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Self-Reported Spatial Hearing Abilities Across Different Cochlear Implant Profiles

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Abstract

Purpose—The goal of this study was to determine how self-reported spatial hearing abilities differ across various cochlear implant (CI) profiles and to examine the degree of subjective benefit following cochlear implantation across different groups of CI users.

Method—This was a retrospective study of subjective spatial hearing ability of CI recipients. The subjects consisted of 99 unilateral CI users, 49 bilateral CI users, 32 subjects with a CI and contralateral hearing aid (bimodal users), and 37 short-electrode CI users. All subjects completed the Spatial Hearing Questionnaire (Tyler, Perreau, & Ji, 2009), a questionnaire assessing spatial hearing ability, after implantation, and a subset of the subjects completed the questionnaire pre- and postimplantation.

Results—Subjective spatial hearing ability was rated higher for the bilateral and short electrode CI users compared to the unilateral and bimodal users. There was no significant difference in subjective spatial hearing performance between the bilateral and short electrode CI users and the unilateral CI and bimodal users. A separate analysis of pre- and postimplant performance revealed that all CI groups reported significant improvements in spatial hearing ability after implantation.

Conclusion—This study suggests that there are substantial differences in perceived spatial hearing ability among unilateral and bimodal CI users compared with bilateral and short electrode CI users.

Cochlear implantation has become a very successful treatment for individuals with significant hearing loss, producing improved speech perception abilities, such as the ability to talk on the phone, among other benefits. As a result, cochlear implants (CIs) are now considered the standard of care for individuals with severe-to-profound hearing loss. With that success, the candidacy criteria have expanded; persons with better residual hearing and unilateral hearing loss are now being implanted (e.g., Firszt, Holden, Reeder, Waltzman, & Arndt, 2012; Gantz & Turner, 2003). Furthermore, bilateral device use is now also recommended for many individuals with significant hearing loss, either through the use of bilateral CIs or the combined use of a CI and hearing aid in opposite ears (or bimodal

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stimulation; see, e.g., Ching, Incerti, Hill, & van Wanrooy, 2006; Dunn, Tyler, & Witt, 2005).

Research has shown that bilateral device use provides numerous advantages to the listener compared to monaural use. These improvements are attributed to the physiological binaural hearing processes that arise from the effects of *binaural summation* (an increase in loudness summation of sound when presented binaurally versus monaurally), *binaural squelch* (the ability to suppress background noise when the noise is spatially separate from the target source), the *head shadow effect* (the improvement in speech recognition when the head attenuates the background noise), and *localization* (the ability to determine the location of a sound source based on interaural timing and level cues). Studies that have investigated the performance of bilateral CI users suggest that these listeners are able to make use of these binaural processes, as perceptually bilateral CIs provide significant benefits for sound localization and for speech perception in noise (Ching, van Wanrooy, & Dillon, 2007; Dunn, Noble, et al., 2010; Firszt, Reeder, & Skinner, 2008; Noble, Tyler, Dunn, & Witt, 2005; Tyler, Dunn, Witt, & Noble, 2007; Tyler, Noble, Dunn, & Witt, 2006; van Schoonhoven et al., 2013).

Furthermore, studies have also indicated that bimodal use also provides notable benefits for listeners compared to monaural CI use only. These benefits have been reported for speech perception in noise (Armstrong, Pegg, James, & Blamey, 1997; Ching, Incerti, & Hill, 2004; Dunn et al., 2005; Flynn & Schmidtke, 2004; Tyler, Parkinson, et al., 2002), for sound localization (Dunn et al., 2005; Tyler, Parkinson, et al., 2002), and for music perception and sound quality (Ching et al., 2007; Kong, Stickney, & Zeng, 2005). However, by comparison, these benefits are not observed consistently for bimodal listeners across all studies. Moreover, a review of 12 CI studies suggested that about half of the bimodal users across all studies showed a significant binaural advantage for localization (Ching et al., 2007), compared with nearly 90% of the subjects using bilateral CIs. When combining the effects of head shadow, binaural squelch, and binaural summation, this provides a 1- to 3-dB speech-in-noise advantage for bimodal users compared to as much as 6 dB for bilateral CI users (Ching et al., 2007). Finally, studies that have compared performance among bilateral CI users and bimodal users have indicated that bilateral CI users have an advantage on speech-in-noise tasks, especially for binaural squelch (Schafer, Amlani, Paiva, Nozari, & Verret, 2011).

Despite these measured differences, few studies have investigated the subjective outcomes of CI users related to spatial hearing. In one such study, Noble, Tyler, Dunn, and Bhullar (2008b) compared the self-assessed abilities across 182 CI users on the Speech, Spatial, and Qualities of Hearing Scale (SSQ; Gatehouse & Noble, 2004). The SSQ is a 49-item questionnaire with three subscales relating to (a) speech perception, (b) localization and distance perception, and (c) sound quality and listening effort. The subjects were grouped into three categories—(a) 36 with bilateral CIs, (b) 105 with uni-lateral CIs, and (c) 41 bimodal users—and results on the SSQ were compared pre- and postimplant. The results indicated that, postimplantation, bilateral CI users provided the highest subjective ratings among the CI groups for all 10 subscales of the SSQ. In addition, ratings from the bimodal users were not significantly higher than the ratings from the unilateral CI users or any of the

10 subscales. Comparing pre- to postimplant benefit, the bimodal and unilateral CI groups were not significantly different on four of the speech subscales. On many of the subscales (Localization, Distance and Movement, Segregation of Sounds, and Listening Effort), the bimodal users had higher preimplant scores, but this did not translate into higher postimplant scores than unilateral or bilateral users. As a whole, this suggests that bimodal users report the same degree of subjective benefit from cochlear implantation as compared to unilateral users and far less than bilateral users (Noble et al., 2008b).

Still other studies that have compared self-report outcomes from different CI groups have shown that perceived hearing handicap may be increased in bimodal users compared to unilateral and bilateral users (Noble, Tyler, Dunn, & Bhullar, 2008a). In Noble et al.'s (2008a) study, data were obtained using the Hearing Handicap Inventory for the Elderly (HHIE; Ventry & Weinstein, 1982) and the Hearing Handicap Questionnaire (HHQ; Gatehouse & Noble, 2004) from 183 total subjects: 106 unilateral CI users, 35 bilateral CI users, and 42 bimodal users. The results revealed that the bimodal users reported a greater level of emotional distress as measured on the HHIE and the HHQ compared to bilateral and unilateral users. Across all other subscales of the HHIE and HHQ, bilateral users had significantly higher ratings than the bimodal and unilateral users, and no significant difference was found between the bimodal and unilateral users.

By comparison, few studies have reported on the subjective ratings of CI users with preserved bilateral residual hearing. Research combining acoustic and electric hearing in the same ear has shown remarkable results for pitch perception and melody recognition over electrical only (Gfeller et al., 2007; Gfeller, Olszewski, Turner, Gantz, & Oleson, 2006) and for speech perception (Gantz & Turner 2003; James et al., 2006; Turner, Gantz, Vidal, Behrens, & Henry, 2004) using a variety of electrode designs (Gantz, Turner, & Gfeller, 2006; Lenarz et al., 2009). The integration of good low-frequency hearing in combination with high-frequency input from the CI allows for better coding of acoustic cues (Turner et al., 2004), thereby improving speech and pitch perception. Recently, Lenarz et al. (2013) reported on outcomes from implantation of the Nucleus Hybrid L24 device in 66 adult subjects with bilateral severe-to-profound high-frequency hearing loss. The Hybrid L24 CI has 22 electrodes spaced over 15 mm and is expected to be inserted about 17 mm into the cochlea, with the aim to preserve acoustic hearing in the implanted ear. In that study, test measures included a monosyllabic word test presented in quiet; a sentence test presented in noise; and questionnaires, including the SSQ. Gains of 65% and 73% were found for monosyllable words in quiet and sentences in noise, respectively, after implantation of the L24 Hybrid CI. In addition, on the SSQ, results revealed a significant improvement pre- to postimplantation across all three subscales of Speech, Spatial, and Quality of Hearing. As observed in that study, the subjective ratings from the Hybrid CI recipients were consistent with the performance data.

Therefore, previous studies suggest there are differences in subjective outcomes related to disability and perceived benefit among unilateral CI users, bilateral CI users, and users of a CI plus hearing aid. In cases of hearing preservation, however, very limited data are available from users of a Hybrid short electrode CI with bilateral acoustic hearing to determine how this profile compares to other CI users in terms of subjective outcomes.

Documenting self-assessed hearing abilities from the perspective of the actual CI user helps determine the difficulties that are experienced in one's everyday life, beyond what can be measured by routine clinical tests. In other words, are the findings of the benefits of low-frequency residual hearing and bilateral device use consistent with what is experienced by subjects in their everyday life? In this way, a comparison of subjective outcomes across different CI groups, including unilateral and bilateral CI users, and bimodal and Hybrid short electrode users, is needed to determine the benefits of preserved residual hearing and bilateral cochlear implantation.

Here, we report subjective performance data from four different CI groups using the Spatial Hearing Questionnaire (SHQ; Tyler, Perreau, & Ji, 2009), a 24-item questionnaire that assesses subjective performance of listeners in different listening situations where binaural hearing, or listening with two ears, is emphasized (see the Appendix for the SHQ). Compared to the SSQ, which includes a subscale on spatial hearing as well as general questions about hearing ability, the SHQ focuses specifically on spatial hearing ability. Spatial hearing relates to hearing in the sound field, including localization of a sound source or speech perception in noise with separate target and noise sources. One of the benefits of binaural hearing is thought to be better spatial hearing abilities compared to monaural hearing.

Furthermore, the SHQ assesses subjective hearing ability using stimuli with different frequency content (e.g., male's voices vs. children's voices). These subscales include Males’ Voices (Items 1, 5, 9, 13, and 17), Females’ Voices (Items 2, 6, 10, 14, and 18), Children's Voices (Items 3, 7, 11, 15, and 19), Music (Items 4, 8, 12, 16, and 20), Sound Localization (Items 13–24), Understanding of Speech in Quiet (Items 1–4), Understanding of Speech in Noise With Target and Noise Sources From the Front (Items 5–8), and Understanding of Speech in Noise With Target and Noise Sources Spatially Separate (Items 9–12). An overall or total score is calculated as the average of all 24 items. Previous factor analyses and reliability tests have been performed with the SHQ based on data from unilateral and bilateral CI users (Tyler et al., 2009), individuals with asymmetrical and symmetrical hearing loss (Potvin, Kleine Punte, & Van de Heyning, 2011), and listeners with normal hearing (Perreau, Spejcher, Ou, & Tyler, 2014). The results of these studies have confirmed that seven of the eight SHQ subscales measure self-assessed spatial hearing ability, with one subscale assessing speech perception abilities in quiet. In addition, the SHQ has been shown to have good reliability, with Cronbach's $\alpha = .98$ when assessing performance of CI listeners (Tyler et al., 2009).

Therefore, the purpose of this study was to determine how self-reported spatial hearing abilities differ across various CI profiles and to document the degree of subjective benefit following cochlear implantation across different groups of CI users. Three research questions were addressed:

1. How do various CI profiles compare subjectively on spatial hearing tasks after cochlear implantation?
2. Do all CI users show improvement in postimplant self-assessed hearing abilities compared with preimplant abilities?

3. Across various CI profiles, which hearing mode results in the most benefit for self-reported hearing ability?

Method and Materials

Subjects

The subjects in this study included 217 CI users who were research subjects from the University of Iowa Adult Cochlear Implant Program. Of the 217 total CI users, 99 were unilaterally implanted, 49 were bilaterally implanted (46 simultaneously and three sequentially implanted), 32 were unilaterally implanted and used a hearing aid in the non-implanted ear (bimodal), and 37 were unilaterally implanted with a Hybrid-S or short-electrode CI. In total, there were 102 male and 115 female subjects. Demographic information for all CI subjects, including gender, age at implantation (in years), length of auditory deprivation, length of device use, and type of implant, is shown in Table 1. All subjects were experienced CI users, with 55.6 months (short electrode) to 105.3 months (unilateral CI) of CI experience. In addition, most subjects reported that there was an unknown cause of hearing loss, followed by hereditary or family history of hearing loss as the second most common etiology for deafness. Because the length of device use was substantially longer for the unilateral CI group than all other subject groups, we compared SHQ scores separately for unilateral CI users implanted before or after 100 months. Total SHQ and subscale scores were not significantly different among the two unilateral CI subject groups implanted before or after 100 months, indicating that performance on the SHQ stabilizes following the initial acclimatization to a CI. Therefore, all 99 unilateral CI users were included in this analysis. For the short-electrode CI subjects, 22 used bilateral hearing aids, nine used a contralateral hearing aid only, two used an ipsilateral hearing aid only, and four used no hearing aids. Mean hearing thresholds in the implanted ear for the short-electrode group ($n = 37$) are displayed in Figure 1.

Procedure

To be eligible for this study, all subjects had to have completed the SHQ (see the Appendix for the questionnaire items) after using their CI device(s) for at least 12 months. The SHQ was routinely administered to the CI research subjects at the University of Iowa as part of an ongoing research protocol starting in the early 2000s. Subjects completed the questionnaire prior, during, or shortly after their research sessions at the University of Iowa using a paper-and-pencil method, and data were entered and stored in a database for later retrieval.

Here, questionnaire data obtained from March 2004 to July 2013 were included. If multiple responses were gathered for a given subject, only the most recent data points were analyzed in this study. The local institutional review board approved this study.

Subjective benefit after cochlear implantation was also assessed by comparing pre- and postimplant scores using the SHQ. Because this was a retrospective study and the SHQ was not administered routinely prior to implantation, pre- to postimplant scores were compared for a smaller group of subjects only, including 13 unilateral, 15 bilateral, 12 bimodal, and 13 Hybrid short-electrode CI subjects. Preimplant data were collected from 2001 to 2010, and postimplant scores were collected from 2003 to 2013 using the same methods described earlier. All CI subjects had to have used their CI for at least 12 months prior to the postimplant interval. Demographic information for the subjects included in the pre- and postimplant analysis are shown in Table 2.

Data Analysis

To compare mean differences in scores on the SHQ among the four CI groups, generalized linear models and contrasts were performed. To compare pre- versus postimplant SHQ scores within each group of CI users (using a smaller sample of subjects), two-tailed, paired t tests were performed. For all tests, statistical significance was defined as $p < .05$. Data were analyzed using several statistical packages, including SPSS (Version 21.0), SAS (Version 9.3), and Microsoft Excel.

Results

To answer the first research question on how CI users compare subjectively on spatial hearing ability tasks, results on the SHQ were compared for the total and eight subscale scores. These results for the unilateral (black bars), bilateral (white bars), bimodal (gray bars), and short-electrode (dashed bars) CI users are displayed in Figure 2. Total scores on the SHQ, shown on the far right of the figure, averaged 49.9% ($SD = 23.3$, $SE = 2.3$, range: 6–93) for unilateral users, 59.2% ($SD = 21.9$, $SE = 3.1$, range: 5–99) for bilateral users, 47.2% ($SD = 20.7$, $SE = 3.7$, range: 3–83) for bimodal users, and 58.2% ($SD = 18.9$, $SE = 3.1$, range: 19–93) for short-electrode CI users. The results indicated that the main effect of CI profile was significant, $F(3, 213) = 3.41$, $p = .018$. Follow-up tests using contrast analyses revealed that there was no significant difference in the total SHQ score among the bilateral CI and Hybrid short-electrode users, $F(1, 213) = 0.04$, $p = .84$. Also, total SHQ scores for unilateral CI and bimodal users were not significantly different, $F(1, 213) = 0.37$, $p = .54$. However, bilateral CI users and Hybrid short-electrode users reported significantly higher spatial hearing ability compared to unilateral CI users and bimodal users, $F(1, 213) = 9.67$, $p = .0021$. Furthermore, the results indicated significant differences in the total SHQ score between bilateral and unilateral CI users, $F(1, 213) = 5.91$, $p = .016$, as well as bimodal users, $F(1, 213) = 5.81$, $p = .0017$. The Hybrid short-electrode users reported significantly higher spatial hearing ability than bimodal users, $F(1, 213) = 4.32$, $p = .039$, and borderline significantly different compared to unilateral CI users, $F(1, 213) = 3.86$, $p = .050$.

For the subscales of the SHQ, contrast analyses revealed no significant differences between bilateral CI and short-electrode CI users on any of the eight subscales. As with the total score, none of the subscale scores were significantly different for the unilateral and bimodal groups. When comparing bilateral and short-electrode to unilateral and bimodal users, scores were significantly different across many, but not all eight, subscales. Scores were significantly higher for bilateral and short-electrode users compared to unilateral and bimodal users for five of eight subscales: Males' Voices, $F(1, 213) = 8.42$, $p = .0041$; Females' Voices, $F(1, 213) = 6.02$, $p = .0149$; Children's Voices, $F(1, 213) = 4.02$, $p = .046$; Music, $F(1, 213) = 9.28$, $p = .0026$; and Sound Localization, $F(1, 213) = 16.72$, $p \leq .0001$. For all CI groups, there was no significant difference in scores among the speech subscales, including in-quiet and in-noise subscales with target and noise sources from the front or spatially separated.

Across the CI subjects, the highest mean score on the SHQ was reported for the Understanding of Speech in Quiet subscale (scores ranged from ~78% for unilateral and bimodal to 82%–84% for bilateral and short electrode users). In contrast, the lowest mean score was found for the Sound Localization subscale (scores ranged from 35.3%–38.6% for unilateral and bimodal users and 50.2% for Hybrid users), with the exception of the bilateral users. For the bilateral CI users, scores were lowest for the Understanding of Speech in Noise subscales with and without spatially separate target and noise sources (51.9% and 53.5%) and the Music subscale (53.8%).

To more closely investigate differences in subjective performance among the CI subjects, results from individual items on the SHQ were also compared (see Tables 3 and 4). Shown in Table 3 are the mean subjective ratings for four items on spatial hearing ability for unilateral, bilateral, bimodal, and short-electrode CI users. The items assessed the following: location of stationary voice (Item 13), the direction of a car (Item 22), the movement of an approaching car (Item 23), and the distance of a sound source (Item 24). For all CI users, judging the direction of a car (scores of 33.3%–53.9%) and the distance of a sound source (scores of 33.0%–52.0%) were reportedly the most difficult listening situations compared to other spatial hearing tasks, such as judging the location of a stationary voice and movement of a car. Across all four items, bilateral and Hybrid CI users rated their abilities significantly higher than unilateral CI and bimodal users ($p < .05$), with scores 11%–27% higher than the other groups. SHQ scores on these four spatial hearing tasks were not significantly different ($p > .05$) for unilateral to bimodal users and bilateral and short-electrode CI users.

Subjective results from two items on music perception are displayed in Table 4 for the CI subjects. On these two items, subjects were asked to rate their music perception abilities when listening in quiet (Item 4) and in a background of noise (Item 12). For music perception in quiet, scores for the short-electrode users were significantly higher (i.e., 23.6%, $p = .0001$) compared to the unilateral CI users but not significantly different from the bilateral and bimodal groups. Similarly, for music perception in noise, short-electrode users had higher ratings than all other implant groups (58.8% vs. 43.8%–46.5%), although the difference was significant only between short-electrode and unilateral CI users ($p = .010$) and the short-electrode to bilateral CI users ($p = .047$). The bilateral CI users, on average, rated their music listening abilities higher than the unilateral CI users in both quiet and noise environments. However, these differences were not significantly different ($p > .05$). Finally, music perception in quiet and in noisy backgrounds did not reveal a statistically significant difference between unilateral and bimodal users. As expected, for all CI subjects, subjective ratings when listening to music in a background of noise (Item 12) were lower than those reported when listening to music in quiet (Item 4).

Next, pre- versus postimplant scores were compared for a separate group of CI subjects, and results are shown in Figures 3 and 4. In Figure 3, data for the total SHQ score are displayed for the unilateral ($n = 13$), bilateral ($n = 15$), bimodal ($n = 12$), and short-electrode ($n = 13$) groups, pre- and postimplantation. Preimplant scores are shown on the left (open symbols), and postimplant scores are shown on the right (filled symbols). Preimplantation mean scores were less than ~50% for all groups and considerably higher for the short-electrode subjects, as would be expected given their overall better preimplant performance than the other CI groups. Postimplantation, bilateral subjects rated their subjective ability higher than the other subject groups. Finally, a two-tailed, paired t test was used to compare pre- versus postimplant scores within each CI group on the total SHQ score. All subjects showed a significant improvement in subjective ratings for the total score after cochlear implantation (unilateral CI, $p = .013$; bilateral CI, $p < .0001$; bimodal CI, $p = .042$; short-electrode CI, $p = .034$).

To examine the amount of improvement pre- to postimplant on the SHQ, normalized benefit scores were calculated for each CI group. Normalized benefit was computed because the preimplant scores obtained here vary significantly between groups based on differing CI candidacy criteria; that is, short-electrode CI candidates should have better speech perception abilities and more residual hearing than traditional long-electrode candidates, and normalizing scores based on preimplant performance will likely yield more appropriate scores for a between-groups comparison than typical difference scores. The normalized benefit scores were derived using the following equation (modified from Zhang, Spahr Dorman, & Saoji, 2013): [100 × (post – pre) / (100 – pre)], where *pre* indicates the preimplant total SHQ score, and *post* indicates the postimplant total SHQ score. The results are displayed in Figure 4. Overall, the bilateral users reported more subjective benefit after implantation compared to the other CI groups. Although no statistical tests were used to compare differences, normalized benefit as shown in Figure 4 was higher for the bilateral CI subjects (i.e., median score > 60%) than the unilateral CI, bimodal, and short-electrode users (i.e., median scores < 40%).

Finally, Figure 5 shows individual scores for the unilateral ($n = 13$), bilateral ($n = 15$), bimodal ($n = 12$), and short-electrode users ($n = 13$), pre- versus postimplantation for the SHQ total score. Postimplant scores are shown along the x-axis, and preimplant scores are shown along the y-axis. Scores to the right of the dashed line indicate lower preimplant and higher postimplant SHQ scores, whereas scores to the left of the dashed line indicate higher preimplant and lower postimplant scores. The majority of individual scores (43/53, or 81.1%) are along or to the right of the dashed line, suggesting higher subjective ratings after implantation for most subjects. Considering differences among the four CI groups, individual scores for the bilateral subjects are higher than those from the other CI groups, and the data are more clustered toward higher postimplant performance. The individual data from the other groups are vastly more scattered, indicating more variability in subjective performance for this sample of unilateral, bimodal, and short-electrode users.

Discussion

This study was aimed at examining the differences in subjective spatial hearing ability across subjects using unilateral, bilateral, bimodal, and short-electrode CI devices. Overall, the results revealed that subjective spatial hearing ability was significantly higher for the bilateral and short-electrode CI users compared to the unilateral and bimodal users. However, there were several interesting findings that we explore here in more depth.

First, the results indicated that, for the subjects in this study, bilateral CI use provided better subjective spatial hearing performance compared to either unilateral or bimodal CI use. This difference was measured on several aspects of the SHQ, including on individual items of spatial hearing ability; on the subscales of Sound Localization, Music, and Males', Females', and Children's Voices; and for the total score. In general, the greatest difference in subjective ratings favoring bilateral cochlear implantation was found on the Sound Localization subscale, where scores were 17.3% and 20.6% higher than the unilateral and bimodal subjects, respectively.

As found in other studies, bilateral CI users can effectively utilize high-frequency interaural level difference (ILD) cues in determining the location of a sound source (e.g., Laback, Pok, Baumgartner, Deutsch, & Schmid, 2004; van Hoesel & Tyler, 2003). Even despite asymmetrical input from the two CIs (i.e., different insertion depths, frequency allocations, and stimulation modes between the right and left ears), generally speaking, bilateral CI users are able to make use of available ILD cues for accurate sound judgments (e.g., Dorman & Dahlstrom, 2004; Tyler et al., 2007; Tyler, Gantz, et al., 2002). In contrast, bimodal users often have limited high-frequency residual hearing in the aided ear, which limits comparison of ILD cues that are high frequency in nature. In addition, use of a CI in one ear and a hearing aid in the other produces differences in the overall hearing level and how sound is coded across the two ears, which may be difficult for bimodal users to integrate input binaurally and lead to low or no use of the contralateral hearing aid (e.g., Fitzgerald, Seguin, Schramm, Chenier, & Armstrong, 2009, Fitzgerald & Leblanc, 2011; Tyler, Parkinson, et al., 2002). For these reasons, bimodal users may be at a further disadvantage compared to bilateral CI users on sound localization tasks. Studies comparing sound localization ability across these modes within a given individual have shown that bilateral CI use provides improved sound localization and better subjective outcomes compared to bimodal use for adult listeners (Ching et al., 2007; Potts & Litovsky, 2014), suggesting that, at least for some individuals, bilateral CI use may provide better spatial hearing ability than bimodal use.

Second, the results indicated that the short-electrode users in this study reported better sound localization ability; music perception; and perception of male, female, and child's voices than the unilateral and bimodal users. For the short-electrode CI users, residual low-frequency hearing allows for coding of low-frequency interaural timing difference cues, which are necessary for binaural processing. Dunn, Perreau, Gantz, and Tyler (2010) reported on 11 subjects using a short-electrode CI and bilateral hearing aids completing a localization task and found that the addition of the short-electrode CI did not disrupt the ability to take advantage of interaural timing difference cues for better sound localization. However, a recent study indicated that the benefits of preserved bilateral hearing for short-electrode users may be more related to the ability to code spectral, rather than temporal, information (Golub, Won, Drennan, Worman, & Rubinstein, 2012). In support of this notion, we found that the largest performance difference in favor of short-electrode users compared to all other CI subject groups was for music perception. Music perception was rated consistently higher for the short-electrode users in this study, suggesting that these individuals make use of their low-frequency residual hearing to improve coding of pitch and spectral shape. The subjective data from this study agree with previous reports in the literature from objective studies that preserved low-frequency hearing allows for better music perception and appreciation (e.g., Gantz, Turner, & Gfeller, 2004; Gfeller et al., 2006, 2007).

Furthermore, the results from this study provide evidence that bimodal users have subjective outcomes similar to those of unilateral CI users and reportedly less benefit than bilateral CI users. The mean ratings from the unilateral CI and bimodal users were not significantly different across all eight subscales and for the total score on the SHQ. Furthermore, an examination of the individual data suggested similar improvements pre- to postimplant for bimodal and unilateral CI users, which was reportedly less than bilateral CI users. These data are in agreement with those of Noble et al. (2008a, 2008b), suggesting that bimodal subjects report their subjective performance lower than would be expected given their use of bilateral devices. In addition, Fitzgerald and Leblanc (2011) showed that more than half of bimodal individuals (18 of 27) who used a hearing aid preoperatively discontinued using the hearing aid after receiving their implant. In that study, subjects reportedly discontinued hearing aid use after implantation because of several factors, including improved sound quality with the CI, no perceived additional benefit of the hearing aid, and a degraded acoustic signal when both devices were used together (Fitzgerald & Leblanc, 2011). This finding that bimodal use is reportedly not improved compared to unilateral CI use is concerning and should be investigated further.

Previous explanations for why bimodal users do not report higher subjective outcomes and lower disability than unilateral CI users have been explored, including the fact that experienced bimodal users on average perform more poorly on speech perception tasks than new bimodal users (Ching et al., 2004; Noble et al., 2008b). In this study, all bimodal users had significant experience with both of their devices, so that could explain why these results were poorer than expected for the bimodal users and more similar to uni-lateral subjects. Also, it is possible that these subjects could be underestimating their performance compared to the other CI subjects. By maintaining some residual hearing after implantation, it may be difficult for individuals to integrate inputs from the hearing aid and CI (e.g., Tyler, Parkinson, et al., 2002), thereby producing lower subjective performance than unilateral and bilateral users who do not have this difficulty.

When comparing pre- and postimplant scores for a subset of subjects, significant improvements were reported by all CI groups. Although the amount of improvement appeared to be greatest for bilateral CI users and least for the short-electrode users, it is important to consider the differences in CI candidacy that may influence a direct comparison across groups. Thus, more detailed comparisons should be considered with caution given that not all users of a CI will have the same preoperative characteristics and potential for improvement. Despite our efforts to control for this confounding factor, these data, subjective in nature, were from a smaller group of subjects ($n < 15$) and should be interpreted cautiously.

In sum, this study suggests that there are substantial differences in self-reported spatial hearing ability among various CI profiles. Individuals with bilateral, severe-to-profound deafness using bilateral CIs reported better spatial hearing performance than unilateral CI and bimodal users, especially for sound localization. Furthermore, subjects with residual hearing using a short-electrode CI, on average, reported better music perception and spatial hearing abilities than unilateral CI users and users of a long-electrode and with a hearing aid worn in the opposite ear. However, these results are based on average data (see Figure 5 for individual performance of a subset of CI users) and therefore likely do not capture the individual differences that exist. To help determine the best option for a given individual, selection strategies that focus on each ear's contribution to the binaural advantage were provided by Perreau, Tyler, Witt, and Dunn (2007), who proposed an approach for attempting to maximize the performance of signal processing in hearing aid and CI users. This approach can be expanded into selection issues involved in some of the binaural applications reviewed here. For example, if a person uses a CI and a contralateral hearing aid and there is minimal contribution of the hearing aid to the binaural score, bilateral CIs could be the next step. Indeed, studies conducted by Ching et al. (2007) and Potts and Litovsky (2014) have reported on these client outcomes comparing bimodal to bilateral CI use, with encouraging results.

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Appendix

The Spatial Hearing Questionnaire

Name: ______________________________
Date: ______________________________

Please respond to each question with a number from 0-100. Number 0 means the situation would be very difficult. Number 100 means the situation would be very easy.

0 = *Very Difficult* **100 = *Very Easy***

1.	A **man** talking to you is standing in front of you. It is a **very quiet room**. How well can you understand **him**?	
2.	A **woman** talking to you is standing in front of you. It is a **very quiet room**. How well can you understand **her**?	
3.	A **child** talking to you is standing in front of you. It is a **very quiet room**. How well can you understand the **child**?	
4.	You are listening to **music** that is comfortably loud coming from in front of you. It is a **very quiet room**. How easy or difficult is it to hear the **music** clearly?	
5.	A **man** talking to you is standing in front of you. There is a loud fan **directly behind him**. How well can you understand **him**?	
6.	A **woman** talking to you is standing in front of you. There is a loud fan **directly behind her**. How well can you understand **her**?	
7.	A **child** talking to you is standing in front of you. There is a loud fan **directly behind them**. How well can you understand the **child**?	
8.	**You** are listening to comfortably loud **music** coming from **in front** of you. There is also a loud fan **in front** of you. How easy or difficult is it to hear the **music** clearly?	
9.	A **man** talking to you is standing in front of you. There is a loud fan **off to one side**. How well can you understand **him**?	
10.	A **woman** talking to you is standing **in front** of you. There is a loud fan **off to one side**. How well can you understand **her**?	
11.	A **child** talking to you is standing **in front** of you. There is a loud fan **off to one side**. How well can you understand the **child**?	
12.	You are listening to comfortably loud **music** coming from **in front** of you. There is also a loud fan **off to one side**. How easy or difficult is it to hear the **music** clearly?	
13.	How well are you able to **determine the location** of a **man's** voice when you **cannot see** him?	
14.	How well are you able to **determine the location** of a **woman's** voice when you **cannot see** her?	
15.	How well are you able to **determine the location** of a **child's** voice when you **cannot see** the child?	
16.	How well are you able to **determine the location** of a **music** source, say a radio, when you **cannot see** it?	
17.	How well are you able to **determine the location** of a **man's** voice when he is **behind you**?	
18.	How well are you able to **determine the location** of a **woman's** voice when she is **behind you**?	
19.	How well are you able to **determine the location** of a **child's** voice when the child is **behind you**?	
20.	How well are you able to **determine the location** of a **music** source, say a radio, when it is **behind you**?	
21.	How well are you able to **determine the location** of a **flying airplane** when you **cannot see** it?	
22.	You hear a **car off in the distance**, but you cannot see it. How accurately can you tell **where it is coming from**?	
23.	If you were to stand **beside a road** and close your eyes, how well could you tell what **direction a car was going** as it passed by?	
24.	You are in a room in a house and hear a loud **sound**. How easily can you tell **how far away** the **sound** was?	

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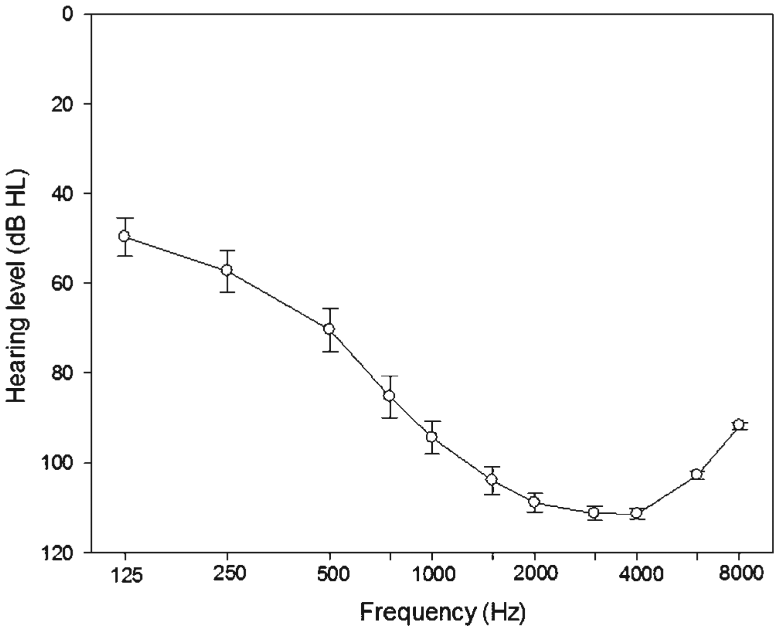

Figure 1.

Mean pure-tone hearing thresholds (in dB HL) for the implanted ear for all 37 short-electrode cochlear implant (CI) users. Mean thresholds are plotted in the filled circles. Error bars represent standard errors.

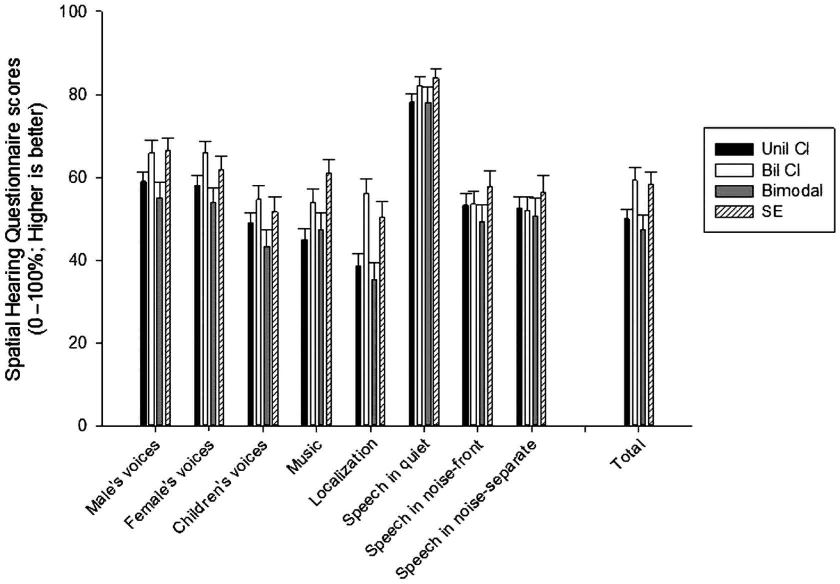

Figure 2.

Mean performance for unilateral (Unil; black bars, *n* = 99), bilateral (Bil; white bars, *n* = 49), bimodal (gray bars, *n* = 32), and short-electrode (SE; dashed bars, *n* = 37) users on the Spatial Hearing Questionnaire (SHQ) for all eight subscales and the total score. Higher scores indicate better subjective hearing abilities. Error bars represent standard errors.

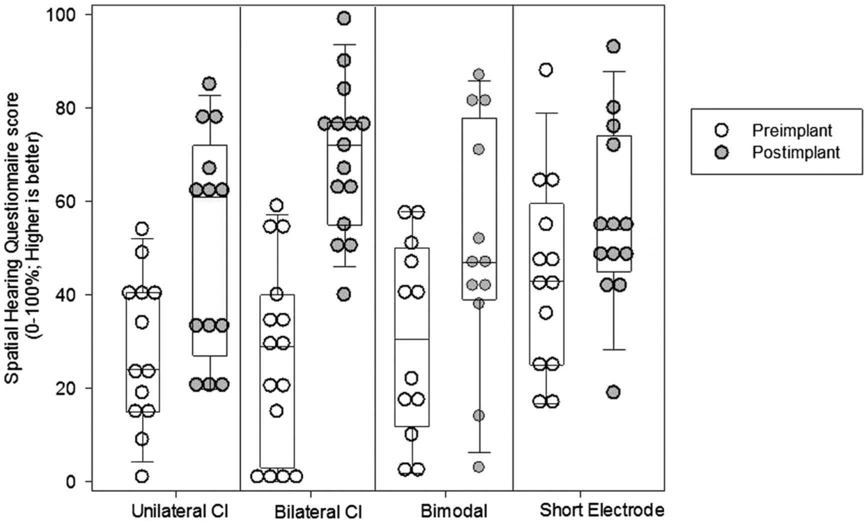

Figure 3.

Pre- and postimplant Spatial Hearing Questionnaire total scores for unilateral CI, bilateral CI, bimodal, and short-electrode users. Open symbols show preimplant scores (left), and filled symbols show postimplant scores (right). Higher scores indicate better subjective hearing abilities. Error bars represent standard errors.

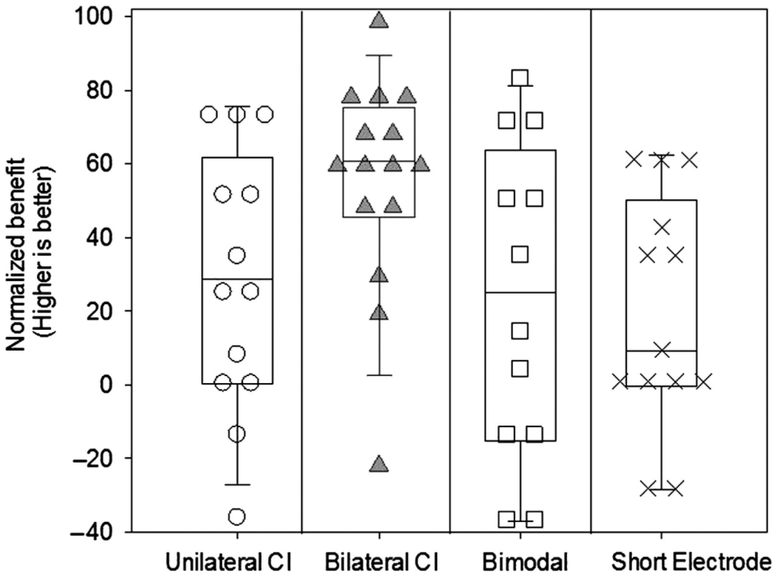

Figure 4.

Normalized benefit for the CI subjects as measured on the SHQ total score. Scores are shown for unilateral (open circles, *n* = 13), bilateral (filled triangles, *n* = 15), bimodal (open squares, *n* = 12), and short electrode (Xs, *n* = 13) users. Scores were calculated by calculating normalized benefit from pre- and postimplant performance using the equation [100 × (post – pre) / (100 – pre)]. Higher scores indicate better spatial hearing benefit. Error bars represent standard errors.

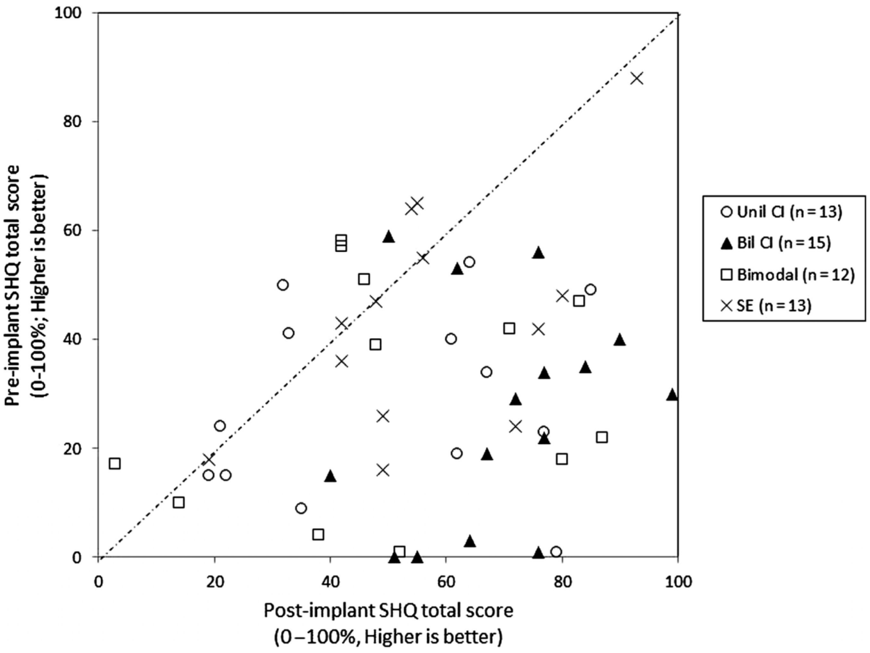

Figure 5.

Individual pre- and postimplant SHQ total scores for the CI subjects. Scores are shown for unilateral (open circles, *n* = 13), bilateral (filled triangles, *n* = 15), bimodal (open squares, *n* = 12), and short-electrode (Xs, *n* = 13) users. Postimplant scores are shown along the *x*-axis, and preimplant scores are shown along the *y*-axis. Scores to the right of the dashed line indicate lower preimplant and higher postimplant SHQ scores, and scores to the left of the dashed line indicate higher preimplant and lower postimplant scores.

Table 1

Subject demographics for the four participant groups.

Characteristic	**Unilateral CI (*n* = 99)**	**Bilateral CI (*n* = 49)**	**Bimodal (*n* = 32)**	**Short electrode (*n* = 37)**
Gender (%)				
Male	50.5	42.9	50	40.5
Female	49.5	57.1	50	59.05
Age at implantation (in years)	55.3 (15.2)	55.3 (15.1)	61.8 (13.1)	56.1 (11.4)
Length of auditory deprivation (in years)	11.5 (13.5)	7.8 (9.1)	10.1 (14.0)	
Length of device use (in months)	105.3 (70.9)	69.8 (44.5)	66.1 (46.7)	55.6 (38.0)
Type of implant (quantity)				
Nu	55	21	15	37
Cl	37	26	17	
In	7	2		

Note. Numbers in parentheses are standard deviations. CI = cochlear implant; Nu = Nucleus; Cl = Clarion; In = Ineraid. Auditory deprivation data are not applicable for short electrode CI users due to preserved acoustic hearing.

Table 2

Subject demographics for CI participants comparing performance pre- vs. postimplantation.

Characteristic	Unilateral	Bilateral	Bimodal	Short electrode
Gender (%)	13	15	12	13
Male	38.5	40	42	46.2
Female	61.5	60	58	53.8
Age at implantation (in years)	64.1 (14.0)	59.9 (16.9)	67.2 (8.4)	59.1 (11.9)
Length of auditory deprivation (in years)	8.9 (7.3)	5.6 (5.0)	7.5 (8.7)	
Length of device use (in months)	39.8 (18.5)	52.3 (34.0)	46.8 (27.5)	55.2 (31.7)
Type of implant (quantity)				
Nu	7	4	5	13
Cl	6	11	7	
In				

Note. Numbers in parentheses are standard deviations. Auditory deprivation data are not applicable for short electrode CI users due to preserved acoustic hearing.

Table 3

Mean subjective ratings on four items assessing spatial hearing ability for the CI users.

	Unilateral		Bilateral		Bimodal		Short electrode	
Item	***M***	***SE***	***M***	***SE***	***M***	***SE***	***M***	***SE***
Location of stationary voice (Item 13)	42.4	3.1	60.8	4.0*	38.1	4.8	54.3	4.5*
Direction of car (Item 22)	36.1	2.9	53.9	4.3*	33.3	4.0	47.1	4.5*
Movement of car (Item 23)	38.3	3.2	61.5	4.2*	34.0	5.0	53.7	4.5*
Distance of sound source (Item 24)	35.9	3.0	52.0	4.0*	33.0	4.6	47.6	4.4*

[*] Significant difference from unilateral and bimodal at $p < .05$.

Table 4

Mean subjective ratings on two items assessing music perception for the CI participants.

	Unilateral		Bilateral		Bimodal		Short electrode	
Item	***M***	***SE***	***M***	***SE***	***M***	***SE***	***M***	***SE***
Music perception: Quiet (Item 4)	60.6	3.8	71.0	4.0	70.6	4.9	84.2	3.0 *
Music perception: Noise (Item 12)	43.8	3.3	45.7	4.0	46.5	5.2	58.8	4.3 †

*Significant difference from unilateral at $p < .05$.

†Significant difference from unilateral and bilateral at $p < .05$.