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Research Article

# Using ILD or ITD Cues for Sound Source Localization and Speech Understanding in a Complex Listening Environment by Listeners With Bilateral and With Hearing-Preservation Cochlear Implants

Louise H. Loiselle,[a] Michael F. Dorman,[a] William A. Yost,[a]
Sarah J. Cook,[a] and Rene H. Gifford[b]

**Purpose:** To assess the role of interaural time differences and interaural level differences in (a) sound-source localization, and (b) speech understanding in a cocktail party listening environment for listeners with bilateral cochlear implants (CIs) and for listeners with hearing-preservation CIs.
**Methods:** Eleven bilateral listeners with MED-EL (Durham, NC) CIs and 8 listeners with hearing-preservation CIs with symmetrical low frequency, acoustic hearing using the MED-EL or Cochlear device were evaluated using 2 tests designed to task binaural hearing, localization, and a simulated cocktail party. Access to interaural cues for localization was constrained by the use of low-pass, high-pass, and wideband noise stimuli.
**Results:** Sound-source localization accuracy for listeners with bilateral CIs in response to the high-pass noise stimulus and sound-source localization accuracy for the listeners with hearing-preservation CIs in response to the low-pass noise stimulus did not differ significantly. Speech understanding in a cocktail party listening environment improved for all listeners when interaural cues, either interaural time difference or interaural level difference, were available.
**Conclusions:** The findings of the current study indicate that similar degrees of benefit to sound-source localization and speech understanding in complex listening environments are possible with 2 very different rehabilitation strategies: the provision of bilateral CIs and the preservation of hearing.

The information embodied in interaural time differences (ITDs) and interaural level differences (ILDs) (a) allows listeners with normal hearing (NH) to locate sound sources on the horizontal plane, and (b) has a significant role in generating high levels of speech recognition in complex listening environments, for example, at a cocktail party (e.g., Blauert, 1997; Cherry, 1953; Hirsh, 1948, 1950; Koenig, 1950; Licklider, 1948; Stevens & Newman, 1936; Yost, Dye, & Sheft, 1996). ILDs are dominant for signals with frequencies above 1500 Hz, and ITDs are dominant for frequencies below 1000 Hz (e.g., Blauert, 1997; Stevens & Newman, 1936). Previous studies have focused largely on the use of ITD information to separate speech from background noise. There is little information about whether ILD cues provide this same benefit (see Kidd, Mason, Best, & Marrone, 2010).

Two groups of listeners fit with cochlear implants (CIs) could have access to ITDs or ILDs and could enjoy the benefits of having these two sources of auditory information about the sound environment. One group comprises listeners with bilateral CIs. These listeners have access to ILDs but very little access to ITDs and are able to locate sound sources (Grantham, Ashmead, Rickets, Haynes, & Labadie, 2008; Grantham, Ashmead, Ricketts, Labadie, & Haynes, 2007; Schoen, Mueller, Helms, & Nopp, 2005; van Hoesel & Tyler 2003; Wilson, Lawson, Muller, Tyler, & Kiefer, 2003). However, accuracy, on average, is poorer than normal (e.g., Dorman et al., 2014; Grantham et al., 2007).

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[a]Arizona State University, Tempe, AZ
[b]Vanderbilt University, Nashville, TN
Correspondence to Louise H. Loiselle: lhloiselle@gmail.com

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There is no doubt that listeners with bilateral CIs can use ILD cues for sound-source localization (see references above). Of interest is whether some patients have access to ITD cues. Aronoff et al. (2010) used head-related transfer functions to manipulate ITD and ILD cues. All listeners showed better localization performance using ILD cues than they did using ITD cues. Only two of the six listeners had better-than-chance performance using ITD cues. Kerber and Seeber (2013) used direct streaming of the stimulus to pitch-matched electrodes on a localization task. All seven subjects lateralized using ILD cues. Lateralization performance using envelope ITD cues varied. Two of the seven had "ITD discriminability" under 700 µs, the other five listeners had ITD discriminability outside the range considered physiologically useful (for studies using pitch-matched electrode pairs see also Laback, Pok, Baumgartner, Deutsch, & Schmid, 2004; van Hoesel & Tyler, 2003). Because ITD discriminability is poor even with pitch-matched electrodes and laboratory processors controlling stimulus presentation, it is very unlikely that ITDs have a role in sound-source localization in an open field (i.e., the condition used in this article) by patients fit with independent signal processors on the two ears and having electrodes inserted to different depths in the two ears (see also Grantham et al., 2007).

A second group comprises listeners with CIs who have undergone hearing-preservation surgery. For these listeners, successful preservation of low-frequency hearing in the operated ear, in conjunction with low-frequency hearing in the contralateral ear, allows access to ITD cues but minimal access to ILD cues (Gifford, Dorman, Sheffield, Teece, & Olund, 2014; Gifford, Grantham, et al., 2014). Listeners with hearing-preservation CIs, similar to listeners with bilateral CIs, are able to locate sound sources and have poorer than normal-localization accuracy (Dunn, Perreau, Gantz, & Tyler, 2010; Loiselle, Dorman, Yost, & Gifford, 2015).

In Experiment 1, we reexamined sound-source localization by listeners with bilateral CIs and hearing-preservation CIs. Results from previous studies suggest that listeners with bilateral CIs and hearing-preservation CIs achieve similar levels of sound source localization despite having access to very different cues for location—that is, ILDs for listeners with bilateral CIs and ITDs for listeners with hearing-preservation CIs. However, the previous studies used different test environments (e.g., they used a different number of loudspeakers and used different stimuli when testing the two groups of patients). For that reason, it is very difficult to (a) compare the results for the two groups, and (b) compare the CI results with results for normal-hearing listeners. We remediate this problem by testing listeners with NH, with bilateral CI, and with hearing-preservation CIs in the same test environment and by using high-pass (HP), low-pass (LP), and wideband (WB) noise stimuli that constrain access to ITD and ILD cues.

In Experiment 2, we examined speech recognition in a cocktail party environment for the listeners in Experiment 1. In our simulation of a cocktail party, spatial separation of the target and maskers was always maintained. Female-voice target sentences were presented from a loudspeaker at 0°, whereas sentences from two different male talkers were presented from loudspeakers at ±90°.

A critical aspect of this experiment was the use of maskers presented to both ears. In this environment, the effect of the head shadow was minimized. This is relevant because, of the three binaural phenomena (head shadow, squelch, and summation), the head shadow produces the largest benefit for listeners with bilateral CIs (Chan, Freed, Vermiglio, & Soli, 2008; Laszig et al., 2004; Litovsky, 2012; Loizou et al., 2009; Muller, Schon, & Helms, 2004; Schleich, Nopp, & D'Haese, 2004). By minimizing the head shadow, the benefits of summation and squelch can be better viewed. Loizou et al. (2009) used the term *binaural advantage* to describe the combined effects of summation and squelch. We will do the same in this article. Neural computations underlying the binaural advantage are presumably central and involve the processing of interaural time and/or level differences.

At issue is the magnitude of the improvement in performance for conditions in which the listeners with CIs have access to binaural cues—that is, ILD or ITD information, versus those conditions for which they do not have access to that information. Thus, we compared listening with two ears versus with one ear for listeners with NH and those with bilateral CIs. For the listeners with hearing-preservation CIs, we compared speech understanding when listening with a CI and contralateral low-frequency acoustic hearing—that is, the bimodal condition versus listening in the combined condition—that is, CI plus bilateral low-frequency acoustic hearing. Our rationale for Experiment 2 was identical to that for Experiment 1: The two patient groups have access to different sources of information about sound sources—that is, ILDs for listeners with bilateral CI and with ITDs for hearing preservation. Do these differences in the source of information engender differences in performance; in this case, speech understanding in a complex sound environment with spatially separated speech and noise sources?

## Experiment 1: Sound Source Localization

### *Method*

#### Subjects

Two groups of listeners with CIs were tested. One group was composed of 11 postlingually deafened adults with bilateral CIs and a mean age of 57 years. All listeners used MED-EL (Innsbruck, Austria) Opus 2 processors, which implemented the fine-structure processing (FSP) coding strategy. Demographics for these listeners are shown in Table 1. A second group was composed of eight adults who had undergone hearing-preservation surgery during cochlear implantation (mean age = 57 years). Following surgery, these listeners had similar and symmetrical, low-frequency, acoustic thresholds in both ears—with differences no greater than 15 dB between ears at 250 Hz (see Figure 1). Five of the listeners used the MED-EL device, and three used the Cochlear device. Demographics for the listeners with hearing-preservation CIs are listed in Table 2. In a

**Table 1.** Demographic information for 11 listeners with bilateral MED-EL fine-structure processing.

| Subject | Age (y) | Gender | Age HL onset (y) | Etiology | CI use RE/LE (y) | Device RE/LE | No. active channels of 12 RE/LE | Frequency allocation (Hz) |
|---|---|---|---|---|---|---|---|---|
| S1 | 79 | M | 19 | Hereditary | 1 | Sonata S | 9/10 | 70–8500 |
| S2 | 53 | F | 20 | Unknown | 8 | Combi40+ | 9/10 | 70–7500 |
| S3 | 59 | M | 25 | Head trauma | 1/2 | Sonata S | 11/10 | 70–8500 |
| S4 | 77 | F | 20 | Unknown | 6/2 | Combi40+/Sonata S | 12/12 | 100–8500 |
| S5 | 65 | F | 30 | Unknown | 7/1 | Combi40+/Sonata S | 9/9 | 70–8500 |
| S6 | 43 | M | 42 | Head trauma | 0.6/0.5 | Sonata | 12/12 | 70–8500 |
| S7 | 50 | F | 3 | Hereditary/progressive | 5/8 | Pulsar/Combi 40+ | 12/11 | 70–7000 |
| S8 | 66 | M | 38 | Unknown | 0.8/0.7 | Sonata S | 11/11 | 70–8500 |
| S9 | 60 | M | 38 | Unknown | 2.5/2 | Sonata S | 7/10 | 70–8500 |
| S10 | 32 | F | 14 | Viral infection | 2/2 | Sonata Med. | 9/10 | 100–5500 |
| S11 | 41 | M | 37 | Bacterial infection | 2 | Sonata S | 8/9 | 70–8500 |

*Note.* HL = hearing loss; CI = cochlear implant; RE = right ear; LE = left ear; M = male, F = female; Med. = medium; S = Standard.

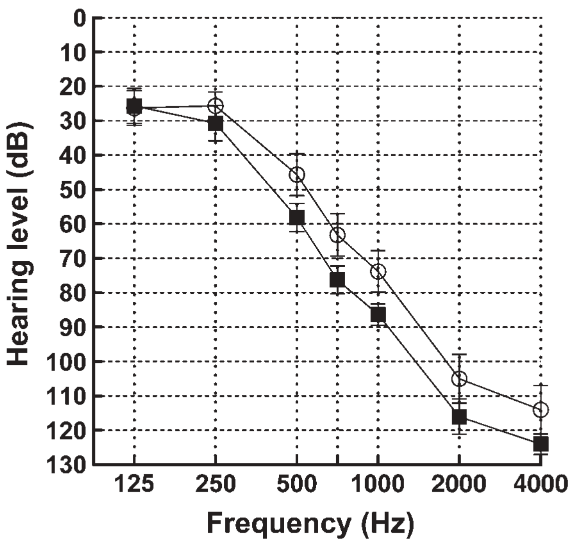
previous study, 45 young listeners with NH were tested using the same protocol as in this study (Yost, Loiselle, Dorman, Brown, & Burns, 2013). We reproduce those data here.

In a pilot study, young listeners with a mean age of 27 years and mature listeners with a mean age of 63 years were tested in our laboratory. There was no difference in accuracy of sound-source localization. Therefore, the published data on young listeners with NH serves as our NH reference.

### Test Signals

Three noise-band signals, with 200-ms duration and 20-ms rise-time, were created. The WB signal was bandpass filtered between 125 and 6000 Hz. The LP signal was filtered between 125 and 500 Hz. The HP signal was filtered between 1500 and 6000 Hz. Butterworth band pass filter roll-offs were 48 dB/octave. The overall signal level was 65 dBA (for details see Yost et al., 2013).

**Figure 1.** Mean auditory thresholds as a function of frequency for listeners with hearing-preservation cochlear implants (CIs). Open circles show thresholds for the ear contralateral to the CI. Filled squares show thresholds for the ear ipsilateral to the CI. Error bars = ±1 *SEM*.



### Test Environment

The stimuli were presented from 11 of 13 loudspeakers (100×, Boston Acoustics, Peabody, MA) arrayed within an arc of 180° on the frontal plane. The speakers were separated by 15°. For additional details, see Yost et al. (2013).

### Test Conditions

Presentation of the three noise stimuli was controlled by Matlab (MathWorks, Natick, MA). The stimuli were randomized, and each stimulus was presented four times from each loudspeaker. The overall presentation level was 65 dBA, including a 4-dB rove. Level roving was used to minimize cues that might be provided by the acoustic characteristics of the loudspeakers. Subjects were instructed to look at the midline (center loudspeaker) until a stimulus was presented. Responses were recorded by having the subject enter the number of the source loudspeaker (1–13) via a numerical keypad. The loudspeakers at the ends of the loudspeaker array, 1 and 13, did not present sound to minimize edge effects (see Rakerd & Hartmann, 1986).

Before testing, a broadband signal was presented at midline and listeners with bilateral CIs adjusted their volume controls to equate loudness between ears so that the signal was perceived to be of equal loudness at both ears and was heard directly in front. Listeners with hearing-preservation CIs were tested in the combined condition and had both hearing aids verified with real-ear measures before experimentation. Hearing aid output was verified to match NAL-NL1 (Dillon, 2006; National Acoustic Laboratories, Macquarie, NSW, Australia) target audibility for the low-frequency region.

### Institutional Review Board Approval

The experiments presented here were reviewed and approved by the Arizona State University Institutional Review Board.

**Table 2.** Demographic information for eight listeners with hearing-preservation CIs with symmetrical, low-frequency hearing.

| Subject | Age (y) | Gender | Age HL onset (y) | Etiology | CI Use (y) | CI Ear/ Device | Processor/HA | Strategy | No. active channels/total channels | Frequency allocation (Hz) |
|---|---|---|---|---|---|---|---|---|---|---|
| S12 | 39 | F | 14 | Unknown | 1 | R/ME Pulsar$^{EAS}$ | Tempo+Duet/ Tempo+Duet | CIS | 12/12 | 300–8500 |
| S13 | 79 | M | 40 | Hereditary | 2 | R/CC Hybrid L24 | Freedom/Phonak | ACE | 20/22 | 1188–7938 |
| S14 | 55 | F | 40 | Unknown | 2 | R/CC Hybrid L24 | Freedom/Phonak | ACE | 20/22 | 1188–7938 |
| S15 | 35 | M | 5 | Unknown | 2 | L/ME Sonata$^{M}$ | Opus 2/Unaided | FSP | 11/12 | 332–7500 |
| S16 | 50 | F | 32 | Hereditary | 3 | R/CC Hybrid L24 | Freedom/Phonak | ACE | 20/22 | 1188–7938 |
| S17 | 62 | F | 52 | Viral infection | 2 | L/ ME Sonata$^{EAS}$ | Tempo+Duet/Phonak | CIS | 12/12 | 500–8500 |
| S18 | 68 | M | 27 | Unknown | 5 | L/ME Pulsar$^{EAS}$ | Tempo+Duet/Widex | CIS | 10/12 | 500–8500 |
| S19 | 67 | M | 21 | Noise exposure | 1 | R/ME Sonata$^{EAS}$ | Tempo+Duet/Phonak | CIS | 10/12 | 500–8500 |

*Note.* This is a subset of the data reported in Loiselle et al. (2015). Reprinted with one-time, nonexclusive permission from S. Karger AG, Basel, Switzerland. HL = hearing loss; CI = cochlear implant; HA = hearing aid; F = female; M = male; R = right; ME = MED-EL; CIS = continuous interleaved sampling; CC = Cochlear Corporation; ACE = advanced combined encoder; L = left; FSP = fine-structure processing.

## *Results*

Localization accuracy was calculated in terms of root-mean-square (rms) error in degrees using the *D* statistic (Rakerd & Hartmann, 1986). Chance was calculated using a Monte Carlo method using 100 runs of 1,000 Monte Carlo trials. Mean chance performance was 73.5° with an *SD* of 3.2° for the three noise stimuli.

Localization accuracy for all listeners is shown in Figure 2. Individual rms errors are listed in Table 3. As reported in Yost et al. (2013), for listeners with NH, the mean rms error for the LP noise was 7°; for the HP noise, 7°; and for the WB noise, 6°. For the listeners with bilateral CIs, the mean rms error for the LP noise was 46°; for the HP noise, 20°; and for the WB noise, 20°. For the listeners with hearing-preservation CIs, the mean rms error for the LP noise band was 22°; for the HP noise, 58°; and for the WB noise, 31°.

For the listeners with bilateral CIs, a repeated-measures analysis of variance (ANOVA) on rms errors indicated a main effect for conditions, $F(2, 32) = 20.24$, $p < .0005$. Posttests (Holm Šidák) showed that performance in the HP condition (20° error) did not differ from the WB conditions (20° error). Performance in the LP condition was poorer than performance was in either the HP or WB conditions.

For the listeners with hearing-preservation CIs, a repeated-measures ANOVA on rms errors indicated a main effect for conditions, $F(2, 23) = 19.6$, $p = .0006$. Posttests showed that performance in the LP (22° error) and WB conditions (31° error) did not differ and that performance

**Figure 2.** Root-mean-square (rms) error for sound-source localization for listeners with normal hearing, those with bilateral cochlear implants (CIs), and those with hearing-preservation CIs. For each group, rms error is plotted as a function of the noise bands used to elicit localization judgments. LP = low pass; HP = high pass; WB = wideband.

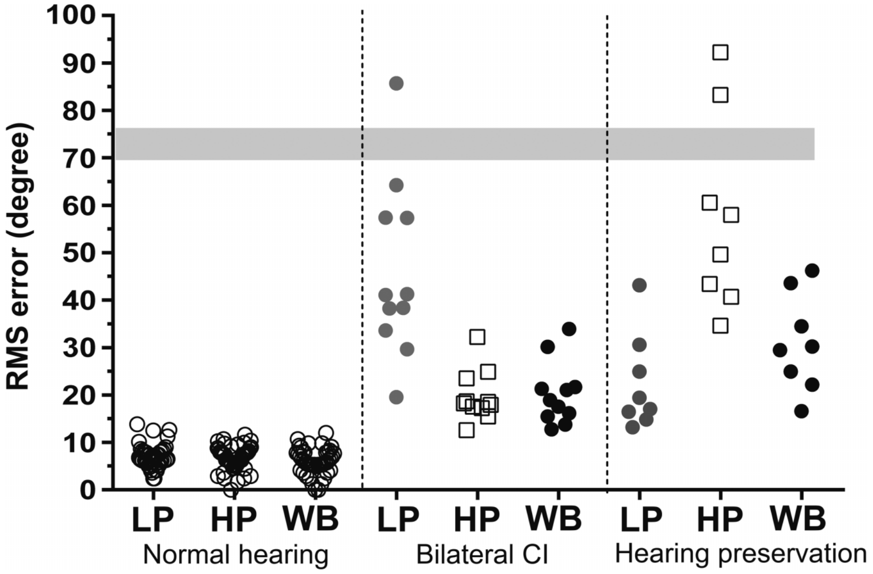


**Table 3.** Individual root-mean-square errors for the three noise conditions (low pass [LP], high pass [HP], and wideband [WB]) for both groups with cochlear implants (CIs) on the localization task.

| Bilateral CI | LP | HP | WB | Hearing preservation | LP | HP | WB |
|---|---|---|---|---|---|---|---|
| 1 | 57.34 | 18.23 | 17.52 | 12 | 43.14 | 92.24 | 34.52 |
| 2 | 64.24 | 23.50 | 21.33 | 13 | 17.07 | 34.59 | 24.98 |
| 3 | 85.75 | 24.87 | 15.50 | 14 | 19.45 | 83.27 | 46.23 |
| 4 | 57.39 | 15.50 | 33.92 | 15 | 16.46 | 58.00 | 16.62 |
| 5 | 41.08 | 17.52 | 16.15 | 16 | 14.83 | 40.70 | 29.48 |
| 6 | 41.27 | 17.22 | 18.92 | 17 | 13.19 | 60.65 | 22.16 |
| 7 | 38.24 | 18.65 | 13.76 | 18 | 30.59 | 43.48 | 43.62 |
| 8 | 29.66 | 12.59 | 12.79 | 19 | 24.98 | 49.65 | 30.25 |
| 9 | 33.64 | 18.56 | 21.68 | | | | |
| 10 | 38.38 | 32.22 | 30.17 | | | | |
| 11 | 19.58 | 17.95 | 21.09 | | | | |
| *M* | 46.05 | 19.71 | 20.26 | *M* | 22.46 | 57.80 | 30.98 |
| *SD* | 18.58 | 5.34 | 6.60 | *SD* | 10.13 | 20.52 | 10.20 |

in the LP and WB conditions was significantly better than was the HP condition (58° error).

## *Discussion*

Our interest in Experiment 1 was the pattern of localization accuracy in the three noise conditions for the CI groups. Listeners with bilateral CIs should be sensitive to ILD information but not to ITD information. If this were the case, then localization accuracy should be best in the HP and WB noise conditions and poorest in the LP noise conditions. Ten of 11 listeners met this prediction. One listener's LP score was 1° better than his WB score. His LP score was poorer than his HP score. In contrast, listeners with hearing-preservation CIs should be sensitive to ITD information but should receive little information from ILDs. If this were the case, then localization accuracy should be best in the LP and WB conditions and poorest in the HP noise condition. Seven of eight listeners met this prediction. One listener had an rms error to the LP stimulus that was poorer than the rms error to the WB stimulus. Her LP error was better than her HP error. Thus, the pattern of errors as a function of noise-band condition is consistent with the standard view of the frequency domains in which ILDs and ITDs operate. There was no difference in sound-source localization accuracy across the three filter conditions for listeners with NH (Yost et al., 2013).

For the subjects with bilateral CIs, rms errors in the LP condition, although poorer than the errors in the WB and HP noise conditions, were better than chance (for all but one listener). For the subjects in the hearing-preservation group, rms errors in the HP condition, although poorer than errors in the LP or WB conditions, were better than chance for six of eight listeners. Our experimental design does not provide data that speak to the cues used by the listeners to achieve better-than-chance performance. We can speculate that, in the LP condition, the listeners with bilateral CIs were using the very small ILDs that occur for low-frequency signals (e.g., Dorman et al., 2014). In the HP condition, the listeners with hearing-preservation CIs may have used the differences in level for HP signals at the CI ear and in the ear without the CI to achieve some lateralization of sound sources.

Our outcomes show that ILDs and ITDs can support equivalent levels of sound-source localization for listeners with CIs. Listeners with bilateral CIs, in the HP noise condition had access to ILD cues and showed a mean rms error of 20°. Listeners with hearing-preservation CIs, in the LP noise condition, had access to ITD cues and showed a mean rms error of 22°. Thus, ILDs and ITDs provide functionally equivalent information for sound-source location for the two groups of listeners with CIs.

# Experiment 2: Speech Understanding in a Cocktail Party Listening Environment

## *Method*

### Subjects

The listeners with bilateral and hearing preservation CIs from Experiment 1 also participated in Experiment 2. Nine young listeners with NH who were undergraduates at Arizona State University served as a reference group. All listeners were compensated for their time.

### Test Environment

Signal delivery was accomplished with the R-SPACE (Revitronix, Braintree, VT) sound-simulation system (for greater detail, see Compton-Conley, Neuman, Killion, & Levitt, 2004). This system consists of an eight-loudspeaker array, which is placed in a circular pattern around the subject. Each speaker is placed at a distance of 60 cm from the subject's head, with each speaker separated by 45°. In the current study, however, just three speakers were employed: 0°, 90°, and 270° (or −90°).

### Test Stimuli

The target signals were sentences from the Pediatric AzBio test corpus (Spahr et al., 2014). The sentences were spoken by one female talker with a fundamental frequency ($F_0$) of 215 Hz. The sentences were reproduced via the center loudspeaker of the R-SPACE array. To create one of the other members of the "cocktail party," 10 sentences from the Institute of Electrical and Electronics Engineers (IEEE; 1969) sentences, spoken by one male talker with an $F_0$ of 94 Hz, were concatenated with a 0-ms delay. This sequence was then put into a loop and output was continuous from the loudspeaker at 90°. To create the other "speaker," 10 IEEE sentences from a different male talker with an $F_0$ of 100 Hz were concatenated and looped. These sentences were reproduced from the speaker at 270° (or −90°).

### Test Conditions

The test conditions were designed to examine differences in speech understanding when subjects did or did not have access to ILD or ITD cues. For listeners with NH, one ear was plugged and muffed (earplug plus ultrasonic muffs) to create a no-binaural-cues condition. Half of the listeners were tested with the right ear as the single ear and half were tested with the left ear as the single ear. The earplug and earmuff were removed for the two ears or with-binaural-cues condition.

Listeners with bilateral CIs were tested with their better ear alone and with both ears. Before testing in the cocktail party environment, CNC word scores in quiet and AzBio sentence scores in noise at a signal-to-noise ratio (SNR) of +10 dB and +5 dB were obtained in a traditional audiometric setting using a single loudspeaker and were scored in terms of the percentage of correct answers. These scores allowed us to designate one ear as *better*.

The listeners with hearing-preservation CIs were tested in two conditions: (a) CI plus contralateral acoustic hearing (bimodal condition)—that is, without access to binaural cues, and (b) CI plus acoustic hearing in both ears (combined condition)—that is, with access to ITD cues.

### Test Protocol

For the listeners with NH and those with bilateral CIs, the level of the two male maskers, relative to the target speech, was first increased until performance near 50% correct was attained for the single-ear condition. In this way, ceiling effects in performance, when the second ear was allowed to participate, were minimized. In this one-ear condition, there were no binaural cues. To determine the value of binaural cues—that is, the binaural advantage, for speech understanding in the second condition, the listeners with NH and those with bilateral CIs were allowed to listen with both ears—that is, the poorer ear was added. The percentage of correct responses was calculated for the unilateral and bilateral listening conditions on the basis of the number of words identified correctly on the AzBio sentences. The same SNR was used for both conditions.

For the listeners with hearing-preservation CIs, a single ear—that is, the CI plus ipsilateral acoustic hearing, was first used to determine the SNR necessary to achieve near 50% correct. For the bimodal condition, the ear canal was plugged and muffed on the side ipsilateral to the CI. Subjects with bimodal CIs have relatively good access to fine, temporal structure from the ear with low-frequency acoustic hearing and have access to signal-level information from the ear fit with a CI. Neither timing nor level information is well represented at both ears. In the second condition—that is, the combined condition, the plug and muff were removed from the implanted ear. In this condition, the listeners, because they have two ears with low-frequency acoustic hearing, had access to ITDs. The same SNR was used for the bimodal and combined conditions. Scores were calculated based on the number of words correctly identified on the AzBio sentences.

### Signal Levels

For the listeners with NH, the target sentences were presented at 50 dB SPL. This level was chosen so that plugging and muffing one ear would result in low-level signals in that ear. However, plugging and muffing did not completely eliminate sound sensation in the ear. For the two CI groups, the target sentences were presented at 60 dB SPL—that is, a normal conversational level. Plugging and muffing was more effective for the listeners with hearing-preservation CIs, when compared with the listeners with NH, because they all had significant hearing loss in the low-frequency region (see Figure 1).

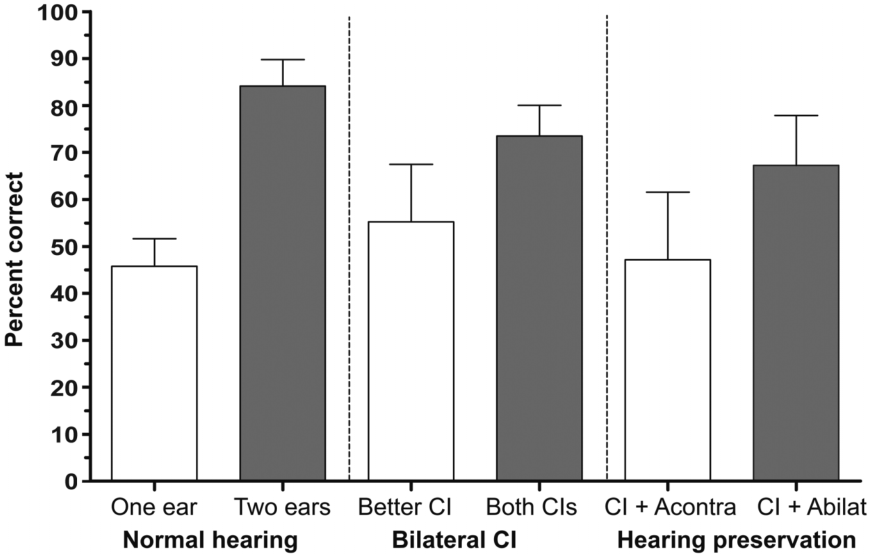
## Results

Speech understanding scores for the cocktail party environment are shown in Figure 3. For listeners with NH, mean sentence understanding improved significantly in the two-ear condition (84% correct) versus the one-ear condition (46% correct), $t(8) = 6.74$, $p < .001$. For the listeners with bilateral CIs, speech understanding improved significantly in the two-ear condition (73% correct) versus the single-ear condition (55% correct), $t(10) = 5.48$, $p < .0003$. For listeners with hearing-preservation CIs, speech understanding improved significantly in the combined condition with two acoustic hearing ears (67% correct) versus the bimodal condition with just one acoustic hearing ear (47% correct), $t(7) = 5.48$, $p < .009$.

Individual differences in performance were large but were roughly equivalent across the two CI groups and the NH group. For individual listeners with bilateral CIs, the binaural advantage was as small as 4 percentage points and as large as 34 percentage points. For the listeners with hearing-preservation CIs, the binaural advantage was as small as 8 percentage points and as large as 38 points. For the listeners with NH, the binaural advantage ranged from 9 to 62 percentage points.

The change or improvement in scores for the three groups of listeners was entered into a one-way ANOVA. There was a main effect of group, $F(2, 26) = 5.76$, $p < .009$. Posttests (Holm Šidák) showed that the mean improvement score for the listeners with NH (38 percentage points) differed from the mean improvement scores for both the listeners with bilateral CIs (18 percentage points) and those with hearing-preservation CIs (20 percentage points). The improvement score or binaural advantage for the listeners with bilateral CIs and those with hearing-preservation CIs did not differ. Individual scores and the SNRs are presented

**Figure 3.** Sentence understanding in a cocktail party setting for listeners with normal hearing, those with bilateral cochlear implants (CIs), and those with hearing-preservation CIs. For each group, performance is shown in two conditions: first, without binaural cues; and second, with binaural cues. Acontra = low-frequency, acoustic hearing in the ear contralateral to the implant; Abilat = low-frequency, acoustic hearing in both the implanted ear and in the contralateral ear.



in Tables 4 and 5 for the listeners with bilateral and hearing-preservation CIs, respectively. Consistent with the findings of Experiment 1, the ILDs available for listeners with bilateral CIs and the ITDs available for those with hearing-preservation CIs provide functionally equivalent information for speech understanding in a cocktail party environment.

### *Discussion*

Our interest in Experiment 2 was whether both listeners with bilateral CIs and those with hearing-preservation CIs would show spatial release from masking, the binaural advantage, when listening in a complex sound environment with spatially separated speech and noise sources. Of particular interest was whether the listeners with bilateral CIs, who did not have access to ITD cues, would show a binaural advantage. The outcome showed that they did have that advantage. Indeed, the magnitude of the advantage was as large as that shown by the listeners with hearing-preservation CIs who had access to ITD cues. Thus, both ITDs and ILDs can underlie binaural benefit to listeners with CIs.

**Table 4.** Individual scores for the listeners with bilateral cochlear implants in the better ear and bilateral conditions in the cocktail party condition.

| Subjects | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bilateral | 66 | 85 | 82 | 68 | 80 | 69 | 66 | 75 | 73 | 72 | 71 |
| Better ear | 62 | 78 | 51 | 34 | 51 | 44 | 52 | 63 | 59 | 67 | 47 |
| Binaural advantage | 4 | 7 | 31 | 34 | 29 | 25 | 14 | 12 | 13 | 5 | 24 |
| Signal-to-noise ratio | 3 | 0 | 4 | 2 | −2 | −3 | 5 | −2 | 2 | −1 | −2 |

## General Discussion

The research reported here was motivated by the observation that listeners with bilateral CIs have access to ILD information but not to ITD information, and listeners with hearing-preservation CIs have access to ITD information but little access to ILD information. At issue was whether the two different cue sets for sound-source localization would lead to different levels of performance on tasks of sound-source location and on tasks of speech understanding in a cocktail party. Our data suggest that the two cue sets can provide functionally equivalent information.

### *Sound-Source Localization*

The data from Experiment 1 show that when stimulation is filtered so as to limit access to ILD and ITD cues, listeners with bilateral CIs (when responding to HP-filtered noise) and those with hearing-preservation CIs

**Table 5.** Individual scores for the hearing preservation listeners in electric plus ipsilateral acoustic hearing (EAS), bimodal hearing, and combined conditions in the cocktail party scenario.

| Subjects | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|
| EAS | 41 | 44 | 21 | 48 | 74 | 69 | 65 | 52 |
| Combined | 68 | 60 | 55 | 53 | 69 | 79 | 82 | 72 |
| Bimodal | 55 | 22 | 32 | 40 | 61 | 49 | 58 | 60 |
| Binaural advantage | 13 | 38 | 24 | 13 | 8 | 30 | 24 | 12 |
| Signal-to-noise ratio | −6 | −4 | −5 | −6 | −7 | −3 | 0 | 7 |

*Note*. The EAS condition is listed for baseline.

(when responding to LP-filtered noise) show the same level of sound-source localization.

The poorer-than-normal localization shown by the listeners with bilateral CIs is likely due to several factors. First, the ILDs available to listeners with CIs are far smaller than the ILDs available to listeners with NH. This is due to the input and output compression inherent in CI signal processing (e.g., Dorman et al., 2014). Second, Grantham et al. (2007) found that ILD thresholds ranged from 1 to more than 10 dB for listeners with bilateral CIs. In addition, factors such as individual differences in (a) between-ear automatic gain control settings, (b) between-ear frequency-allocation tables, (c) pitch mismatches between electrodes to which common filter outputs are assigned, (d) unequal numbers of electrodes between ears, (e) electrode-specific dynamic ranges, (f) output-compression settings, and (g) processor volumes, could alter the normal representation of signal levels as a function of frequency for different sound-source locations.

The mechanisms underlying the poorer-than-normal localization exhibited by the listeners with hearing-preservation CIs are less clear. The cochlear damage that resulted in elevated low-frequency thresholds likely alters the internal representation of fine-timing information. The Gifford, Dorman, et al. (2014) and Gifford, Grantham, et al. (2014) reports of significantly poorer-than-normal ITD thresholds for listeners with hearing-preservation CIs are consistent with this hypothesis. In addition, the settings, for example, gain and automatic gain-control settings, employed on two independent hearing aids may add to the distortion of the internal representation of fine-timing information.

If cochlear damage alters the internal representation of fine-timing information, then it is possible that listeners with less, or more, threshold elevation would show different levels of sound-source localization. Ching, van Wanrooy, Hill, & Dillon (2005) report that listeners with bilateral hearing impairment with low-frequency threshold elevation of greater than 65 dB did not benefit from ITD information when measuring speech-reception thresholds. At the other end of the continuum, listeners with hearing-preservation CIs with better than 20 dB HL thresholds may show better localization accuracy than the group tested for this report.

### *Speech Understanding in a Cocktail Party Listening Environment*

The similarity in localization accuracy between the two CI groups was mirrored by the similar levels of binaural advantage for the two groups in the cocktail party.

As discussed at the beginning of the article, the study of the spatial release from masking goes back, at least, to 1948 and the two articles on the masking-level difference (Hirsh, 1948; Licklider, 1948) and to the 1953 article by Colin Cherry (Cherry, 1953) on the "cocktail party problem." A great many articles, involving a wide range of subject populations, have been published since then (see Litovsky, 2012, for a recent brief review of some of this literature). The amount of spatial release from masking is variable across these many studies (see Yost 1997 for an early review of this variability). Some of the key variables that appear to affect the amount of spatial release from masking include the subject population, the spatial or interaural configuration of the target (signal) and interfering (masker) sounds, and the similarity of the target and masker. In the present study, the subject populations included listeners with bilateral CIs, listeners with hearing-preservation CIs, and listeners with NH. The spatial configuration used in this study (a signal sound source symmetrically centered between two masker sound sources) probably eliminated head shadow as a variable affecting spatial release from masking, meaning binaural processing (summation and squelch, although the experimental design did not allow for determining the relative contribution of each), was most likely used. Given that both the target and maskers were speech, the present study is most likely relevant to the literature on informational masking and spatial release from masking (again, see Litovsky, 2012). The existing literature (see the Litovsky, 2012, review) suggests that, for listeners with NH, substantial spatial release from masking would occur in this informational-masking condition, which is what we showed. This literature also indicates that subjects with hearing loss, even when fit with prosthetic devices, demonstrate less spatial release from masking than do subjects with NH. A finding we also obtained. The comparison of spatial release from masking for listeners with bilateral CIs and those with hearing-preservation CIs in the present article has not, to our knowledge, been previously reported. Thus, the spatial release from masking reported in this article appears generally consistent with that reported in the literature, and the present article adds a comparison of listeners with bilateral CIs to listeners with hearing-preservation CIs to this literature.

## Conclusions

The findings of the current study indicate that, for listeners with CIs, similar degrees of benefit to sound-source localization and speech understanding in complex listening environments are possible with two very different rehabilitation strategies—the provision of bilateral CIs and the preservation of hearing in the operated ear when there is low-frequency residual hearing in the contralateral ear. The results presented here provide the first evidence, to our knowledge, that, for listeners with CIs, ILD cues can provide a similar level of sound-source localization and a similar level of speech-understanding benefit in a complex listening environment as that provided by ITD cues.

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