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Head movements allow listeners bilaterally implanted with cochlear implants to resolve front-back confusions

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Abstract

Objectives—We report on the ability of patients fit with bilateral cochlear implants (CIs) to distinguish the front-back location of sound sources both with and without head movements. At issue was (i) whether CI patients are more prone to front-back confusions than normal hearing (NH) listeners for wideband, high-frequency stimuli, and (ii) if CI patients can utilize dynamic binaural difference cues, in tandem with their own head rotation, to resolve these front-back confusions. Front-back confusions offer a binary metric to gain insight into CI patients' ability to localize sound sources under dynamic conditions not generally measured in laboratory settings where both the sound source and patient are static.

Design—Three-second duration Gaussian noise samples were bandpass filtered to 2-8 kHz and presented from one of six loudspeaker locations located 60° apart, surrounding the listener. Perceived sound source localization for 7 listeners bilaterally implanted with cochlear implants, was tested under conditions where the patient faced forward and did not move their head and under conditions where they were encouraged to moderately rotate their head. The same conditions were repeated for 5 of the patients with one implant turned off (the implant at the better ear remained on). A control group of NH listeners was also tested for a baseline of comparison.

Results—All 7 CI patients demonstrated a high rate of front-back confusions when their head was stationary (41.9%). The proportion of front-back confusions was reduced to 6.7% when these patients were allowed to rotate their head within a range of approximately $\pm 30^\circ$. When only one implant was turned on, listeners' localization acuity suffered greatly. In these conditions, head movement or the lack thereof made little difference to listeners' performance.

Conclusions—Bilateral implantation can offer CI listeners the ability to track dynamic auditory spatial difference cues and compare these changes to changes in their own head position, resulting in a reduced rate of front-back confusions. This suggests that, for these patients, estimates of auditory acuity based solely on static laboratory settings may underestimate their real-world localization abilities.

Introduction

Auditory spatial acuity is useful to listeners in real-world scenarios because it can lead to improvements in speech comprehension when sound sources are perceived to come from

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different locations (spatial release from masking) which can, in turn, improve listeners' ability to segregate multiple auditory streams from each other, giving the listener an improved ability to choose to listen to one sound source over others. Furthermore, sound source localization is important for directing a listener's visual gaze to salient sounding objects, such as an oncoming car or a friend calling from across a crowded restaurant. Much of what we understand about auditory sound source localization in normal hearing (NH) and hearing impaired (HI) populations is based on experimental conditions that hold listeners and sound sources stationary. However, in everyday life listeners move through their environment, turn their heads in response to salient auditory and visual stimuli, and localize sound sources that are sometimes also in motion. As they move, listeners must integrate information from various sensory modalities, from motor feedback, and from cognitive processes, to distinguish their own motion from that of moving sources of sound. However, while a listener's motion introduces complexities, it also offers strategic opportunities to disambiguate confusing sound environments. One such ambiguity listeners face is whether a sound source lies in front or behind them.

In a sound field, any given natural combination of interaural differences of time (ITD) and intensity (ILD) corresponds not to a single sound source location, but to whole range of locations, often described as a 'cone of confusion.' In the azimuth plane, this ambiguity can result in front-back confusions, where listeners localize sound sources to the correct lateral location, but in the wrong front-back hemifield. However, sounds with sufficient high-frequency information allow NH listeners to resolve front-back confusions. That is, listeners can exploit the spectral differences (especially from 4 kHz to 16 kHz) which arise as a result of differences in filtering by the pinnae for sounds coming from the front versus from behind – e.g., see Stevens and Newman (1936), Hebrank & Wright, (1974), Zahorik et al. (2006). This "pinna cue" appears to rely on a pattern of spectral shape across auditory bands, as evidenced by the fact that NH listeners are less prone to front-back reversals as the bandwidth of high-frequency increases.

Figure 1 shows a simplified visual explanation of how listeners can resolve front-back confusions using head movements. When a stimulus has insufficient high frequency information (i.e. low-frequency stimuli or very narrow band high-frequency stimuli), NH listeners are prone to front-back confusions (see column A in the figure). However, they can then resolve front-back confusions by tracking the rate and direction of change in binaural cues, especially inter-aural time differences, as they turn their head and by comparing this to what they expect for a sound source behind or in front of them. Column B shows an example where a sound source is in front of the listener. In this case the sound source will present spatial auditory cues that move in the direction opposite to a listener's head turn. However, a sound source located behind the listener, as shown in column C of the figure, will present spatial auditory cues that move in the same direction as the listener's head turn. Even for high frequency stimuli, NH listeners can similarly track changes in inter-aural level differences (ILD) as they rotate their head to further reduce the incidence of front-back reversals. That listeners can use this information as a strategy to avoid front-back confusions is well documented for NH listeners. For further information on front-back reversals and the role of head movement in avoiding them, see Wallach, (1938, 1939, 1940); Burger (1958);

Makous and Middle brooks (1990); Perrett & Noble, (1997);Wightman & Kistler, (1999), Macpherson, (2011); Brimijoin, (2012).

It has been shown that listeners with hearing loss are far more prone to front-back confusions than are normal hearing listeners (Akeroyd & Whitmer, 2016; Vaillancourt, Laroche, Giguère, Beaulieu, & Legault, 2011; Van den Bogaert, Carette, & Wouters, 2011). While there is substantial inter-subject variability, the overwhelming trend is that wearing hearing aids offers little-to-no improvement in distinguishing front from back and can even make matters worse with hearing aids placed behind the ear (Best et al., 2010; Van den Bogaert et al., 2011). Furthermore, no significant improvement in front-back discrimination has been identified for bilaterally fitted hearing aids over unilateral fittings. The explanation for this generally relies on HI listeners' greater loss of hearing at the high frequencies NH listeners use to distinguish front from back under static conditions. This reduced sensitivity to high frequencies may be compounded by the placement of the mic behind the ear (Akeroyd & Whitmer, 2016), which could further minimize any front-back level differences at high frequencies. One might assume that listeners fitted with bilateral hearing aids could benefit from head movement in a manner similar to NH listeners, but it is not clear that this would be the case. Head movement may offer little help because the combination of reduced sensitivity to high frequencies, at which ILDs are sizeable, and automatic gain control (AGC) which distorts ILDs, results in a very weak, unreliable dynamic ILD cue. It may also be that hearing impaired (HI) listeners' auditory filter bandwidths are so wide at high frequencies that, regardless of the type of hearing aid in use, they may not be able to extract the spectral details necessary to make front-back distinctions.

Regardless of the explanation, one might assume that head rotations could resolve this problem, at least when HI listeners are wearing hearing aids. Brimijoin & Akeroyd (2017) tested this hypothesis and found that listeners with hearing loss were considerably less effective in using head turns to resolve front-back confusions than normal hearing listeners. Wearing hearing aids, regardless of whether they were uni- or bi- lateral, offered no improvement. In addition, including high frequency information in the stimulus offered no improvement in the outcome of the head rotation strategy. Brimijoin and Akeroyd therefore concluded that “hearing aids may not always reproduce dynamic self-motion-related cues with sufficient fidelity to allow reliable front/back discrimination.” Note that, on average, the listeners in Brimijoin and Akeroyd, (2017) had ~40 dB of low-frequency HI. Results for hearing aid listeners with normal low-frequency hearing and impaired high-frequency hearing may be different.

Cochlear implant (CI) patients appear to face challenges similar to those faced by HI listeners wearing hearing aids. CI listeners have limited access to the high-frequency pinna cues NH listeners use to distinguish front from back because, for most, the location of the implant microphone is on the head instead of at the concha, in the pinna. Even if the CI mic were placed in the ear canal, spectral resolution is limited for CI listeners due to the required wide spacing of implant electrodes along the basilar membrane and interactions between channels, resulting in fewer channels in the frequency allocation maps than would be represented in NH listeners' auditory bands. Compounding these limitations in spectral resolution, speech processing algorithms typically encode only frequencies between 0.1 and

8 kHz, reducing the range of frequencies available to the CI listener. Note that encoding 0.1 kHz is likely to be accurate for the subjects in this study, given that they largely use Med-El fine structure strategies, but not typical for CIs in general (other manufacturers, and even Med-El's HDCIS strategy default to above 150, and often 250 Hz). Such a limited frequency resolution may therefore render moot any pinna cues gained through mic placement. Given these challenges, we might expect CI patients to be especially prone to front-back confusions. The vast majority of localization studies for cochlear implants have been limited to the frontal hemifield and so there are only a few studies that have reported front-back confusions in cochlear implant users (e.g., Majdak, Goupell, & Laback, 2011, in virtual auditory space). While bilateral implantation has been shown to markedly improve spatial acuity (Grantham et al., 2007; Nopp, Schleich, & D'Haese, 2004; van Hoesel & Tyler, 2003), Senn, Kompis, Vischer, & Haeusler (2005) found no improvement in front-back discrimination over using a single implant.

Bilaterally implanted CI listeners generally show very poor ITD resolution and therefore localize sound sources almost entirely on the basis of ILDs (e.g., Grantham, 2007, 2008). CI patients usually demonstrate, on average, fairly poor spatial resolution, even with bilateral implantation (Dorman et al., 2014; Dorman, Loiselle, Cook, Yost, & Gifford, 2016; Grantham, Ashmead, Ricketts, Haynes, & Labadie, 2008; Grantham, Ashmead, Ricketts, Labadie, & Haynes, 2007; Seeber, Baumann, & Fastl, 2004). Given bilaterally implanted CI patients' compromised auditory spatial acuity relative to NH listeners, and the results reported by (Brimijoin & Akeroyd, 2017) for listeners wearing hearing aids, we might expect that bilateral CI patients are unlikely to profit from efforts to resolve front-back confusions using rotational head movements. However, that there are significant differences between the two groups; listeners using hearing aids are primarily stimulated in low-frequency pathways and will have best access to ITDs, though hearing aid processing may distort these as well, while CI users are primarily dependent on high frequency ILDs. While automatic gain control in CI processing does reduce ILD resolution (Grantham 2008), CI listeners may nevertheless be able to compare changes in ILDs to their own head movements to determine the front-back location of sound sources, in a process analogous to what NH listeners do with dynamic ITDs. We are unaware, however, of anything in the literature demonstrating that CI patients cannot use their own motion to improve their ability to resolve front-back confusions. In fact, there has been little research concerning the effects of head movement on CI patients' spatial hearing in general (though see presented research by Macpherson and colleagues, e.g. Birtch-Kaminskas and Macpherson (2013)).

If CI patients can make use of head movements to disambiguate and simplify their auditory scene, then current estimates based on static listening conditions may underestimate the effective auditory spatial acuity of CI patients under real-world conditions. Conversely, CI patients' decreased auditory spatial acuity may render information gained during their motion useless for resolving front-back confusions. In this case, we may overestimate the effective auditory spatial acuity of CI listeners in real-world, dynamic conditions. With these hypotheses in mind, we sought to estimate (1) how prevalent front-back confusions are among CI users, and (2) what assistance, if any, self-induced head movement might have in resolving these confusions.

Methods

Subjects

Seven listeners (5 females and 2 males between the ages of 44.9 and 75.3, mean = 61.9 years), all of who were bilaterally implanted with MED-EL cochlear implants, constituted the CI group. All listeners used their CIs as they normally were, with all settings as they were normally used in everyday life. All CI subjects were experienced bilateral CI users with at least one year of experience with two implants. The average time, across listeners, with two implants was 6.6 years. See Table 1 for characteristics of the individual CI patients and details of their devices and settings. Seven other subjects who reported normal hearing served as the normal hearing (NH) subject group. All procedures reported in this study were approved by the Arizona State University Institutional Review Board (IRB).

Stimuli

Gaussian noise bursts of 3-second duration were bandpass filtered to 2-8 kHz with a 3-pole, Butterworth filter implemented in Matlab and windowed with 20-ms cosine-squared onset and offset ramps. The resulting stimulus should give CI listeners favorable conditions to localize sound sources as well as they can because ILDs, the primary localization cue for CI listeners, are greatest at high frequencies as a result of head shadowing. This should offer CI listeners their best chances of using dynamic binaural difference cues during head movement. This stimulus also offers a high frequency pinna cue that is more than sufficient for NH listeners, and has the best chances of being useful, if at all, to stationary CI listeners if they could exploit some version of the “pinna cue.” CI listeners' localization acuity is usually quite poor at low frequencies as a result of their poor sensitivity to ITD cues and the small magnitude of ILD cues, and so low-pass filtered stimuli were not tested for front-back confusions. All sounds were presented at 60 dBA as measured at the center of the room where the listener's head would be.

Some experiments testing for front-back confusions rove the level of the stimulus so that listeners cannot learn the spectral contour of the stimulus and use a simple level difference at high frequencies to distinguish front from back. The aim of this experiment was to determine listeners' “best performance” and give them the best possible chances of using a “pinna cue” if it was indeed available to them. For these reasons, the level of the stimulus was the same for all presentations.

Test environment for localization

The Spatial Hearing Laboratory, used in Yost et al., (2015), was used for this group of experiments. The room measures 10' × 15' × 10', with all six surfaces covered by 4" thick acoustic foam. The broadband reverberation time (RT_{60}) is 102 ms. Twenty-four loudspeakers (Boston Acoustics 100×, Peabody, MA) are spaced equidistant from each other on a five-foot radius circle (i.e., azimuth array with 15° loudspeaker spacing) at approximately the same height as listeners' pinnae. Stimuli were presented from every fourth loudspeaker, resulting in a spacing of 60° between possible sound source positions. The average RMS error of localization for CI listeners, using all 24 loudspeakers spaced 15° apart, has been measured at ~29° in the frontal hemifield -- in contrast to ~6° for NH

listeners in the same setup (Dorman et al., 2016). The 60° spacing between the utilized loudspeakers was chosen to simplify the task of distinguishing front-back confusions from other localization errors. Those loudspeakers presenting stimuli were clearly labeled 1-6, as shown in Figure 2. An intercom and camera enabled the experimenter to monitor and communicate with the listener from a remote control room. The experimenter monitored the listener's head position via a webcam from the adjacent control room. Listeners entered their response on a number keypad. All sounds were presented via a 24-channel Digital-to-Analog (DA) converter (two Echo Gina 12 DAs, Santa Barbara, CA) at a rate of 44,100 samples/sec/channel.

Procedure

Listeners sat in a stationary chair, facing toward the loudspeaker directly in front of them at 0 degrees. For the stationary condition, listeners were asked to keep their head fixed, facing loudspeaker 1 (see Fig 2), focused on a red dot on loudspeaker 1. For the head movement condition, listeners were asked to make whatever rotational head movements they wished, between approximately $\pm 30^\circ$ (the corresponding loudspeakers were marked so listeners could have a visual estimate) in order to aid them in localizing the sound source. Listeners were asked to keep their movements relatively slow and continuous, as opposed to simply moving to one position and comparing it to another. Continuous observation, via webcam, confirmed that all listeners' head movements took the form of a “sweep” between a maximum of $\pm 30^\circ$. The 3-second stimulus duration afforded listeners ample time to rotate their head several times. For both conditions, listeners were not naïve to the purpose of the experiment, but were rather encouraged to do their best to distinguish the location of sounds located in front of them from those located behind them.

Upon presentation of a noise stimulus, listeners were asked to indicate which of the 6 labeled loudspeakers corresponded best with the sound source location they perceived. For both the stationary and head movement conditions, the stimulus was presented randomly from the 6 loudspeaker locations for a total of 12 times at each location.

Results

NH Listeners

Figure 3 shows the results, pooled across all 7 NH listeners, for the stationary (left panel) and head movement (right panel) conditions. Listeners' responses are presented in a confusion matrix, with the loudspeakers from which stimuli were presented indicated along the horizontal axis and the reported perceived location, also in terms of the same loudspeakers, along the vertical axis. In order for correct responses and front-back reversals to be represented along the positive and negative diagonals, and thereby be easy to recognize, the loudspeaker order along the two axes is . Blue circles, along the positive diagonal, represent correct responses, while front-back reversed responses lie on the negative diagonal and are indicated in red. The remaining erroneous responses are shown as empty black circles. The relative frequency of each combination of presented and reported loudspeaker location is indicated with the size of the circles.

As expected, most NH listeners in the stationary condition (left panel) exhibited only occasional front-back confusions. Calculated across all listeners and loudspeakers, NH listeners were correct 94.8% of the time. Only 4.6 % of responses were front-back confusions, with the remaining 0.6% being lateral errors. Five out of seven of the NH listeners showed at least one reversal, but the majority of reversals came from one listener, who showed an average rate of 22.23% reversals without head movement, which was then reduced to 1.38% with head movement. The average rate of reversals across the other 6 NH listeners, without head movement, was 1.62%. None of these 6 listeners made any reversals when head movement was allowed.

Consistent with previous studies of front-back reversals in NH listeners, the wideband, high frequency content of the stimulus appears to have been sufficient for listeners to exploit “pinna cues” to distinguish between stimuli presented from the front and the rear. When listeners were asked to utilize their own head movements (right panel), the few front-back confusions they had made were eliminated and their performance was near perfect (99.8% correct, 0.2% front-back confusions).

CI Listeners using both implants

Figure 4 presents results for the 7 tested CI patients, all of whom were bilaterally implanted. The figure is otherwise read the same as Fig. 3. In the left panel, where listeners kept their head stationary, a strong pattern of front-back confusions is readily apparent. Calculated across all listeners and loudspeakers, CI patients correctly indicated the speaker that presented the sound stimulus 49.4 percent of the time (SD 17.8%). A large portion, 41.9% (SD 18.7%), of these listeners' responses were classified as front-back confusions. When these same patients were encouraged to rotate their head during playback of the stimulus, their percent correct increased to 81.7% (SD 16.7%). Front-back reversals decreased to only 6.7% (SD 6.4) of responses when head rotation was allowed.

CI listeners demonstrated a considerable bias toward localizing sounds to the front. The majority of reversals were for back-to-front reversals (see Fig. 4, both panels, lower right quadrant) versus reversals for stimuli presented from the front (see Fig. 4, both panels, upper left quadrant). When listeners kept their head stationary, an average of 63.6% (SD 9.5%) of listeners' reversals were back-to-front reversals. When listeners were allowed to make head rotations, an average of 91.1% of their reversals (SD 13.1%) were back-to-front.

Figure 5 shows the performance of each patient as a function of the change in performance brought about, presumably, by allowing them to rotate their head as they attempted to localize the sound stimulus. This metric is calculated as the average percentage of the measure in question (e.g., correct responses, front-back reversals, localization errors that were not attributable to front-back reversals) for the condition where listeners could move their head minus that same measure for the condition where listeners could not move their head.

Inspection of Fig. 5 yields two clear trends. First, all CI patients showed a marked increase in the number of correct responses when they were allowed to rotate their head during presentation of the sound stimulus. Second, all patients showed a similar decrease in the

incidence of front-back reversals. While the magnitude of this effect varies between listeners, no listener failed to improve with head turns. There is no clear trend for the effect of head motion on the incidence of localization errors that could not be attributed to front-back confusions. That is, some listeners show an increase and others show a decrease (in these non-front-back confusions) errors, and there appears to be no clear predictor for this outcome in either the percent correct or the percentage of front-back confusions.

A two-way repeated-measures analysis of variance confirmed that the main effects for head rotation [$F(1,6)=71.02$, $p<0.05$] and for presentation from the front versus presentation from behind the listener [$F(1,6)=10.26$, $p<0.05$] were statistically significant. There was no statistically significant interaction between head movement and presentation from front versus back. Also, differences between listeners were not a significant main effect ($F(1,6)=0.45$, $p=0.827$). A rationalized arcsine transformation (RAU) of the data, to account for the non-Gaussian distribution of a bounded range of possible percent correct (from 0% - 100%), yielded no qualitative change to the outcome of the ANOVA (e.g. p-values remained essentially the same).

Given that all CI subjects showed the same trends, and with only 7 subjects, there is not enough variation to investigate subtle differences in sound source localization performance as a function of individual differences in CI subjects' hearing and use of their CIs, no attempt is made to correlate individual performance with subject etiology.

CI Listeners using only one implant

A possible explanation for the results shown in Figures 4 and 5 is that CI patients relied not on interaural difference cues (presumably ILDs, e.g. Grantham et al., 2007) but rather on some monaural loudness cue. The hypothesis here would be that as a listener rotated his or her head the stimulus would be more or less intense at each ear as a result of head shadowing, and that a listener could attend to just one ear and distinguish front from back based on this intensity change in that single ear. This hypothesis was tested by asking patients to turn off the implant at what they judged to be their 'worse' ear. The same testing procedure was then run again. Figure 6 shows the results of this experiment. It is clear that using one implant has an impact on localization acuity in general: the ability to localize is reduced to the extent that it is not feasible to partition front-back reversals from other errors of localization. The change in localization acuity introduced by head rotation, from 20.8% correct without head movements to 22.2% correct with head movements, was not significant in a paired t-test, ($p = 0.688$). For all but one listener, localization responses were heavily biased toward the side of the working cochlear implant. Head movement did little to change this. One listener showed a small reduction in front-back confusions for stimuli presented from the front, although, again, partitioning front-back errors from other errors is problematic considering the generally poor localization acuity all listeners showed with only one implant turned on.

Discussion

While a great many studies have probed the localization abilities of CI users under conditions where listener and sound source are stationary, only a few have considered how

these measured outcomes might translate to everyday, dynamic sound environments. Perhaps one reason for this is that dynamic conditions are far more complex and that controlled conditions with clear outcomes are not easily designed. The measurement of front-back confusions offers an unambiguous, binary outcome to investigate the ability of bilaterally-implanted CI users to process dynamic auditory spatial cues resulting from these listeners' own movements.

The results of the present study firstly demonstrate that, under static conditions, listeners fitted with bilateral cochlear implants are vulnerable to front-back confusions at a rate that far exceeds NH listeners for the same stimuli. This outcome is consistent with reports by Senn, Kompis, Vischer, & Haeusler (2005) and the observations of Majdak, Goupell, & Laback, (2011). The high rate of front-back confusions suggests that, at least for stationary CI listeners, the auditory scene may be even more complex and confused, in the sense that perceived sound source locations may not be reliably useful for auditory stream segregation and spatial release from masking, than previous reports of CI patients' auditory spatial acuity would suggest.

For the listeners tested in this study, head movements resulted in a considerable reduction in front-back confusions. It should be noted that these results may be quite different under the reverberant, noisy, acoustically complex scenarios encountered routinely in everyday real-world settings. It should also be noted that such real-world complexities are also likely to impact the performance of NH listeners as well.

The decrease in front-back reversals with head movements for CI listeners reported here is in direct contrast to outcomes for listeners wearing hearing aids - e.g., Brimijoin & Akeroyd (2017), suggesting that dynamic auditory spatial cues are preserved in the processing of the CI devices we tested to such a degree that the cues, presumably high frequency ILDs, remain useful during head movement. It is possible that these different outcomes might arise because many hearing aid listeners present with high frequency hearing loss, and this decreases their sensitivity to ILDs. Hearing aid listeners' ILD insensitivity may be further compounded by the heavy automatic gain control (AGC) that is common in many hearing aids. CI listeners may also avoid some of this problem by virtue of the fact that CIs primarily stimulate areas of the basal cochlea that are receptive to high frequencies.

The placement of the cochlear implant's mic may make a difference in a non-moving CI listeners' ability to distinguish sound sources coming from the front versus the back. While all of the listeners used MED-EL devices with behind-the-ear placement of the microphone, Advanced Bionics' t-mic is placed at the entrance to the ear canal, and may offer listeners more useable "pinnae cues," thereby potentially reducing the incidence of front-back reversals for stimuli with sufficient high-frequency content, without the need for head movement. However, most cochlear implants' relatively poor spectral resolution may limit the functional gains such mic placement could offer. Future studies could focus on potential effects of mic placement of devices made by other manufacturers.

The stimulus duration was fairly long (3 ms) and stimulus level was not roved from presentation to presentation. Roving the level of the stimulus could have resulted in some

increase in front-back reversals for the no head movement condition, but this would have made the head movement condition essentially different, in that the listener would have plenty of time to make multiple comparisons of the stimulus during head movement, making it essentially a “no level change” condition. Our aim was to see the best listeners could do when their head was not moving. If they could possibly use a high-frequency ‘pinnacue,’ we wanted to give them the chance to use it so that we could detect this in their performance. It could well have been that, with no level change from stimulus to stimulus, they would have been able to use whatever ‘pinna cue’ they had. Roving the stimulus intensity would have effectively removed such a cue (e.g., see Stevens and Newman, 1936) and so we would have reduced our chances of detecting CI listeners' ability to use such a cue if they had the ability. The results strongly suggest no such cue was available to the CI listeners, but was rather robust for NH listeners.

Macpherson, (2013) found dynamic ITDs to be the more robust dynamic spatial auditory cue for normal hearing listeners. As mentioned in the introduction, CI listeners have essentially no useful sensitivity to ITD cues. For the CI listeners we tested, dynamic ILDs appear to provide robust information for the resolution of front-back confusions despite what is likely to be a reduced ILD resolution. For NH listeners, high frequency stimuli offer spectral cues caused by interference with the pinnae. These spectral pinna cues, when present in the stimulus, are a robust cue for distinguishing front from back so much so that they dominate dynamic interaural difference cues (e.g., Brimijoin & Akeroyd, 2012; Macpherson, 2011) in NH listeners. If exploitation of this cue is a learned behavior, the simple, acute removal of these spectral cues, as in Macpherson, (2013), might not be expected to result in a strongly-used dynamic high-frequency ILD cue, at least in the short term. The bilaterally-implanted CI listeners tested in our study, on the other hand, demonstrate that dynamic ILDs, coupled with head motion, are a fairly robust cue for resolution of front from back. This appears to suggest that, since these CI listeners generally do not have access to a reliable (static or dynamic) ITD cue, they develop an ability to track and exploit dynamic ILD cues that NH listeners may disregard. Note again, that applying this reasoning to the performance of hearing impaired listeners wearing hearing aides is not straightforward, as the two groups are likely to listen differently based on the relative degree of auditory information available to them (e.g., see Noble et al. (1998)).

It is not clear whether listeners CI and/or NH, track dynamic spatial auditory cues continuously or in a series of “snapshots” – see Grantham (1997) and Carlisle (2016) for reviews of these concepts. Furthermore, it is also unclear whether such analysis of changes in spatial auditory cues is different depending on whether the change comes as a result of sound source movement or head movement. As such, the behavior reported in this study may result from comparison of head movements with a series of static samples (“snapshots”) of auditory spatial cues during the head movement or a comparison of some more “continuous” form of auditory motion estimates with the listener's head movement.

Compared with NH listeners, the reduced auditory spatial acuity demonstrated by most bilaterally implanted CI listeners likely results in a decreased ability to leverage spatial cues to simplify and analyze complex auditory scenes (e.g., spatial release from masking, but see Loizou et al. 2009 and Litovsky et al. 2009). An inability to resolve the front-back

dimension of the sound field could considerably increase the complexity of analyzing auditory scenes when location of the sound source is a useful cue. It is therefore likely that the resolution of front-back confusions via head movements, and the ability to track dynamic spatial cues that is implied by this behavior, is of considerable value and utility for these CI listeners. Indeed, it is likely that the ability to localize sound sources in front and in back plays a role in the improved quality of life reported by patients fit with bilateral CIs (Bichey & Miyamoto, 2008).

References

- Akeroyd MA, Whitmer WM. Spatial hearing and hearing aids. In: Popelka G, Moore BCJ, Fay R, Popper A, editors *Hearing Aids*. Springer International; 2016. 181–215. SHAR 56
- Best V, Kalluri S, McLachlan S, Valentine S, Edwards B, Carlile S. A comparison of CIC and BTE hearing aids for three-dimensional localization of speech. *International Journal of Audiology*. 2010; 49(10):723–32. <http://doi.org/10.3109/14992027.2010.484827> [PubMed: 20515424]
- Bichey BG, Miyamoto RT. Outcomes in bilateral cochlear implantation. *Otolaryngology - Head and Neck Surgery*. 2008; 138(5):655–661. <http://doi.org/10.1016/j.otohns.2007.12.020> [PubMed: 18439474]
- Birtch-Kaminskas KAH, Macpherson EA. Head Movement Benefit for Sound Localization in Simulations of Cochlear Implant and Electroacoustic Stimulation Paired With Contralateral Hearing Aid, Cochlear Implant, or Electroacoustic Stimulation; Conference on Implantable Auditory Prostheses; 2013; Lake Tahoe, California. 2013.
- Brimijoin WO, Akeroyd MA. The role of head movements and signal spectrum in an auditory front/back illusion. *I-Perception*. 2012; 3(3):179–181. <http://doi.org/10.1068/i7173sas> [PubMed: 23145279]
- Brimijoin WO, Akeroyd MA. The effects of hearing impairment, age, and hearing aids on the use of self motion for determining front/back location. *J Am Acad Audiol*. 2017; 27(7):588–600. <http://doi.org/10.3766/jaaa.15101>
- Burger JF. Front-back discrimination of the hearing system. *Acustica*. 1958; 8:301–302.
- Carlisle S, Leung J. The perception of auditory motion. *Trends Hear*. 2016; 20:1–19. <http://tia.sagepub.com/cgi/doi/10.1177/2331216516644254>.
- Dorman MF, Loiselle LH, Cook SJ, Yost WA, Gifford RH. Sound source localization by normal hearing listeners, hearing-impaired listeners and cochlear implant listeners. *Audio and Neuro*. 2016; 21:127–131.
- Dorman MF, Loiselle LH, Stohl J, Yost WA, Spahr AJ, Brown CA, Cook SJ. Interaural level differences and sound source localization for bilateral cochlear implant patients. *Ear Hear*. 2014; 35(6):633–640. <http://doi.org/10.1097/AUD.0000000000000057> [PubMed: 25127322]
- Grantham W. *Binaural and Spatial Hearing in Real and Virtual Environments*. New York: Erlbaum; 1997. 295–313.
- Grantham DW, Ashmead DH, Ricketts TA, Haynes DS, Labadie RF. Interaural Time and Level Difference Thresholds for Acoustically Presented Signals in Post-Lingually Deafened Adults Fitted with Bilateral Cochlear Implants Using CIS+ Processing. *Ear Hear PAP*. 2008; 1:33–44. <http://doi.org/10.1097/AUD.0b013e31815d636f>
- Grantham DW, Ashmead DH, Ricketts TA, Labadie RF, Haynes DS. Horizontal-Plane Localization of Noise and Speech Signals by Postlingually Deafened Adults Fitted With Bilateral Cochlear Implants. *Ear Hear*. 2007; 28(4):524–541. <http://doi.org/10.1097/AUD.0b013e31806dc21a> [PubMed: 17609614]
- Hebrank J, Wright D. Spectral cues used in the localization of sound sources on the median plane. *J Acoust Soc Am*. 1974; 56(6):1829–1834. <http://doi.org/10.1121/1.1903520> [PubMed: 4443482]
- Litovsky RY, Parkinson A, Arcaroli J. Spatial hearing and speech intelligibility in bilateral cochlear implant users. *Ear Hear*. 2009; 30(4):419–431. <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2873678/>. [PubMed: 19455039]

- Loizou PC, Hu Y, Litovsky R, Yu G, Peters R, Lake J. Speech recognition by bilateral cochlear implant users in a cocktail-party setting. *J Acoust Soc Am*. 2009; 125(1):372–383. <http://asa.scitation.org/doi/10.1121/1.3036175>. [PubMed: 19173424]
- Macpherson EA. Head motion, spectral cues, and Wallach's 'principle of least displacement' in sound localization. In: Suzuki Y, Brungart D, Kato H, editors *Principles and Applications of Spatial Hearing*. World Scientific; 2011. 103–120.
- Majdak P, Goupell MJ, Laback B. Two-dimensional localization of virtual sound sources in cochlear-implant listeners. *Ear Hear*. 2011; 32(2):198–208. <http://doi.org/10.1097/AUD.0b013e3181f4dfe9> [PubMed: 21052005]
- Makous J, Middlebrooks J. Two-dimensional sound localization by human listeners. *J Acoust Soc Am*. 1990; 87(5):2188–2200. <http://asa.scitation.org/doi/10.1121/1.399186>. [PubMed: 2348023]
- Noble W, Sinclair S, Byrne D. Improvement in aided sound localization with open earmolds: observations in people with high-frequency hearing loss. *J Am Acad Aud*. 1998:25–34.
- Nopp P, Schleich P, D'Haese P. Sound Localization in Bilateral Users of MED-EL COMBI 40/40+ Cochlear Implants. *Ear Hear*. 2004; 25(3):205–214. <http://doi.org/10.1097/01.AUD.0000130793.20444.50> [PubMed: 15179112]
- Perrett S, Noble W. The contribution of head motion cues to localization of low-pass noise. *Percept Psychophys*. 1997; 59(7):1018–1026. <http://doi.org/10.3758/BF03205517> [PubMed: 9360475]
- Roland P, Macpherson EA. Cue weighting and vestibular mediation of temporal dynamics in sound localization via head rotation. *J Acoust Soc Am*. 2013 May. 133:3459. <http://doi.org/http://dx.doi.org/10.1121/1.4806153>
- Seeber BU, Baumann U, Fastl H. Localization ability with bimodal hearing aids and bilateral cochlear implants. *J Acoust Soc Am*. 2004; 116(3):1698. <http://doi.org/10.1121/1.1776192> [PubMed: 15478437]
- Senn P, Kompis M, Vischer M, Haeusler R. Minimum audible angle, just noticeable interaural differences and speech intelligibility with bilateral cochlear implants using clinical speech processors. *Audiol Neurotol*. 2005; 10:342–352.
- Stevens S, Newman E. The localization of actual sources of sound. *Am J Psychol*. 1936; 48(2):297–306.
- Vaillancourt V, Laroche C, Giguère C, Beaulieu MA, Legault JP. Evaluation of auditory functions for Royal mounted police officers. *Journal of the American Academy of Audiology*. 2011; 22(6):313–331. [PubMed: 21864470]
- Van den Bogaert T, Carette E, Wouters J. Sound source localization using hearing aids with microphones placed behind-the-ear, in-the-canal, and in-the-pinna. *International Journal of Audiology*. 2011; 50(3):164–176. <http://doi.org/10.3109/14992027.2010.537376> [PubMed: 21208034]
- van Hoesel RJM, Tyler RS. Speech perception, localization, and lateralization with bilateral cochlear implants. *J Acoust Soc Am*. 2003; 113(3):1617–1630. <http://doi.org/10.1121/1.1539520> [PubMed: 12656396]
- Wallach H. Über die Wahrnehmung der Sehallrichtung. *Psychol Forsch*. 1938; 22(3–4):238–266.
- Wallach H. On sound localization. *J Acoust Soc Am*. 1939; 10(4):270–274.
- Wallach H. The role of head movements and vestibular and visual cues in sound localization. *J Exp Psychol*. 1940; 27(4):339–368.
- Wightman FL, Kistler DJ. Resolution of front-back ambiguity in spatial hearing by listener and source movement. *J Acoust Soc Am*. 1999; 105(5):2841–53. <http://doi.org/10.1121/1.426899> [PubMed: 10335634]
- Yost WA, Zhong X, Najam A. Judging sound rotation when listeners and sounds rotate: Sound source localization is a multisystem process. *J Acoust Soc Am*. 2015; 138(5):3293–3310. <http://doi.org/10.1121/1.4920001> [PubMed: 26627802]
- Zahorik P, Bangayan P, Sundareswaran V, Wang K, Tam C. Perceptual recalibration in human sound localization: Learning to remediate front-back reversals. *J Acoust Soc Am*. 2006; 120(1):343–359. <http://doi.org/10.1121/1.2208429> [PubMed: 16875231]

Figure 1.

Conceptual illustration of the front-back confusions and their resolution with head movements. (A) binaural difference cues are the same for stimuli in front and behind the listener (B) if the listener turns the head to the right, binaural difference cues will migrate towards the left if the sound source is stationary in front of the listener and (C) to the right if the sound source is behind the listener.

Figure 2.

Schematic illustration of the experimental apparatus. Stimuli were presented from loudspeakers spaced 60° apart. In previous experiments where all 24 loudspeakers were used, (for a separation of 15°) the root-mean-squared (RMS) localization error in the frontal hemifield for normal hearing listeners was approximately 6° . RMS error for cochlear implant listeners in the same set-up was approximately 29° .

Figure 3.

Localization measured as loudspeaker identification for 7 normal hearing listeners. Stimuli were 3-s duration, bandpass-filtered Gaussian noise (2 kHz - 8 kHz). The radius of each bubble is proportional to the total number of responses, pooled across listeners. Correct responses are plotted along the positively-sloped diagonal in blue. Reversals are plotted along the negatively-sloped diagonal in red.

Figure 4.
Localization measured as loudspeaker identification for 7 bilaterally implanted listeners.
Otherwise same as Fig. 3.

Figure 5.

Summary of the change in performance due to head movements for each of the 7 CI patients calculated as performance with head movements minus performance without head movements. After head movements, all listeners showed an increase in correct localization (blue) and a decrease in front-back reversals (red). Head movement produced no clear trend across listeners for other errors.

Figure 6.

Localization measured as loudspeaker identification for 7 patients bilaterally implanted with MED-EL cochlear implants, with the implant at the worse ear turned off. Otherwise same as Fig. 2.

Table 1

Subject demographics. All listeners are bilaterally implanted

Subject	Brand of CI	AGC	Processor Model (everyday/ tested)	Processing Strategy	AZBio Quiet Score	Age	Duration deafness Left Ear (years)	Duration deafness Right Ear (years)	Duration CI Use Left Ear (years)	Duration CI Use Right Ear (years)
1924	MED-EL	Compression Ratio 3:1; 75%default sensitivity	Sonnet/Sonnet	FS4	71.2%	75.3	9.7	26.2	17.6	1.0
2349	MED-EL	Compression Ratio 2.5:1; 75%default sensitivity	Sonnet/Sonnet	FSP	93.7%	55.7	1.2	1.0	2.8	2.2
815	MED-EL	Compression Ratio 3:1; 75%default sensitivity	Sonnet/Sonnet	FS4	94.0%	58.7	2.7	2.7	13.6	13.6
1596	MED-EL	Compression Ratio 3:1; 50%default sensitivity	Opus 2/Sonnet	HDCIS	89.5%	44.9	12.0	18.2	11.3	4.3
1657	MED-EL	Compression Ratio 3:1; 70%default sensitivity	Sonnet/Sonnet	FS4-P	81.9%	71.5	7.3	7.4	6.0	6.0
709	MED-EL	Compression Ratio 3:1; 75%default sensitivity	Opus 2/Sonnet	FS4	94.9%	55.7	5.9	5.9	14.8	14.8
2457	MED-EL	Compression Ratio 3:1; 75%default sensitivity	Opus 2/Sonnet	FSP	94.8%	54.3	0.2	3.7	4.7	4.4