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Sound source localization by normal hearing listeners, hearing-impaired listeners and cochlear implant listeners

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Abstract

Objective—Our primary aim was to determine whether listeners in patient groups including (i) hearing impaired with bilateral hearing aids, (ii) bimodal cochlear implant (CI), (iii) bilateral CI, (iv) hearing preservation CI, (v) single-sided deaf CI, and (vi) combined bilateral CI and bilateral hearing preservation, achieve localization accuracy within the 95th percentile of accuracy shown by younger or older NH listeners.

Design—The listeners were 57 young normal hearing (NH) listeners, 12 older, normal hearing listeners, 17 listeners fit with hearing aids, 8 bimodal CI listeners, 32 bilateral CI listeners, 8 hearing preservation CI listeners, 13 single-sided deaf CI listeners and 3 listeners with bilateral CIs and bilateral hearing preservation. Sound source localization was assessed in a sound deadened room with 13 loudspeakers arrayed in a 180 degree arc.

Results—The rms error for the normal hearing listeners was 6 degrees. The 95th percentile was 11 degrees. Nine of 16 listeners with bilateral hearing aids achieved scores within the 95th percentile of normal. Only one of 64 CI patients achieved a score within that range. Bimodal CI listeners scored at a level near chance as did the listeners with a single CI or a single normal hearing ear. Listeners with (i) bilateral CIs, (ii) hearing preservation CIs, (iii) single-sided deaf CIs and (iv) listeners with both bilateral CIs and bilateral hearing preservation all showed rms error scores within a similar range (mean scores between 20 and 30 degrees of error).

Conclusion—Modern cochlear implants do not restore a normal level of sound source localization for CI listeners with access to sound information from two ears.

A very large literature describes the ability of normal hearing (NH) listeners to localize sound sources on the horizontal plane (e.g., Stevens and Newman, 1936; Middlebrooks and Green, 1991; Blauert, 1997). Another, more recent, literature describes the ability of patients fit with CIs to localize sound sources on the horizontal plane (e.g., Grantham et al. 2007; van Hoesel and Tyler 2003; Seeber and Fastl, 2008). A major difficulty in comparing the data collected from CI patients with data collected from normal-hearing listeners is that the studies have, most generally, used different numbers and spacing of loudspeakers, signals

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with different spectral and temporal characteristics, and different measures of rms error. These same problems plague attempts to compare data amongst the many studies with CI patients.

In a first step to remedy this problem, we described the sound source localization ability of a large number of young, NH listeners (Yost et al., 2013). Using the same test environment and stimuli, we have now tested five groups of CI patients: 1) bimodal listeners, i.e., CI patients with low-frequency hearing in the contralateral ear (Dorman et al., 2015), 2) bilateral CI recipients (Dorman et al., 2014), 3) hearing preservation patients, i.e., patients with a single CI and bilateral low-frequency, acoustic hearing (Loiselle et al., 2015), 4) single-sided deaf (SSD) patients fit with a CI (Dorman et al., 2015; Zeitler et al., 2015) and 5) a patient with bilateral CIs and bilateral low-frequency hearing preservation (Dorman et al., 2013).

In this paper, we (i) compile our previous results with CI patients (increasing the sample size for two of the groups), (ii) increase the sample size for young, normal-hearing listeners and (iii) add two new comparison groups: older listeners with age-appropriate hearing and older listeners with sensory hearing loss and fit with bilateral hearing aids. Our aim was to determine whether any listener in any patient group achieved localization accuracy within the 95th percentile of accuracy shown by younger or older NH listeners.

Method

Subjects

Adult participants ranged in age from 21–87 years. One child, age 14 years, also participated. Participants were tested following approval by the IRB at Arizona State University.

The young NH group was comprised of 57 participants (15 male; 42 female) between the ages of 21–40 years. 45 were from the sample described by Yost et al. (2013). The group of older listeners with age-appropriate hearing was comprised of 12 participants (4 male, 8 female) between the ages of 51–70 years. These listeners had symmetrical thresholds with no more than a 30-dB loss through 2kHz. Mean audiometric thresholds at .125, .25, .5, 1.0, 2.0 and 4.0 kHz were 9, 9, 7, 9, 11 and 23 dB HL, respectively.

The bilateral hearing aided group was comprised of 17 participants (9 female; 8 male) with symmetrical hearing loss between the ages of 40–87 years. Mean right-ear unaided thresholds at .25, .5, 1.0, 2.0 and 4.0 kHz were 23, 31, 48, 62, 72 dB HL, respectively. The corresponding mean thresholds for the left ear were 24, 33, 44, 63 and 74 dB HL. The participants wore HAs of the same make and model on both ears and each had been verified to provide NAL-NL1 target audibility for 60- and 70-dB-SPL speech.

The bimodal CI group was comprised of 8 participants (4 male and 4 female) between the ages of 42 to 87 years. Devices used: 2 Advanced Bionics, 4 Cochlear Corporation, 2 MED-EL. The group's mean unaided thresholds in the ear contralateral to the CI at .25, .5, 1.0, 2.0 and 4.0 kHz were 50, 56, 75, 96 and 104 dB HL, respectively. All HAs were verified to ensure NAL-NL1 target audibility for 60- and 70-dB-SPL speech. The participants were previously described in Dorman et al. (2015).

The bilateral CI group was comprised of 32 participants (13 male and 19 female) between the ages of 32–79 years. Devices used: 7 Advanced Bionics, 9 Cochlear Corporation, 16 MED-EL. 16 of the 32 listeners were from the sample in Dorman et al. (2014).

The hearing preservation CI group was comprised of 8 participants (4 male; 4 female) between the ages of 35–79 years with symmetrical (no more than a 15-dB difference at 250 Hz) low-frequency acoustic hearing in the CI ear and in the contralateral ear. The mean unaided audiometric thresholds for the non-implanted ear at .125, .25, .5, 1.0, 2.0 and 4.0 kHz were 26, 26, 46, 74, 105 and 114 dB HL, respectively. The mean unaided audiometric thresholds for the implanted ear at .125, .25, .5, 1.0, 2.0 and 4.0 kHz were 27, 31, 58, 86, 116 and 124 dB HL, respectively. Devices used: 1 Cochlear Corporation, 5 MED-EL. All listeners were from the sample in Loiselle et al. (2015).

The single-sided deaf (SSD) group was comprised of 13 participants (6 male; 7 female) between the ages of 11 to 63 years. Devices used: 1 Advanced Bionics, 1 Cochlear Corporation device, 11 MED-EL. Four of the listeners were from the sample in Dorman et al. (2015).

The group with bilateral CIs and bilateral hearing preservation (bi-bi) was comprised of 3 participants (2 male; 1 female) between 36 and 53 years of age. Devices used: 1 Cochlear Corporation, 2 MED-EL. Mean right-ear unaided audiometric thresholds at .25, .5, 1.0, 2.0 and 4.0 kHz were 25, 63, 97, 108 and 118 dB HL, respectively. The corresponding mean thresholds for the left ear were 32, 70, 95, 100 and 120 dB HL. One of the participants was described in Dorman et al. (2013).

Test environment and stimuli

The environment and methods have been previously described in detail in Yost et al. (2013). The stimuli were presented in the frontal horizontal plane using a 13-loudspeaker array with 15 degree spacing. The stimuli consisted of 200msec, Gaussian noise bursts filtered between 125 and 6000 Hz (48dB/octave).

Test Conditions

Each stimulus was presented four times per loudspeaker at 65dBA. Stimuli were not presented from either of the end speakers (1 and 13) along the array.

Prior to testing, the stimuli were presented to ensure audibility and to confirm understanding of the task. During this pre-testing period, patients were allowed to make adjustments to their HA and/or CI volume to ensure comfortable loudness for the 65-dBA stimuli.

Each subject identified the speaker of the sound source by pushing a button on a numbered keypad corresponding to the number of the loud speaker. Subjects were instructed to return to midline (“look at the red dot on speaker #7”) as soon as they pressed the enter button so that they would be positioned in the center when the next stimulus was presented.

Localization accuracy was calculated in terms of rms error using the D statistic of Rakerd and Hartman (1986). Chance performance, calculated using a Monte Carlo method, was 73.5 degrees (sd=3.2).

Results

Localization accuracy, in rms error, is plotted for all patients in all groups in Figure 1.

NH listeners: younger and older

The mean rms error for the younger NH listeners was 6.0 degrees; mean rms error for the older listeners was 5.4 degrees. The scores for the older listeners were entirely contained within the range of scores for the younger listeners. The 95th percentile of rms error scores for the younger, NH listeners was 11 degrees and is indicated by a dotted horizontal line in Figure 1.

Listeners with bilateral HAs

The mean rms error for this group was 12 degrees. Nine of the 16 listeners achieved scores at, or less than, the 95th percentile for young NH listeners. Unaided audiometric thresholds did not account for the variation in rms error scores.

Listeners with a single CI or a single, normal-hearing ear

Eight of 13 SSD-CI patients were tested using their CI alone and with their normal-hearing ear alone. In Figure 1 the open circles show performance with a single CI and the half-filled circles show performance with a single NH ear. The overall mean rms error score was 68 degrees. Scores with a single CI straddle the mean score for chance performance. Scores for the single NH ear tended to be slightly better but near chance.

Bimodal listeners

The distribution of scores for bimodal listeners, with one exception, overlapped completely the distribution of scores for listeners with a single CI or a single NH ear. The mean rms error score was 62 degrees.

Bilateral CI listeners

The mean rms error score for bilateral CI listeners was 29 degrees. The ‘best’ listeners had (i) error scores just above the 95th percentile of scores for the young NH group and (ii) error scores that overlapped the ‘poorer’ scores for the listeners with bilateral HAs. Only three of the 27 patients had scores that overlapped the best scores for bimodal listeners and listeners with a single ear or CI.

Hearing preservation listeners

The mean rms error for hearing preservation listeners was 30 degrees. The distribution of localization scores was similar to that for the listeners with bilateral CIs.

SSD-CI listeners

The mean rms error for the CI recipients with SSD was 28 degrees. The distribution of scores was similar to that found for bilateral listeners (minus the patients at the very end of the distribution) and for hearing preservation listeners. One patient achieved a score at the 95^{th} percentile of NH.

bi-bi listeners

The scores for the three patients in this group were contained within the range below the mean scores for the bilateral CI, hearing preservation CI, and SSD_CI listeners. However, the scores were no better than scores for the best listeners in the bilateral CI, hearing preservation CI, and SSD-CI groups.

Based on visual inspection of the data, three groups of scores were created; Group 1 was composed of the data from younger and older normal hearing listeners, Group 2 was composed of data from the one-ear and bimodal listeners, and Group 3 was composed of data from the bilateral, hearing preservation, SSD and bi-bi listeners. A one-way ANOVA for groups was significant ($F (2, 146) = 450.5$, $p < 0.0001$). Post tests (Holm-Sidak) showed that each group differed from every other group (mean scores: Group 1 = 5.9, Group 2 = 66.7 and Group 3 = 28.5).

Discussion

Localization accuracy varied significantly among, and within, the listener groups. There was a clear separation of performance for three groups of listeners (i) the normal hearing listeners and the hearing-impaired listeners fit with hearing aids, (ii) listeners with a single ear or who were bimodal CI listeners and (iii) bilateral CI, hearing preservation CI, SSD-CI and bi-bi listeners.

Normal hearing and hearing aided listeners

The younger and older normal hearing listeners showed the best sound source localization – approximately 6 degrees of rms error, on average. The 95^{th} percentile of scores for this group was 11 degrees of error. The majority of listeners with sloping, mild-to-severe, bilateral hearing-loss showed rms error scores in the range of normal. However, the distribution of scores was clearly different than that shown by the listeners without threshold elevation as only one of the scores was better than the mean score for the listeners in that group and many were outside of the 95^{th} percentile of normal.

Single ear and bimodal CI listeners

Of the listeners with input to two ears, the listeners in the bimodal CI group showed the poorest sound localization performance – no better than the performance of listeners using a single ear. A common account for this outcome is that bimodal CI patients have access to temporal information from the ear with low-frequency acoustic hearing and have access to signal level information from the ear fit with a CI. However, neither timing nor level information is well represented at both ears (Tyler et al., 2002; Potts et al., 2009, Dorman et al., 2015).

Bilateral CI, hearing preservation CI, SSD-CI and bi-bi listeners

The mean scores for these four groups of listeners were similar (between 20 and 30 degrees of error) but small sample sizes for the hearing preservation listeners and the bi-bi listeners preclude a strong comparison of mean performance. The best performing CI patients in these groups achieved scores that overlapped the poorest scores for the patients fit with bilateral hearing aids. One bi-bi patient was at the 95 percentile of normal performance.

Conclusion

Modern cochlear implants do not restore a normal level of sound source localization for CI listeners with access to sound information from two ears. However, as we have speculated before (Dorman et al., 2015) and consistent with patient report (Bichey and Miyamoto, 2008), the level of localization obtained, for all but the bimodal listeners, is likely sufficient to use sound sources in a functionally useful way in the real world.

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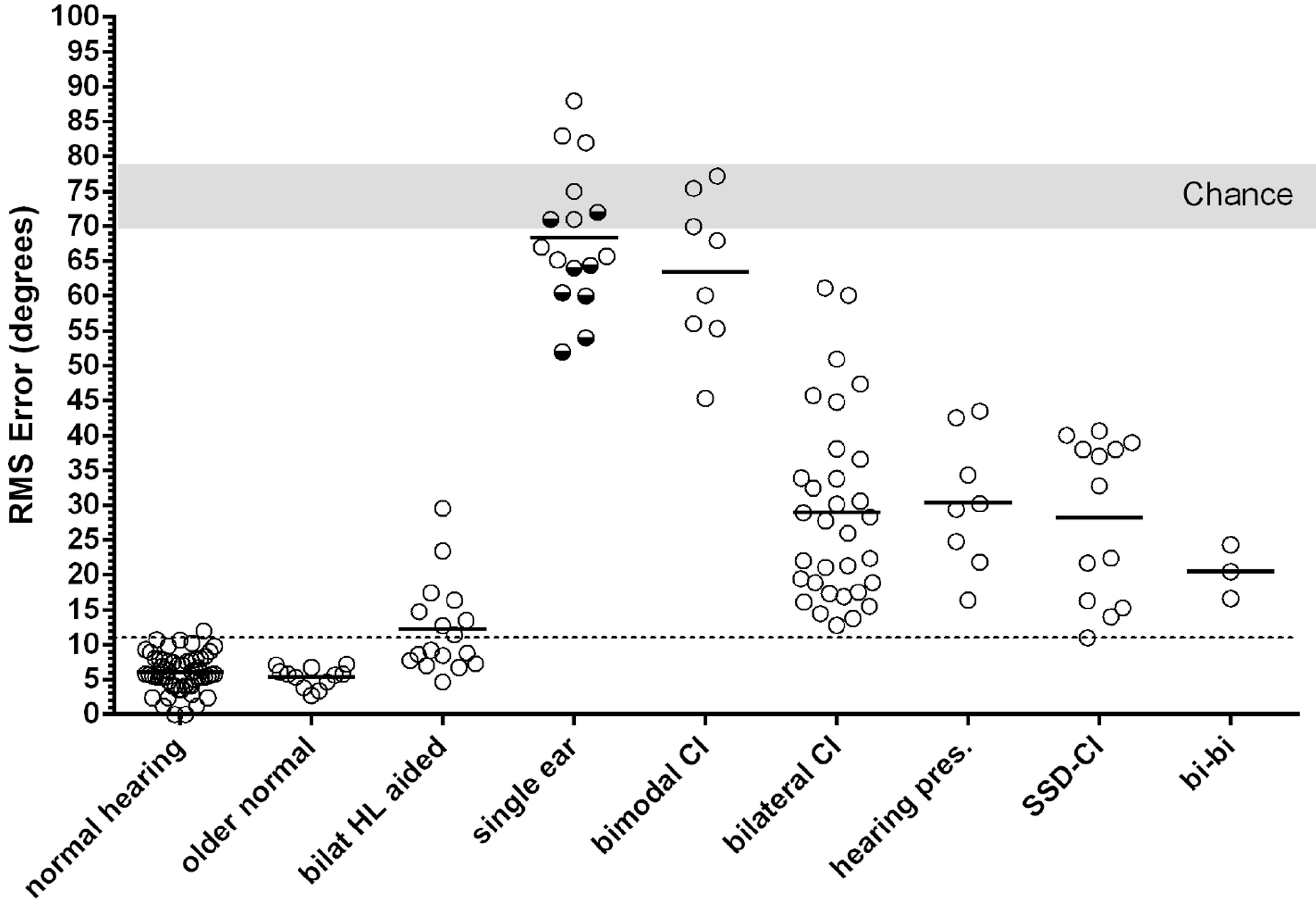

Figure 1.

Sound source localization accuracy for normal hearing, hearing impaired and CI listeners. Each symbol indicates the performance of one listener. In the single ear condition, the half-filled symbols show the performance of SSD-CI patients when using their normal-hearing ear and the open circles show the performance of the same patients using their CI alone. The dotted line indicates the 95^{th} percentile of scores for the normal hearing listeners.