# The Effect of Microphone Placement on Interaural Level Differences and Sound Localization Across the Horizontal Plane in Bilateral Cochlear Implant Users

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**Objective:** This study examined the effect of microphone placement on the interaural level differences (ILDs) available to bilateral cochlear implant (BiCI) users, and the subsequent effects on horizontal-plane sound localization.

**Design:** Virtual acoustic stimuli for sound localization testing were created individually for eight BiCI users by making acoustic transfer function measurements for microphones placed in the ear (ITE), behind the ear (BTE), and on the shoulders (SHD). The ILDs across source locations were calculated for each placement to analyze their effect on sound localization performance. Sound localization was tested using a repeated-measures, within-participant design for the three microphone placements.

**Results:** The ITE microphone placement provided significantly larger ILDs compared to BTE and SHD placements, which correlated with overall localization errors. However, differences in localization errors across the microphone conditions were small.

**Conclusions:** The BTE microphones worn by many BiCI users in everyday life do not capture the full range of acoustic ILDs available, and also reduce the change in cue magnitudes for sound sources across the horizontal plane. Acute testing with an ITE placement reduced sound localization errors along the horizontal plane compared to the other placements in some patients. Larger improvements may be observed if patients had more experience with the new ILD cues provided by an ITE placement.

**Key words:** Bilateral cochlear implants, Microphone placement, Sound localization.

(Ear & Hearing 2016;37;e341–e345)

## INTRODUCTION

Bilateral cochlear implants (BiCIs) offer spatial hearing benefits over a single implant, such as improved sound localization; however, performance remains poor compared with normal-hearing (NH) listeners (Grantham et al. 2007; Litovsky et al. 2009; Jones et al. 2014). While NH listeners are able to use both interaural time differences and interaural level differences (ILDs) for sound localization along the azimuth, BiCI users rely predominately on ILDs with limited interaural time difference use (van Hoesel & Tyler 2003; Grantham et al. 2007, 2008; Aronoff et al. 2010; Dorman et al. 2014). Further complicating matters, speech processor microphones are typically placed behind the ear (BTE), and in children the microphones are also sometimes placed on the shoulders (SHD). Such placements do not capture the natural amplification of the pinna, and potentially reduce the ILDs available compared with a more natural, in the ear (ITE) microphone placement. In addition, microphone placement has been shown to have a significant impact on the frequency response of signals (Ricketts et al. 2006; Durin et al. 2014; Kolberg et al. 2015). As ILDs result from an interaural comparison of signal amplitudes across frequency, we tested the hypothesis that microphone placement impacts the ILDs available to BiCI users, and subsequently affects sound localization performance.

To date, only one study has examined sound localization abilities in BiCI users for different microphone placements (Frohne-Büchner et al. 2004). This was achieved by using an accessory that places the speech processor microphone partially in front of the ear canal (T-Mic, Advanced Bionics). Frohne-Büchner et al. reported improved sound localization performance for a single BiCI user listening with the T-Mic compared with the standard BTE placement. The present study included 8 BiCI users, and examined the impact of (1) 3 different microphone placements (ITE, BTE, and SHD) on ILDs, and (2) each microphone placement on horizontal-plane sound localization. For each participant, acoustic transfer function measurements were used to create individualized virtual acoustic space (VAS) stimuli. This novel approach allowed for the analysis of the acoustic ILDs available to individual participants.

## MATERIALS AND METHODS

### Participants and Equipment

Eight postlingually deafened BiCI users (ages 32 to 71), fitted with Cochlear Freedom or N5 processors (Table 1), participated in this study. Participants signed a consent form approved by the University of Wisconsin-Madison Institutional Review Board and were paid for their participation. Acoustic transfer function measurements and localization testing were conducted in the same sound booth (IAC, RS 254S). A Tucker-Davis Technologies (TDT) System 3 was used to select and drive 19 loudspeakers (Cambridge SoundWorks, Newton, MA) hidden behind a dark, acoustically transparent curtain. Loudspeakers were mounted on a semicircular arc (radius = 1.2 m) at 10 degree increments between ±90 degree along the horizontal plane. All stimulus presentation and data acquisition was done through the use of custom software written in MATLAB (Mathworks, Natick, MA). Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 22.0 (IBM Corp, Armonk, NY).

### Acoustic Measurements

For each participant, acoustic transfer function measurements for all 19 loudspeaker locations were made using established head-related transfer function measurement techniques (Møller 1992; Jones et al. 2014). In brief, participants were seated with their head in the center of the loudspeaker array. Golay codes

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<zdoi; 10.1097/AUD.0000000000000297>

**TABLE 1. Profile and etiology of BiCI subjects**

| Subject | Age | Approx. Age at Hearing Loss Onset | Years CI Experience (L/R) | Years Bilateral Experience | Etiology |
|---|---|---|---|---|---|
| IBX | 71 | 40 | 3/2 | 2 | Progressive/sensorineural |
| IBZ | 44 | 30 | 4/5 | 4 | Sudden loss/unknown |
| ICB | 61 | 9 | 6/9 | 6 | Progressive/hereditary |
| ICF | 70 | 21 | 1/1 | 1 | Otosclerosis |
| ICI | 54 | 31 | 4/3 | 3 | Sudden loss/unknown |
| ICJ | 63 | 13 | 3/3 | 3 | Childhood illness |
| ICK | 69 | 30 | 1/2 | 1 | Noise induced |
| ICO | 32 | 5 | 1/1 | 1 | Unknown |

*BiCI, bilateral cochlear implant; CI, cochlear implant.*

(200 msec long, 5 repetitions) were used as probe signals, and recorded by a pair of omnidirectional microphones (HeadZap binaural probe microphones, AuPMC002, AuSim, Mountain View, CA) placed either ITE, BTE, or on the SHD of participants. Microphone output signals were amplified (MP-1, Sound Devices, Reedsburg, WI) and recorded using a TDT RP2.1 at 48 kHz. For the BTE and SHD placements, the microphones were positioned to face forward.

### Interaural Level Difference Analysis

ILDs were derived by computing the difference in the root mean square (RMS) energy between right and left microphone measurements below 8 kHz, for each location (Fig. 1A). The ILD data were fitted with a four-parameter sigmoid logistic function of the form:

$$\mathrm{ILD}(\mathrm{Loc}) = y_0 + a / \left(1 + \exp\left(-\left(\mathrm{Loc} - \mathrm{Loc}_0\right) / b\right)\right),$$

where Loc is the speaker location, ILD is the predicted ILD magnitude, $y_0$ is the function's minimum value, $a$ is the difference between the function's maximum and minimum value, $\mathrm{Loc}_0$ is the midpoint location of the sigmoid, and $b$ is the slope. Metrics of ILD range (dB) and slope (dB/angle) were computed from the ILD function (Fig. 1B, top panel). The ILD range was defined as the absolute difference between the maximum ILD for left and right hemifield.

### Localization Testing

Localization stimuli were a train of 4 pink noise bursts (170 msec each burst, 10 msec inter-stimulus interval), which were digitally processed to simulate free-field presentation using previously described techniques (Wightman & Kistler 1989; Jones et al. 2014). In brief, individualized VAS stimuli were created for each microphone placement by passing the train of pink noise bursts through a digital filter constructed from the acoustic transfer function measurements made for each participant. A new pink noise burst was generated for each presentation before being filtered by an acoustic transfer function for a particular location. Stimuli were presented at approximately 60 dB SPL directly to the CI speech processors via the auxiliary port. The overall level of the stimuli was roved (±4 dB) trial-by-trial, to reduce the possibility of localizing spatial locations based on the use of monaural cues (Majdak et al. 2011; Dorman et al. 2014; Jones et al. 2014). Participants used their everyday clinical settings during localization testing.

Before testing, the VAS stimulus for the front loudspeaker location (0 degree) created from the BTE acoustic measurements was presented to the participants to ensure acoustical signals were being delivered appropriately. Following this initial presentation, participants confirmed the VAS stimuli being presented to their speech processors via direct connect cables was externalized and at a similar level as free-field presentation. Each microphone condition was fixed within a block of trials, and tested over 3 separate blocks of 95 trials (5 trials × 19 locations) each, for a total of 15 trials per location per microphone condition. The 9 blocks of trials were randomized so that microphone conditions were interleaved across blocks. On each trial, participants initiated testing by pressing a button on a touch-screen computer monitor, and responses were recorded on a graphical user interface that displayed a continuous arc representing the loudspeaker array. Participants were aware the loudspeakers were not active. It is important to note that this was an acute study, thus participants had no experience or training with the novel microphone placements before testing.

## RESULTS

Average ILD dynamic range and slope values are shown in Figure 1C and D, respectively. Each ILD metric was analyzed separately as a dependent variable with microphone placement as the independent variable using a one-way, repeated measures analysis of variance. Results indicated a significant effect for both ILD range [$F(2,23) = 76.49$, $p < 0.001$] and slope [$F(2,23) = 29.87$, $p < 0.001$]. Scheffe's posthoc analyses revealed significantly smaller ranges ($p < 0.05$) and slopes ($p < 0.05$) for BTE and SHD placements compared with ITE placements (Fig. 1C, D, asterisks indicate differences). Thus, BTE and SHD placements have two consequences: (1) they do not capture the full range of acoustic ILDs available in the ITE placement, and (2) they reduce the change in the magnitude of ILD when sound sources vary in location along the horizontal plane.

Individual data are shown in Figure 2A (the across-subject average RMS error and standard deviation plotted on the right). The average RMS error for the ITE placement (25.1 ± 4.4 degree) was lower than the BTE (28.6 ± 7.3 degree) and SHD (29.0 ± 6.5 degree) placements. Ricketts et al. (2006) reported a similar effect size for 7 BiCI users listening "without" front-end compression (24.8 degree RMS error) compared to listening "with" front-end compression activated (29.2 degree RMS error). To understand the relationship between acoustic ILDs and localization errors, RMS errors for

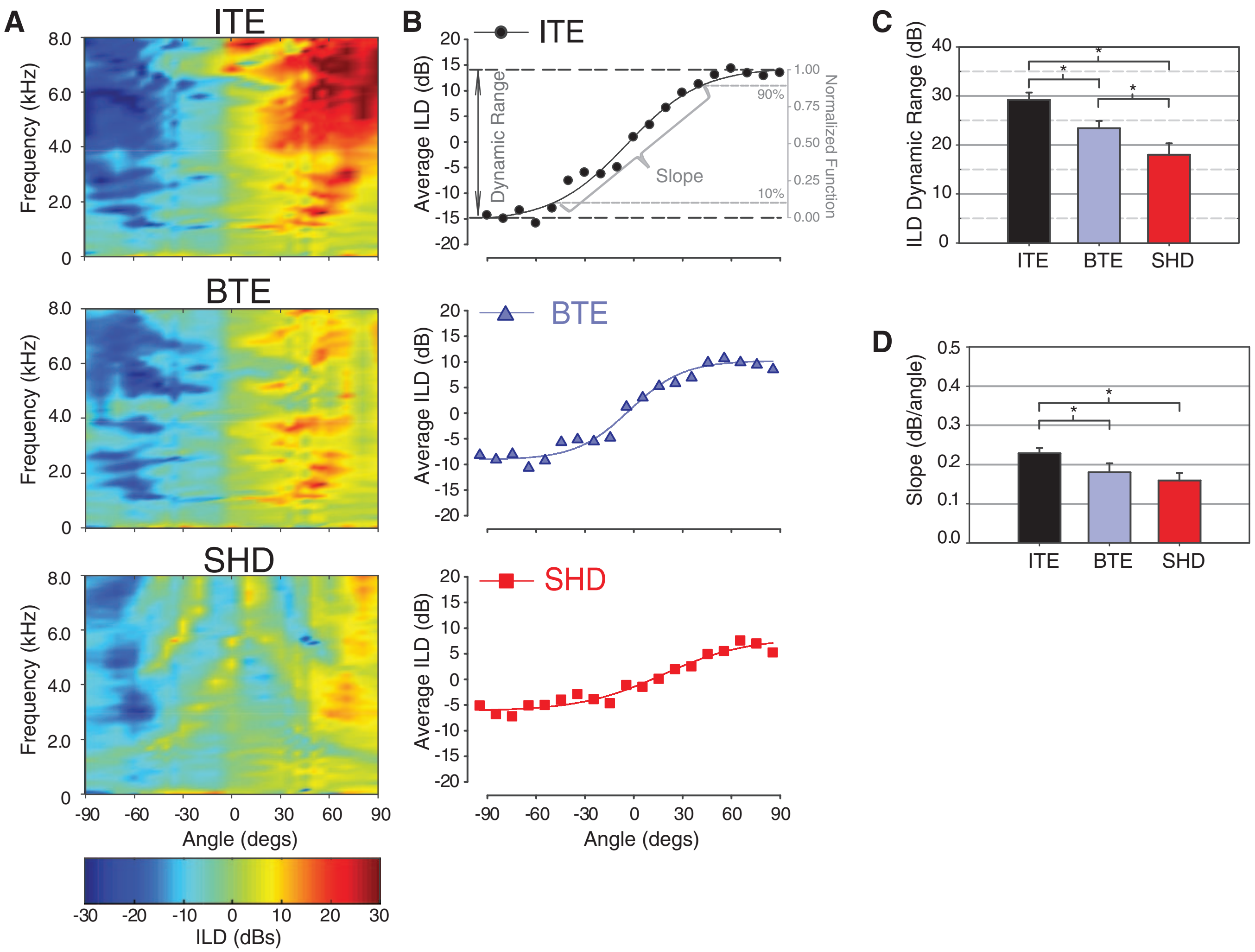

Fig. 1. ILD measurements. A, Acoustic ILDs were derived by computing the difference in the RMS energy between right and left microphone measurements for each location. Color represents the ILD magnitude. B, Mean ILD across frequency plotted as a function of measurement angle. Representation of ILD metrics are also shown in *grey*. C, The average ILD range (dB) across subjects for each microphone placement. D, The average ILD slope (dB/angle) across subjects for each microphone placement. *Asterisks* indicate significant differences revealed from statistical testing and posthoc analysis ($p < 0.05$). ILD indicates interaural level difference; RMS, root mean square.

all three microphone placements were plotted against their ILD range (Fig. 2B) and slope (Fig. 2C) metrics. A linear regression analysis revealed a correlation between ILD range and RMS error (Fig. 2B, $\rho = -0.62$, $p < 0.01$), such that larger ILD ranges typically resulted in lower RMS errors. In addition, there was a correlation between ILD slope and RMS error (Fig. 2C, $\rho = -0.73$, $p < 0.01$), indicating performance was typically better when there was a greater change in ILD magnitude (i.e., steeper slope) as a function of target location angle.

## DISCUSSION

The present study examined the effect of microphone placement on the acoustic ILDs available to BiCI users and the subsequent effects on horizontal-plane sound localization. Changes in the acoustic ILDs available across sound source location were quantified from individual acoustic transfer function measurements made for each microphone placement and each participant. Acoustical analysis revealed that ILDs were reduced for BTE and SHD compared with the ITE placement. Localization testing found ITE placement typically resulted in nominally lower overall localization errors compared with the other conditions. The correlational analysis reported here suggests that localization performance improves as a result of the increased ILDs provided by the ITE microphone placement. However, it should be noted that the average improvement across the group was small (~3 to 4 degree RMS) and not every participant showed improvement.

The dynamic range of the acoustic ILDs available increased significantly for the ITE compared with BTE and SHD placements (Fig. 1). In addition, the slope of the ILD functions increased for the ITE placements (Fig. 1D) indicating a greater change in ILD magnitude as sound sources moved from central to lateral locations. Effectively, the ITE placement increases both the range of useable ILDs and the number of discriminable steps across target locations. Given that many BiCI users often have ILD discrimination thresholds on the order of 1 to 2 dB (Grantham et al. 2008), it was expected that the increased change in ILD magnitudes across target locations would improve sound localization accuracy in BiCI users for

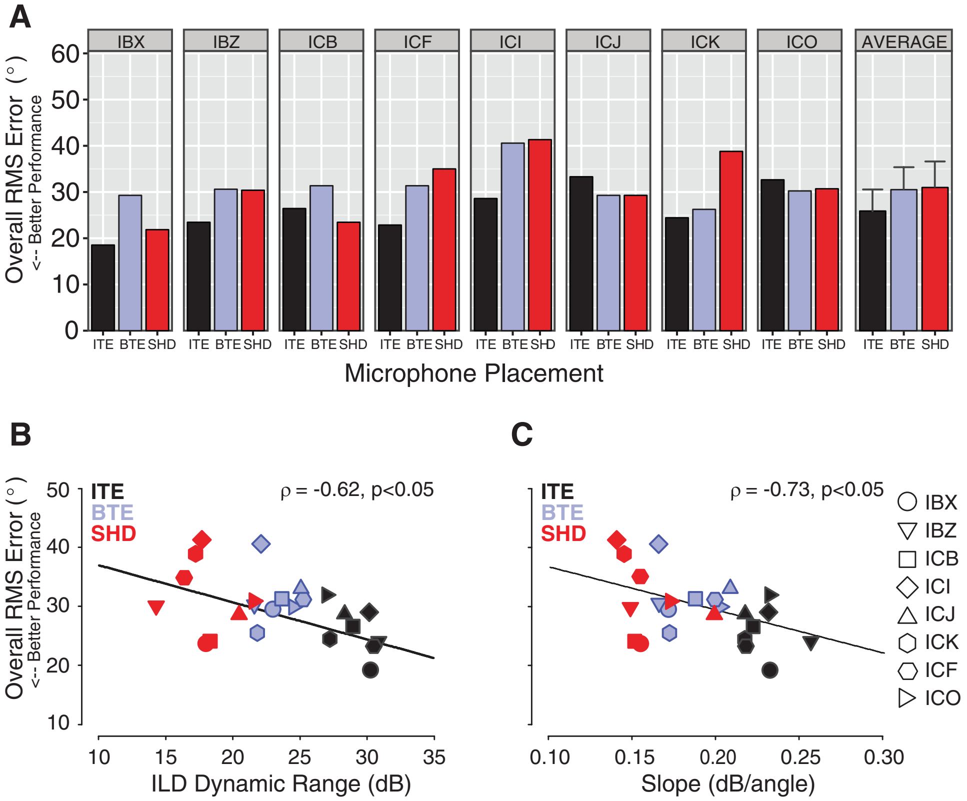

Fig. 2. Localization performance. A, Localization data for each BiCI listener across all listening conditions tested. The group average RMS errors and standard deviations are plotted on the far right (bar and error bars, respectively). B, Linear regression analysis found a negative correlation ($\rho = -0.62$, $p < 0.05$) between dynamic range and overall RMS error, such that smaller ILD dynamic ranges typically resulted in larger RMS errors. C, Linear regression analysis found a negative correlation ($\rho = -0.73$, $p < 0.05$) between dynamic range and overall RMS error, such that shallower slopes (i.e., smaller change in ILDs as a function of location) typically resulted in larger RMS errors. BiCI indicates bilateral cochlear implant; ILD, interaural level difference; RMS, root mean square.

an ITE placement of microphones. Similar effects have been previously reported for studies manipulating the availability of acoustic ILDs provided to BiCI users. Ricketts et al. (2006) showed that turning off front-end compression increased ILDs by approximately 7 to 8 dB for angles around 90 degree and resulted in an average improvement of 4.4 degree RMS error compared with when front-end compression was activated. The acoustical analysis reported here found an increase in ILDs of approximately 6 to 7 dB for 90 degree target angles with the ITE compared with the BTE placement, and an average improvement of 3.5 degree RMS error. In a recent study, Dorman et al. (2014) showed that average localization performance was significantly degraded, on the order of ~23 degree RMS error, for BiCI users listening to low-passed filtered signals. The ILDs for these low-pass stimuli were also shown to be further reduced when front-end compression and automatic gain control (AGC) were simulated. In addition, localization response patterns of BiCI users were shown to be related to the magnitude of the ILDs available to the listeners (Dorman et al. 2014). Consistent with these findings, we observed a similar correlation between individual ILD metrics and overall localization accuracy across listening conditions.

The present study also observed a high variability in localization performance across participants similar to that reported in the two studies mentioned above (Ricketts et al. 2006; Dorman et al. 2014). Nonetheless, acute testing with an ITE placement resulted in lower average sound localization error along the horizontal plane compared with the other placements for the group tested here. The relatively small sound localization improvement for ITE compared with BTE placement reported here differs from a previous study which reported a difference of ~40 degree RMS error in a single BiCI user between these two microphone placements (Frohne-Büchner et al. 2004). However, the lower RMS error reported in that study appears to be a result of fewer front-back errors, and not a reduction in lateral errors (Frohne-Büchner et al. 2004, Fig. 4). In another study using similar techniques as those reported here, Mantokoudis et al. (2011) concluded the placement of ITE microphones improved spatial discrimination on the side of the head by increasing front-to-rear cues compared with BTE placement. The authors verified that acoustic ILDs were only present for an ITE microphone placement and not for the BTE placement (Mantokoudis et al. 2011). Thus, while an ITE microphone placement helps reduce front-back confusions, our data suggest that this placement also has the potential to improve sound localization accuracy for sources along the horizontal plane in the frontal field in some patients.

One important consideration mentioned above is that the AGC and front-end compression independently implemented at each ear reduces ILDs (Ricketts et al. 2006; Dorman et al. 2014). Since AGC and front-end compression are necessary components for converting acoustic signals into electrical stimulation and patient comfort, the presented study tested the effect of microphone placement on sound localization with both features left unchanged. As such, the significant correlation between the individual ILD metrics and overall localization accuracy across listening conditions (Fig. 2B, C) suggest the difference in ILDs between ITE and BTE placements may be somewhat preserved post compression. Recently, significantly higher speech reception scores in noise were reported for BiCI users using the T-Mic accessory compared with the standard BTE (Kolberg et al. 2015) or when presented artificially enlarged ILD magnitudes (Brown 2014). For these studies, the AGC and front-end compression were left on, indicating that BiCI users were able to make use of the additional cues provided. Thus, it may be the case that BiCI users are able to take advantage of an ITE placement or enlarged ILDs for speech understanding in noise, and to a lesser extent sound localization.

## CONCLUSION

The current BTE microphones that many BiCI users use in everyday life do not capture the full range of acoustic ILDs available, and also reduce the change in cue magnitudes for sound source locations across the horizontal plane. Our findings indicate that while an ITE microphone placement provides a larger range of acoustic ILDs, the availability of these enlarged cues does not translate into lateral sound localization improvements along the horizontal plane for all patients. It is important to note that these findings are the result of acute testing with unfamiliar microphone placements and greater improvements might be observed if patients were allowed prolonged experience or training with the new ILD cues provided by an ITE microphone placement.

## ACKNOWLEDGMENTS

The authors thank the bilateral CI research participants who traveled to Madison to participate in these experiments. The authors also thank Cochlear (Dr. Zachary Smith and Dr. Aaron Parkinson) for technical support and equipment.

This study was supported by NIH-NIDCD Grants (R01 DC003083 and R01 DC010494) and in part by a core grant to the Waisman Center from the NIH-NICHD (P30 HD03352).

H.G.J. designed and performed experiments, analyzed data, and wrote the article. A.K. designed experiments and contributed to data analysis and the writing of the article. R.Y.L contributed to data analysis and the writing of the article.

All participants signed a consent form approved by the University of Wisconsin-Madison Institutional Review Board.

The authors have no conflicts of interest to disclose.

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Received August 5, 2015; accepted February 5, 2016.

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