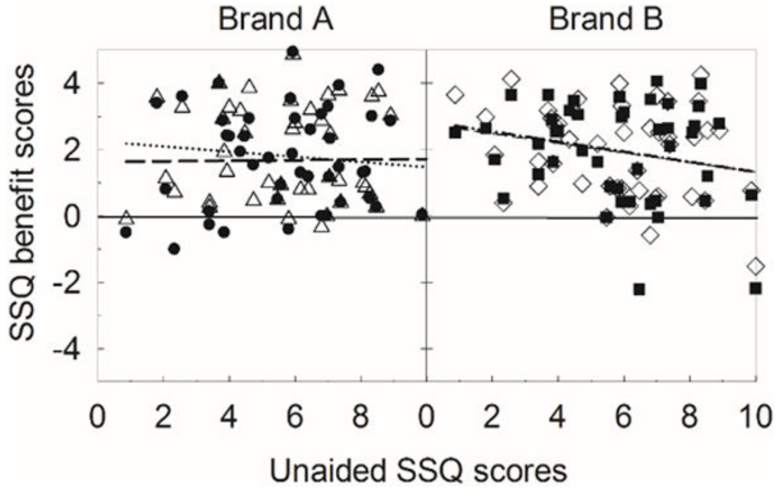

Figure 10.

Scatterplots of individual self-report unaided versus aided localization performance. Each data point in each panel represents a test participant. Open and filled symbols represent data points for premium-feature and basic-feature hearing aids, respectively. The dotted line in each panel is the regression line for the relation between unaided scores and benefit scores with premium-feature hearing aids. The solid line in each panel is the regression line for the relation between unaided scores and benefit scores with basic-feature hearing aids.

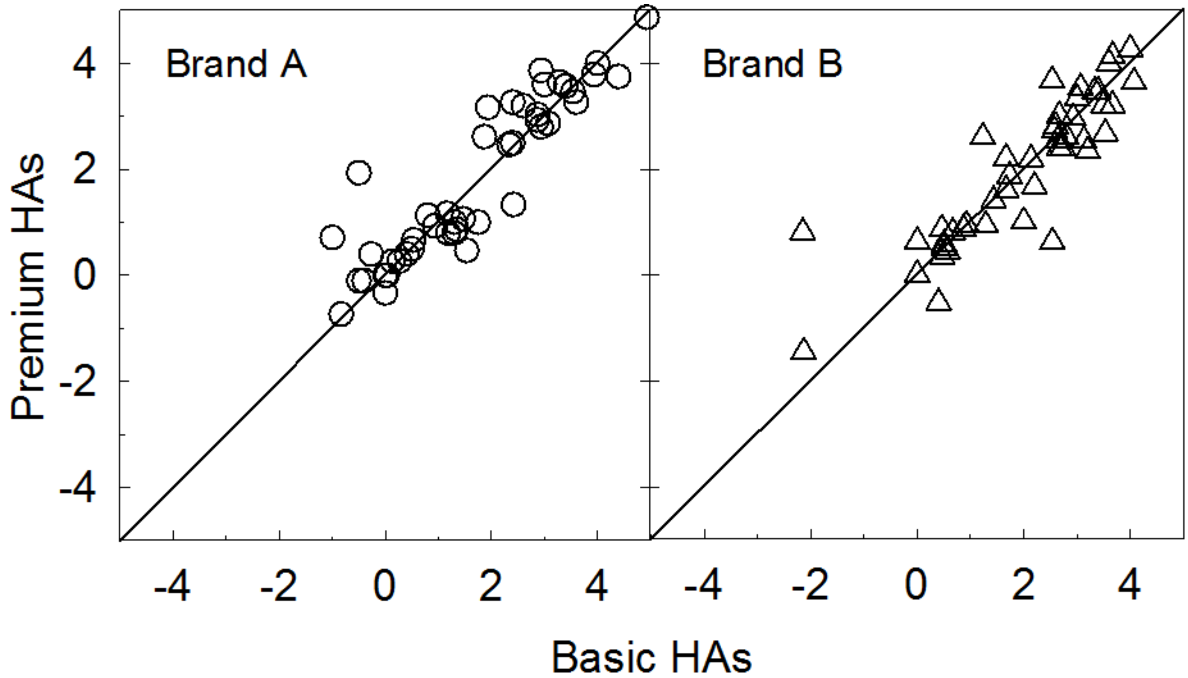

Figure 11.

Scatterplots of individual self-report localization performance with premium-feature and basic-feature hearing aids for each brand. Each data point in each panel represents a test participant.

Table 1

Manufacturer descriptions of the premium and basic features in the four research hearing aids for the automatic program. This program was used for laboratory testing. In addition, release times (estimated by testing using a Fonix 7000 hearing aid test box) are shown.

Feature	Premium A	Basic A	Premium B	Basic B
Pinna Simulation	Yes	No	Yes	No
Elements Synchronized Bilaterally	Volume Noise processing Directional mode	Volume	Volume Noise processing Directional mode	Volume
Approximate Synchronization Update Rate	1 sec	1 sec	5 sec	5 sec
Directional Microphone	Automatic multi-channel adaptive	Automatic single-channel adaptive	Automatic multi-channel adaptive	Automatic single-channel adaptive
Noise Reduction	More steps	Fewer steps	More steps	Fewer steps
Wind Noise Reduction	Yes	Yes	Yes	No
Impulse Noise Reduction	Yes	Yes	Yes	No
Reverberation Reduction	No	No	Yes	No
Compression Channels	16	8	20	6
Estimated Release Time	65 msec	48 msec	34 msec	40 msec
Proprietary HF Processing	Yes	No	Yes	Yes
Environmental Classification	More options	Fewer options	More options	Fewer options