Published in final edited form as:
J Am Acad Audiol. 2010 January ; 21(1): 44–51.

Benefits of Localization and Speech Perception with Multiple Noise Sources in Listeners with a Short-electrode Cochlear Implant

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Abstract

Background—Research suggests that for individuals with significant low-frequency hearing, implantation of a short-electrode cochlear implant may provide benefits of improved speech perception abilities. Because this strategy combines acoustic and electrical hearing within the same ear while at the same time preserving low-frequency residual acoustic hearing in both ears, localization abilities may also be improved. However, very little research has focused on the localization and spatial hearing abilities of users with a short-electrode cochlear implant.

Purpose—The purpose of this study was to evaluate localization abilities for listeners with a short-electrode cochlear implant who continue to wear hearing aids in both ears. A secondary purpose was to document speech perception abilities using a speech in noise test with spatially-separate noise sources.

Research Design—Eleven subjects that utilized a short-electrode cochlear implant and bilateral hearing aids were tested on localization and speech perception with multiple noise locations using an eight-loudspeaker array. Performance was assessed across four listening conditions using various combinations of cochlear implant and/or hearing aid use.

Results—Results for localization showed no significant difference between using bilateral hearing aids and bilateral hearing aids plus the cochlear implant. However, there was a significant difference between the bilateral hearing aid condition and the implant plus use of a contralateral hearing aid for all eleven subjects. Results for speech perception showed a significant benefit when using bilateral hearing aids plus the cochlear implant over use of the implant plus only one hearing aid.

Conclusion—Combined use of both hearing aids and the cochlear implant show significant benefits for both localization and speech perception in noise for users with a short-electrode cochlear implant. These results emphasize the importance of low-frequency information in two ears for the purpose of localization and speech perception in noise.

Keywords

short-electrode; hybrid cochlear implant; cochlear implant and hearing aid; localization; speech perception

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Introduction

The use of cochlear implants as an intervention to remediate hearing loss in listeners with bilateral, profound hearing loss has become widely accepted. Due to the success of cochlear implantation, many people are able to regain hearing function and communicate more effectively in their everyday lives. Furthermore, some cochlear implant users maintain a degree of residual hearing in the opposite ear and choose to use a hearing aid in the non-implanted ear.

Research suggests that use of a cochlear implant plus hearing aid in opposite ears provides binaural advantages to these users and, as a result, improved speech perception abilities (Kong, Stickney & Zeng, 2005; Chmiel, Clark, Jerger, Jenkins & Freeman, 1995; Dunn, Tyler, & Witt, 2005; Shallop, Arndt, & Turnacliff, 1992; Mok, Grayden, Dowell, & Lawrence, 2006; Luntz, Shpak, & Weiss, 2005; Simon-McCandless & Shelton, 2000; Tyler, Parkinson, Wilson, Witt, Preece & Noble, 2002). Another important aspect of hearing, the ability to localize a sound source, also has implications for those using cochlear implants plus hearing aids in opposite ears. Some studies have shown improved localization for subjects using a contralateral hearing aid plus a cochlear implant versus use of either device alone (Ching, Incerti, & Hill, 2004; Tyler et al., 2002). However, other results found that only a few listeners (2 out of 12) showed an improvement in localization despite wearing a cochlear implant and hearing aid in opposite ears (Dunn et al., 2005). Additionally, unpublished data on four subjects at the University of Iowa showed a significant decrement in localization abilities when comparing pre-operative localization abilities using two hearing aids to that after 12 months of cochlear implant plus hearing aid use.

One reason for these findings may be the differences in signal processing between the acoustic and electric signals, which can interfere or even distort the interaural timing and level differences of the incoming signal. Research suggests that cochlear implant and hearing aid devices might not accurately convey interaural timing and level differences (Francart, Brokx, & Wouters, 2008; Tyler et al., 2002; Tyler, Noble, Dunn, & Witt, 2006; Ching, van Wanrooy, & Dillon, 2007). This is likely due to the following: 1) differences in the place of stimulation in the cochlea across ears, 2) the inability of cochlear implant strategies to accurately encode fine structure information in the cycle-by-cycle structure of the stimulus (Kong et al., 2005; Grantham, Ashmead, Ricketts, Labadie, & Haynes, 2007); 3) differences in processing of time delays across the two ears, (Ching et al., 2007; Tyler et al., 2006, 2002) and 4) loudness differences across ears (Tyler et al., 2002; Ching, Psarros, Hill, Dillon, & Incerti, 2001). However, more similar signal processing across ears (i.e., two hearing aids or two cochlear implants) likely results in better coding for spectral, level, and timing cues. Despite this, many people have high-frequency severe-to-profound hearing loss and continuing with two hearing aids does not effectively help them overcome their hearing difficulties. The amount of residual low-frequency hearing may be adequate that this group of listeners would not be candidates for the traditional cochlear implant, yet communication difficulties remain. An alternative method is to implant a shorter-length cochlear implant into the basal end of the cochlea that combines acoustic and electrical hearing within the same ear, while simultaneously preserving low-frequency residual acoustic hearing bilaterally.

Research studying combined unilateral acoustic and electrical hearing shows that listeners are able to successfully integrate low-frequency acoustic hearing with high-frequency electrical stimulation for improved speech perception abilities (Gantz & Turner, 2004, 2003; Gantz, Hanson, Turner, Oleson, Reiss, & Parkinson, 2009). Research has also suggested that a short-electrode cochlear implant may provide more benefits than a standard length cochlear implant for individuals with significant low-frequency hearing (Novak, Black, & Koch 2007, Gantz, Turner, Gfeller, & Lowder, 2005). It is thought that listeners with preserved low-frequency hearing will obtain better speech understanding due to better frequency selectivity from available low-frequency cues (Turner, Reiss, & Gantz, 2007). When compared to preoperative hearing with bilateral hearing aids, these listeners with combined acoustic and electrical signal processing in the same ear showed improvements in word understanding, speech in noise, and melody recognition (Gantz, Turner, Gfeller, & Lowder, 2005). A study by Turner, Gantz, Vidal, Behrens, & Henry, (2004) compared performance on a speech perception in noise task for two groups of subjects who were matched according to their speech recognition ability in quiet: those with combined acoustic and electric hearing in a unilateral ear to those with a single long cochlear implant. Results showed a 9 dB advantage in signal-to-noise ratio for the users with combined acoustic plus electric hearing in the same ear. In addition, studies have shown that preserved low-frequency hearing along with use of a short-electrode cochlear implant provides listeners with improved musical performance, including better melody recognition and greater music appreciation (Turner, Reiss, & Gantz, 2007; Gantz, Turner, & Gfeller, 2006; Gfeller, Olszewski, Turner, Gantz, Oleson, 2006; Gantz, Turner, Gfeller, & Lowder, 2005; Gantz & Turner, 2004; Gantz & Turner, 2003).

To date, very little research has focused on localization and binaural hearing abilities for users of a short-electrode cochlear implant. Localization has important applications for all listeners because it allows for accurate identification of environmental sounds and alarms and allows listeners to attend to a target or speaker when several talkers in a background of noise are presented to the listener. A potential advantage of the short-electrode cochlear implant is that most of these listeners often continue wearing bilateral hearing aids after receiving the cochlear implant which provides them with similar processing across ears. Compared to the traditional standard length cochlear implant worn in one ear and a hearing aid worn on the opposite ear, this could provide a clear advantage for these listeners because important timing and level cues would no longer be dissimilar across ears. The purpose of this study was to evaluate localization abilities for listeners with a short-electrode cochlear implant who continue to wear bilateral hearing aids. A secondary purpose was to document speech perception abilities using a speech in noise test with spatially-separate noise sources.

Method

Subjects

Eleven adults (*M* = 61.3 years; range = 51 to 81 years) implanted with a Nucleus 24 Hybrid 10mm short-electrode cochlear implant served as subjects for this study. Table 1 shows demographic data for all 11 subjects, including age, ear implanted, duration of cochlear implant use, frequency range of the cochlear implant, hearing aid use prior to cochlear implantation, and hearing aid type. Seven subjects denoted with an “A” in their subject name (A2, A4, A7, A8, A9, A10, A12) were implanted with a CI24RE short-electrode cochlear implant and four subjects denoted with an “SE” in their subject name (SE5, SE8, SE9, SE11) were implanted with a CI24M short-electrode cochlear implant. Both cochlear implants had 6 intra-cochlear electrodes; however, the earlier CI24M device allowed for stimulation rates up to 2400Hz where as the CI24RE internal device allowed for stimulation rates up to 3500Hz. All other parameters and specifications were essentially the same across these two implant types. All subjects were provided with a hearing aid in the ipsilateral ear to use in conjunction with the short-electrode cochlear implant following surgery. This hearing aid was a 15-channel digital, Phonak Aero 33 in-the-ear (ITE) hearing aid. No noise reduction or directional microphones were active during testing. On the contralateral ear, subjects used their own hearing aid that was not controlled for in this study. As seen in Table 1, ten of the subjects used bilateral hearing aids for five or more years prior to cochlear implantation. Subject A9 had approximately three months of hearing aid use prior to cochlear implantation. All subjects reportedly wore their hearing aids consistently following implantation except for subject SE9, who reported that he occasionally did not wear the hearing aid contralateral to the implant. All subjects had at least six months of cochlear implant experience at the time of testing.

Pure-Tone Acoustic Thresholds

Pure-tone acoustic thresholds were measured at the time of testing using insert earphones and a clinical audiometer in both ears for all 11 subjects. Figure 1 displays pure tone acoustic thresholds in the ipsilateral (or same side as the implanted ear) (Panel A) and contralateral (Panel B) ears for each subject. Mean thresholds were also calculated and are plotted in bold overlying the individual data. Thresholds in the implanted ear varied from mild-to-severe hearing loss levels for frequencies 125, 250, and 500 Hz, and reached profound hearing loss levels at 2000 Hz and above. Few subjects had responses in the implanted ear from 4000 to 8000 Hz. Results for the contralateral ear showed that all subjects had moderate hearing loss or better at 125, 250, and 500 Hz, sloping to a profound hearing loss at 2000 Hz and above. Per the FDA protocol for the Nucleus Hybrid cochlear implant, the poorer hearing ear always received the cochlear implant.

Hearing Aid and Cochlear Implant Fitting

Hearing aid verification using real ear probe measurements was completed bilaterally for all subjects. The hearing aid settings were adjusted to approximate NAL-RP targets at all low frequencies. Cochlear implant programming was completed for each subject as part of their routine clinical follow-up. The cochlear implant frequency response was set to supplement the subject's acoustic hearing as determined from their audiogram (see Figure 1). Specifically, the cochlear implant was set to stimulate only the high frequencies where acoustic hearing was greater than approximately 90 dB HL and to provide minimal frequency overlap with the hearing aid.

Test Conditions

All subjects were tested in numerous conditions to evaluate localization abilities using the short-electrode cochlear implant and hearing aids in the ipsilateral and contralateral ears. The conditions consisted of the following: 1) combined; 2) hybrid; 3) bimodal; and 4) bilateral hearing aids. In the combined condition, subjects used bilateral hearing aids in addition to the cochlear implant. The hybrid listening condition referred to the cochlear implant and the hearing aid on the same ear, but no hearing aid on the contralateral ear. In comparison, the bimodal condition implied use of the cochlear implant plus the contralateral hearing aid, but no hearing aid on the ear with the cochlear implant. Finally, the bilateral hearing aid mode consisted of hearing aids on both ears, but the cochlear implant processor is turned off. A description of each condition is further summarized in Table 2. The testing order for the above conditions was randomized for each subject. Ear plugs were placed in the subjects' ears by the experimenter when a hearing aid was removed from a test condition. For all test conditions, no modifications were made to the cochlear implant or hearing aid programming and parameters were set identical across test conditions. Subjects were tested acutely in the laboratory and did not have a listening trial with each of the different conditions before testing began.

Test Measures

Localization

Localization ability was assessed on all 11 subjects using an Everyday Sounds: Localization test (Dunn et al., 2005). An array of eight loudspeakers spanning a horizontal arc of 108° was used. Loudspeaker one and eight were placed 54° to the left and to the right of the straight-ahead (0°) position. Sixteen different everyday sounds (i.e., child laughing, baby crying, glass breaking, and telephone ringing) were each presented six times randomly from one of the eight loudspeakers at 70 dB(C) SPL. Subjects were asked to identify the loudspeaker from which the sound originated using a touch screen monitor placed in front of them. No feedback was provided throughout the test. Head movement was restricted throughout the test and subjects were asked to fixate on an object placed directly in front of them. Localization performance was determined by calculating the average Root Mean Square (RMS) error in degrees. Chance performance on the Everyday Sounds Localization test was approximately 40 degrees RMS error and a lower RMS error score indicated better localization performance. All four test conditions (combined, hybrid, bimodal, and bilateral hearing aids) were completed for the localization test.

Speech Perception—The Recognition with Multiple Jammers speech perception in noise test (see Tyler, Noble, Dunn, & Witt, 2006) was administered to nine subjects. This test was used to evaluate binaural hearing abilities as it simulates a situation where listeners have to separate a target signal from similar competing sounds that are introduced from multiple locations (Hawley, Litovsky, & Colburn, 1999; Culling, Hawley, & Litovsky, 2004). In this test, the listener was to select the target spondee word from 12 possible words that was heard in a background noise (Turner et al., 2004). An array of eight loudspeakers spanning an arc of 108° in front of the subject was used to present both the target and background noise. The target spondee word was presented from a front-facing loudspeaker (either +/−8° from 0°-azimuth) and background noise was presented from two loudspeakers to the right and left of the subject (located either at +54° and −38° azimuth, or at +38° and −54° azimuth. The background noise consisted of sentences from randomly-selected male and female talkers presented simultaneously. The sentences were different from from trial-to-trial. Additionally, the level of the background noise varied adaptively while the level of the spondee word remained constant throughout the testing. The target spondee word was played 0.8 seconds following the start of the background noise. Subjects manually entered their responses using a touch screen monitor placed in front of them. The signal-to-noise ratio (SNR) yielding 50% correct was obtained with a 2-up and 2-down adaptive rule with a total of 14 reversals. Each test consisted of five runs and the signal-to-noise ratio (S/N) was calculated based on the average threshold of the last three runs. Because of time constraints while testing, only the combined, hybrid, and bimodal test conditions were completed for this test.

Results

Localization

Figure 2 displays individual data for each subject as well as average results for the Everyday Sounds Localization test comparing the following conditions: combined, hybrid, bimodal, and bilateral hearing aids. A repeated-measures analysis of variance revealed that there was a significant difference in localization scores, $F(1.63, 14.67) = 28.75$, $p < .001$. Post hoc comparisons using a Bonferroni adjustment revealed that the combined and bilateral hearing aid conditions were significantly better than the hybrid and bimodal conditions. No significant difference was found between combined and bilateral hearing aid conditions or between the hybrid and bimodal conditions. Individual results showed that all subjects were able to localize better than chance performance in the combined and bilateral hearing aid test conditions and performed best in these two conditions. In contrast, eight subjects (A12, A8, A2, SE9, SE8, A7, A9, A10) scored above chance performance when using the bimodal condition. Additionally, eight subjects (SE5, A12, A8, A2, A4, A7, A9, and SE11) also scored above chance performance when using the hybrid condition.

Speech Perception

Figure 3 displays individual and average results on the Recognition with Multiple Jammers test comparing the following conditions: combined, hybrid, and bimodal. A repeated-measures analysis of variance revealed a significant difference, $F(2, 16) = 9.65$, $p < .01$. Post hoc comparisons using Bonferroni adjustment showed that the combined listening condition was significantly different than the hybrid and bimodal conditions. Individual results showed that four (SE9, A4, A9, A10) of the nine subjects performed better when using the combined condition over the hybrid and bimodal conditions. No subjects performed best with the hybrid or bimodal conditions, but three subjects (SE5, A8, SE9) performed better in the bimodal condition over the hybrid condition. Only one (A10) subject performed better with the hybrid condition over the bimodal condition. Finally, two subjects (A12, SE8) showed no difference between any of the conditions.

Discussion

One approach to improving speech understanding and hearing function for individuals with significant low-frequency residual hearing is to obtain a shorter-length cochlear implant in addition to conventional hearing aid use. This type of implant stimulates the high-frequencies in the basal region of the cochlea while residual hearing is maintained by not disrupting low-frequencies stimulated via hearing aids in the apex of the cochlea. A potential benefit of providing electro-acoustic stimulation in the same ear is that the listener can utilize bilateral hearing aids and thus rely on similar signal processing across ears.

In this study, performance on sound source localization and speech perception in noise using spatially-separate noise sources was evaluated using different listening configurations: combined, bimodal, hybrid, and bilateral hearing aids. Three of the four listening conditions were conducted in the binaural mode, including combined, bimodal, and bilateral hearing aids, and provided the listener with binaural hearing cues. The binaural auditory system computes differences in interaural timing (ITD) and level (ILD) between ears to determine the azimuthal location of sound sources as well as provide benefits to speech perception. Below about 800 Hz, ITDs are the primary cues used for localization (Carhart, 1965; Dirks & Wilson, 1969; Durlach & Colburn, 1978; Yost & Dye, 1997) and binaural squelch effects (the ability to combine the noise at the ear with the poorer signal-to-noise (S/N) ratio with the noise from the ear with the more favorable S/N ratio [Carhart, 1965; Middlebrooks & Green, 1991; Zurek, 1993]). For higher frequency information (above 1500 Hz), ILD information is the primary cue used for localization and benefits from the head shadow effect (the head acts as an acoustic barrier, which creates a spectral difference between the two ears resulting in a greater S/N ratio at one ear [Shaw, 1974]). However, it should be noted that the ability to use head diffraction is not a direct function of binaural processing, but is the physical consequence of sound diffraction around an object. From about 700 Hz to around 1200 Hz, both ITD and ILD information can be useful for benefits of localization and speech perception (Dunn, Yost, Noble, & Tyler, 2006). In the current study, listeners are provided with mostly low-frequency information through their hearing aids (up to around 1000 Hz) and high-frequency information through the cochlear implant (ranging from 500–8000 Hz or 1000–8000 Hz).

The results from our study indicated that localization abilities were significantly better when using bilateral hearing aids and a cochlear implant worn together compared to using a single hearing aid and a cochlear implant on opposite ears. This might not be surprising given there is little overlap in the bilateral signals since the bimodal condition provides mostly high frequency information via the cochlear implant and only low frequency information via the hearing aid. Additionally, the differences in signal processing might interfere or even distort the available ILD and ITD cues. It appears that when listeners have similar processing bilaterally through the use of bilateral hearing aids, listeners are able to take advantage of the ITD cues and the addition of the cochlear implant did not disrupt their overall performance. In fact, when comparing results between the bilateral hearing aid condition to the use of the cochlear implant condition plus hearing aids, there was no significant difference in performance. In addition, even though the bimodal condition, with a hearing aid in one ear and a cochlear implant in the other, provided binaural stimulation, performance was not significantly different from the hybrid condition where the subjects wore a single cochlear implant and hearing aid on the same ear.

A secondary purpose of this study is to document speech perception in noise abilities using a test with multiple noise sources where listeners have to separate a target signal from similar competing sounds. Results showed that combined use of a cochlear implant plus bilateral hearing aids facilitates the best speech perception performance compared to use of a cochlear implant and a single hearing aid worn on opposite ears or worn on the same ear (hybrid). As demonstrated in this study with the localization, having two ears with similar signal processing enabled the listeners to utilize ITD and ILD cues to benefit them with speech perception in noise. It is likely that the fine-structure information provided by the use of bilateral hearing aids assisted in the detection of the target signal by enabling the listeners to “squelch” information provided by the spatially separated competing sound source (Dunn, Yost, Noble, & Tyler, 2006; Turner et al., 2004).

Conclusion

Preservation of acoustic hearing is very important to maintain localization abilities and speech perception in noise with spatially separate noise sources. While speech perception abilities are often the goal of rehabilitation for individuals with hearing impairment, all aspects of hearing such as sound source localization should be considered. The results of this study indicate that bilateral hearing aid use combined with a short-electrode cochlear implant provides listeners with additional benefits for speech perception and localization. Future studies should continue to investigate the salient features of combined cochlear implant plus hearing aid use and provide more systematic fitting protocols for these devices.

Acknowledgments

This research was supported in part by research grant 5 P50 DC00242 from the National Institutes on Deafness and Other Communication Disorders, National Institutes of Health; grant M01-RR-59 from the General Clinical Research Centers Program, Division of Research Resources, National Institutes of Health; the Lions Clubs International Foundation; and the Iowa Lions Foundation.

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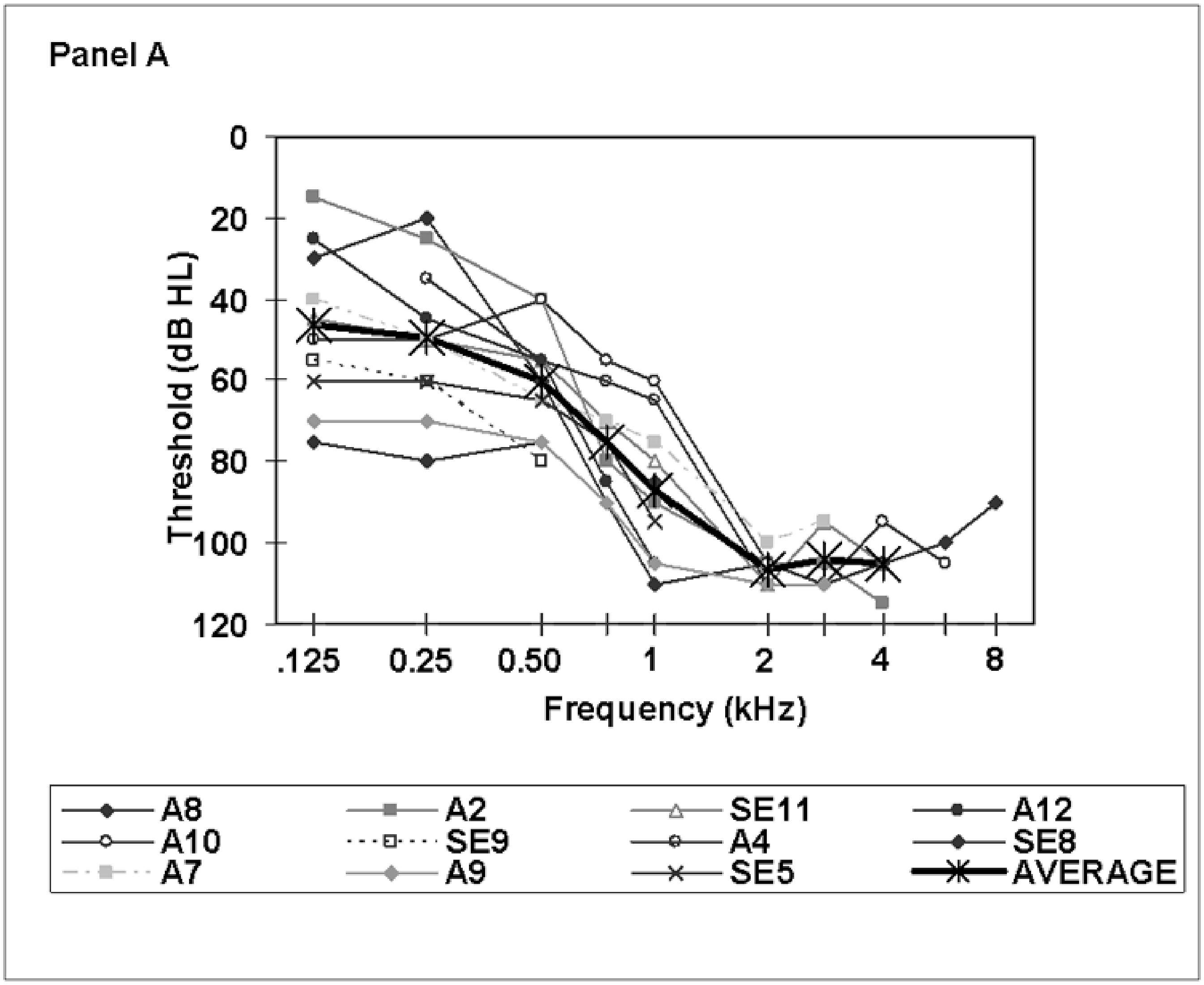

Figure 1.

Panel A: Individual and average implanted ear pure tone thresholds for all subjects. Panel B: Individual and average contralateral ear implanted pure tone thresholds for all subjects.

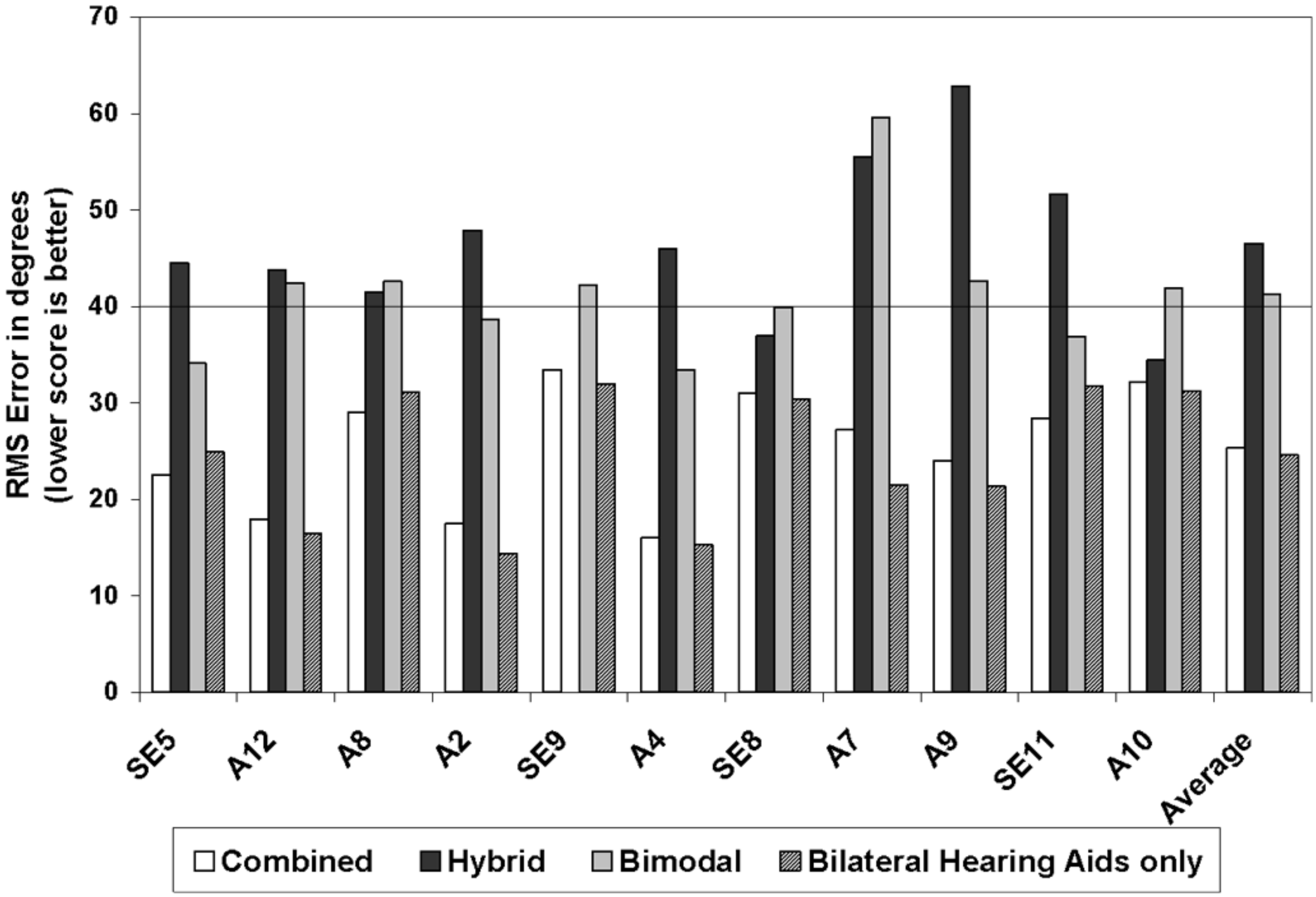

Figure 2.

Individual and average localization scores (RMS error in degrees) for the combined, hybrid, bimodal, and bilateral hearing aid listening conditions. Better performance is reflected by a lower RMS error score.

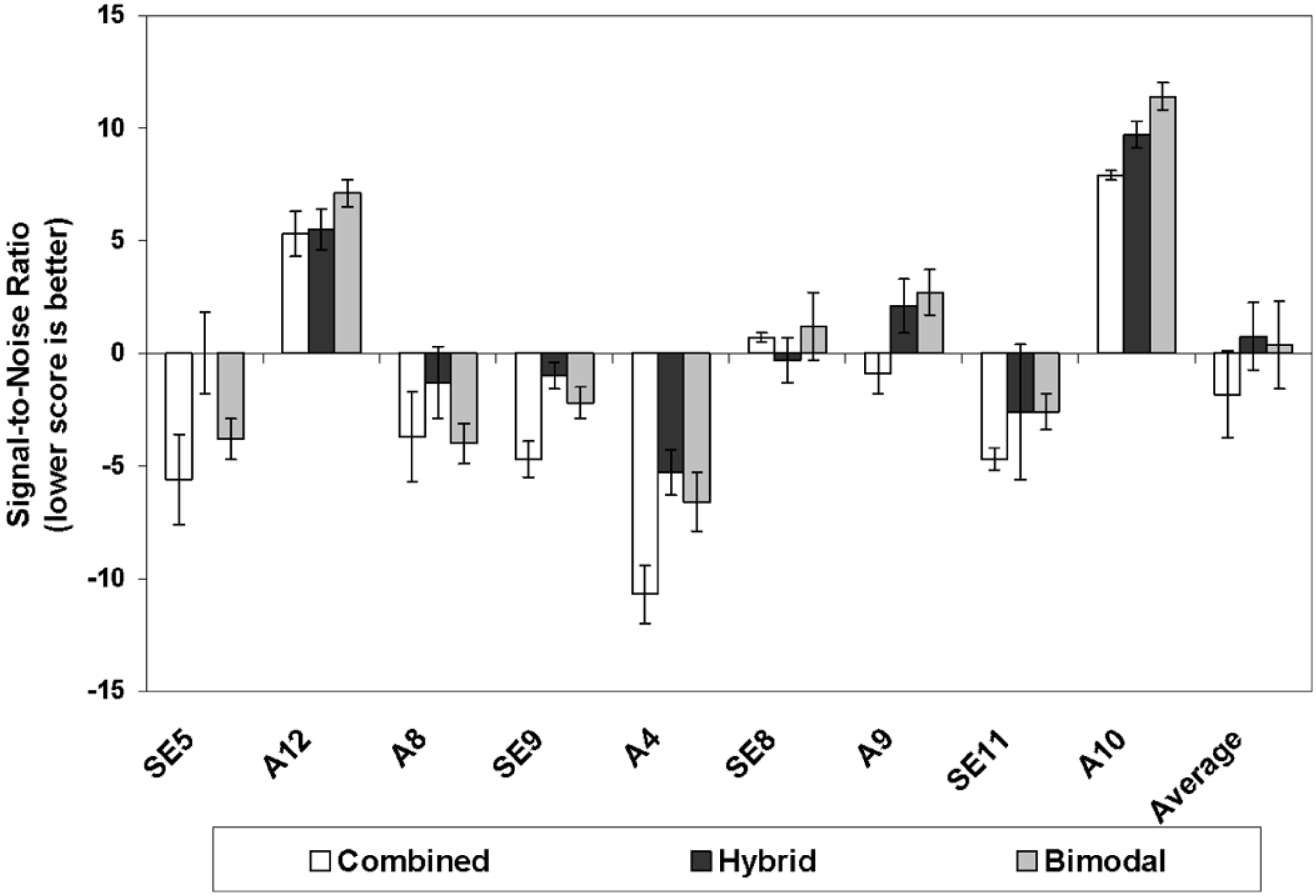

Figure 3.

Recognition of Multiple jammers test individual and average signal-to-noise (S/N) ratio scores for combined, hybrid, and bimodal testing conditions. Lower scores (more negative) indicate better speech perception performance.

Table 1

Individual subject demographics

Subject	Age (yrs)	Implant Ear	CI use (yr, mo)	Frequency Range for Standard Map	Pre-Implant Hearing Aid Use (yrs used, bilateral or unilateral)	Hearing Aid Type (R=Right, L=Left)
A8	56	Right	0, 7	563–7938 Hz	13, bilateral	Phonak ITE, R; Phonak BTE, L
A2	61	Left	1, 6	688–7938 Hz	15, bilateral	Phonak ITE, L; Phonak BTE, R
SE11	69	Right	3, 1	688–7938 Hz	5, bilateral	Phonak ITE, R; Phonak BTE, L
A12	54	Left	0, 6	563–7938 Hz	25, L; 28, R	Phonak ITE, L; AVR Transpositional BTE, R
A10	81	Right	0, 6	688–7938 Hz	15, bilateral	Phonak ITE, R; Beltone BTE, L
SE9	51	Right	3, 6	750–8000 Hz	10, bilateral	Phonak ITE, R; Phonak BTE, L
A4	51	Right	1, 3	688–7938 Hz	9, bilateral	Phonak ITE, R; Phonak BTE, L
SE8	69	Right	3, 10	1063–7938 Hz	12, bilateral	Phonak ITE, R; Phonak BTE, L
A7	74	Right	0, 6	1063–7938 Hz	13, bilateral	Phonak ITE, R; Phonak BTE, L
A9	51	Left	0, 6	688–7938 Hz	.25, bilateral	Phonak ITE, L; Phonak BTE, R
SE5	57	Left	5, 11	688–7938 Hz	25, bilateral	Phonak ITE, L; Phonak BTE, R

Table 2

Test conditions. CI = cochlear implant; HA = hearing aid; Ipsi = same side as the cochlear implant; Contra = opposite side of the cochlear implant.

Condition Number	Mode of testing	Description	Configuration
1	Combined	A cochlear implant and a hearing aid in one ear and a hearing aid in the opposite ear.	CI + Ipsi HA + Contra HA
2	Hybrid	A cochlear implant and a hearing aid in one ear. No hearing aid on the opposite ear.	CI + Ipsi HA
3	Bimodal	A cochlear implant in one ear and a hearing aid in the opposite ear. No hearing aid on the ear with the cochlear implant.	CI + Contra HA
4	Bilateral Hearing Aids	Hearing aids on both ears and no cochlear implant.	Ipsi HA + Contra HA