The use of interaural time and level difference cues by bilateral cochlear implant users

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Abstract: While considerable evidence suggests that bilateral cochlear implant (CI) users' sound localization abilities rely primarily on interaural level difference (ILD) cues, and only secondarily, if at all, on interaural time difference (ITD) cues, this evidence has largely been indirect. This study used head-related transfer functions (HRTFs) to independently manipulate ITD and ILD cues and directly measure their contribution to bilateral CI users' localization abilities. The results revealed a strong reliance on ILD cues, but some CI users also made use of ITD cues. The results also suggest a complex interaction between ITD and ILD cues.

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1. Introduction

Bilateral cochlear implant (CI) users demonstrate a significant bilateral benefit for localization (e.g., van Hoesel, 2004). Although considerable evidence suggests that this localization benefit is dominated by interaural level difference (ILD) cues, as opposed to interaural time difference (ITD) cues (van Hoesel and Tyler, 2003; Schoen *et al.*, 2005; Grantham *et al.*, 2007; Poon *et al.*, 2009), this evidence has largely been indirect. Some studies have only minimized either the ITD or the ILD cues rather than completely eliminating them (Schoen *et al.*, 2005; Grantham *et al.*, 2007). Other studies have measured ITD sensitivity in μs and ILD sensitivity in dB (van Hoesel, 2004; Schoen *et al.*, 2005; Poon *et al.*, 2009) rather than using a secondary measure, such as spatial resolution, that would allow for a direct comparison between the two.

Recently, direct measurements of the relative contribution of ITD and ILD cues were performed by Seeber and Fastl (2008). They used a single participant's own head-related transfer function (HRTF), allowing them to create stimuli that contained the ITD cues for one location and the ILD cues for a separate location. Consequently, they were able to measure the

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Table 1. Participant information.

Participant (gender, age)	Etiology (patient report)	Processor		Length of use (years)	
		Left	Right	Left	Right
FF1 (F, 62)[a]	Ototoxic	Cochlear Freedom	Cochlear Freedom	2	2
FF2 (F, 42)	Ototoxic	Cochlear Freedom	Cochlear Freedom	0.5	0.5
TT1 (M, 42)[a]	Unknown	Med-El Tempo+	Med-El Tempo+	6	6
TT2 (M, 63)[a]	Noise exposure	Med-El Tempo+	Med-El Tempo+	7	7
TT3 (F, 47)	Unknown	Med-El Tempo+	Med-El Tempo+	6	6
OO1 (M, 58)	Mumps/Measles	Med-El Opus 2	Med-El Opus 2	1	1[b]
OO2 (M, 68)	Ménière's	Med-El Opus 2	Med-El Opus 2	2	0.5
OT1 (F, 37)[a]	Familial	Med-El Opus 2	Med-El Tempo+	3	5
TO1 (M, 51)	Ménière's	Med-El Tempo+	Med-El Opus 2	7	1
TO2 (F, 71)	Unknown	Med-El Tempo+	Med-El Opus 2	7	3

[a] These participants only participated in the SF and DC ITD+ILD conditions.

[b] This participant originally was implanted on the right side 3 years before testing, but electrodes started turning on and off unpredictably within 3 months, and the device was replaced approximately 1 year before testing.

availability of each cue using a single measure of performance, the perceived location. Their results demonstrated that ILD cues had a primary role in localization, with no evidence of a secondary role for ITD cues.

One limitation of the Seeber and Fastl (2008) study is that they used stimuli with the ITD cues for one location and the ILD cues for another rather than presenting each cue in isolation. Given that many studies have indicated a strong dominance for ILD cues (van Hoesel and Tyler, 2003; Schoen *et al.*, 2005; Grantham *et al.*, 2007; Poon *et al.*, 2009), any effect the ITD cues might have had on the perceived location in the Seeber and Fastl (2008) study may have been masked by the more dominant ILD cues. Another limitation of the Seeber and Fastl (2008) study is that only a single subject was tested, making it difficult to generalize their findings, especially since other studies have shown considerable variability in ITD sensitivity across CI users (e.g., van Hoesel, 2004; Poon *et al.*, 2009).

The purpose of the present study was to measure bilateral CI users' ability to use ITD cues and determine how this compared and related to their ability to use ILD cues for sound localization. Because HRTFs were used to independently manipulate ITD and ILD cues, the first goal was to verify that the HRTFs appropriately simulated the soundfield (SF). Given that other researchers have demonstrated considerable variability across bilateral CI users in terms of ITD sensitivity (e.g., Poon *et al.*, 2009), the second goal was to determine if the primary role of ILD cues in localization, reported in Seeber and Fastl (2008) based on one subject, extends to a larger population of bilateral CI users. The third goal was to determine if ITD cues played a secondary role in localization.

2. Methods

Six bilateral CI users participated in a localization task both in the SF and with a process that simulates the microphone input by sending HRTF-processed signals through a cable directly connected to the CI processor's auxiliary input port (Chan *et al.*, 2008), referred to as direct connect (DC) testing. For DC testing, there were three conditions: (1) both ITD and ILD cues present (ITD+ILD), (2) only ITD cues present (ITD-only), and (3) only ILD cues present (ILD-only). Four additional bilateral CI users completed only the ITD+ILD condition as well as SF testing (see Table 1 for listener details). Participants were assigned identifiers using the following convention: [Left processor] [Right processor] [sequential number], where the processors were coded as F=Cochlear's Freedom, O=Med-El's Opus 2, and T=Med-El's Tempo+ (e.g., the subject identifier FF2 represents the second bilateral Freedom processor user tested).

Generic HRTFs were created from recordings from each processor's microphone with the processor positioned on a Knowles Electronics Manikin for Acoustic Research (KEMAR). Each HRTF was represented as the impulse response of a 100-tap finite impulse response (FIR) filter at a sampling rate of 24 kHz. Separate filters were created for the left and right ears at each azimuth. Anatomical symmetry was assumed, so the right ear HRTF for azimuth A° was identical to the left ear HRTF for azimuth 360 A°. Details of the process by which the HRTFs were created are given in Chan *et al.* (2008).

The ILD-only HRTFs for each ear had the magnitude responses of the original HRTFs, with the ITD cues eliminated by using the identical phase responses for both ears, derived from the right ear HRTF for a source at 180° (i.e., back center). The ITD-only HRTFs for each ear had the phase response of the original HRTFs, with the ILD cues eliminated by using the identical magnitude response for both ears, derived from the right ear HRTF for a source at 180°.

The testing procedure was similar to that in Chan *et al.* (2008). Participants were asked to locate the stimulus (a broadband impulsive gunshot sound) presented from 1 of 12 locations, ranging from 97.5° to 262.5° (i.e., always located behind the participant) and spaced 15° apart. The locations were numbered from 1–12, with 1 located at 97.5° and 12 located at 262.5°. The participant's task was to identify the location that the stimulus originated from. Prior to testing in each condition, participants were familiarized with the real (SF) or virtual (DC) space by listening to the stimulus presented at each location once in ascending and once in descending order. For DC testing, familiarization also included a reference stimulus presented immediately prior to each stimulus, located at 90° and at 270° when familiarizing in the ascending and descending orders, respectively. After familiarization, participants were presented with a practice block followed by the test. Neither the practice block nor the test contained reference stimuli. For practice and test (but not for familiarization), roving was applied to assure that the task was testing participant's use of ITD and ILD cues rather than their ability to discriminate loudness. For SF testing, the presentation level for each stimulus was roved by a randomly selected offset in the range of ±5 dB. For DC testing, the presentation level was roved by using the overall magnitude of a randomly selected location while maintaining the ILD of the target location. To achieve comparable performance between SF and DC testing, the target was presented once at each location for SF testing and twice for DC testing prior to the participant identifying the location (Chan *et al.*, 2008). The number of stimuli presented during the test varied based on the participant's localization performance (Chan, *et al.*, 2008). All participants completed one block of 24 stimuli. Participants who, at minimum, were able to distinguish adjacent groups of three locations with an accuracy of at least 75% for the first block were presented with another block of 24 stimuli.

3. Results

The first goal was to verify that the HRTFs accurately simulated the SF. To compare localization performance between SF and DC testing, root-mean-square (RMS) error scores were calculated for each participant in each condition (Fig. 1). RMS error scores were used because, in addition to being sensitive to information across all locations, this type of analysis is also sensitive to a wide range of changes in the target-response relationship. A paired *t*-test indicated no significant difference between SF and DC testing ($t(9) = -0.8571$, $p = 0.4$), with the two testing modes resulting in very similar mean performance ($\mathrm{SF} = 26.6°$, $\mathrm{DC} = 24.9°$).

The second goal was to determine if the reduced availability of ITD cues for the CI user reported by Seeber and Fastl (2008) was also found for this larger set of participants. Figure 2 shows RMS error scores per listener in the three DC conditions: ITD+ILD (left panel), ITD-only (middle panel), and ILD-only (right panel). A one-way repeated measures analysis of variance revealed a significant main effect of condition $[F(2,10) = 24.7,\ p < 0.001]$. Paired *t*-tests indicated that performance was significantly worse in the ITD-only condition ($\mathrm{mean} = 57.7°$) than in either of

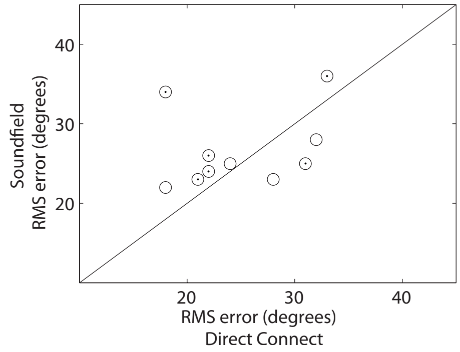

Fig. 1. Scatter plot of RMS error scores obtained when testing in the soundfield and with the ITD+ILD condition of the direct connect testing. Lower scores indicate better performance. Each circle represents one participant. The diagonal line indicates equivalence between the two testing conditions. Dotted circles demarcate participants who also completed the ITD-only and ILD-only conditions.

the other conditions (ITD+ILD mean=24.5° $[t(5)=-5.0,\ p<0.01]$; ILD-only mean=24.5° $[t(5)=-5.4,\ p<0.01]$). Every participant demonstrated this pattern. There was no significant difference in performance between the ITD+ILD and the ILD-only conditions $[t(5)=0,\ p=1]$, both having the same mean RMS error. These results indicated that ILD cues played a primary role in the participants' localization performance.

The third goal was to determine whether bilateral CI users can make use of ITD cues, albeit to a lesser degree than ILD cues. Grantham *et al.* (2007) evaluated whether CI users were performing better than chance by using a computer simulation approach, whereby target lists were randomly generated and paired with randomly generated response sets. This process was repeated to derive a 95% confidence interval for chance performance.

The method of Grantham *et al.* (2007) does not take into account the effects of response bias, e.g., that a given subject might use only a subset of all possible responses. When random guessing is combined with a response bias, the obtained scores can deviate significantly from those resulting from unbiased random guessing. Consequently, confidence intervals were calculated for random guessing that corrected for the response bias for each participant and condition. This was done by randomly sampling with replacement from a given participant's response set for a particular condition to create a generated response set that incorporated the participant's response bias. That generated response set was combined with a randomly generated target list. Ten thousand target-response sets were created per participant and condition following this procedure, and RMS error was calculated for each of these target-response sets.

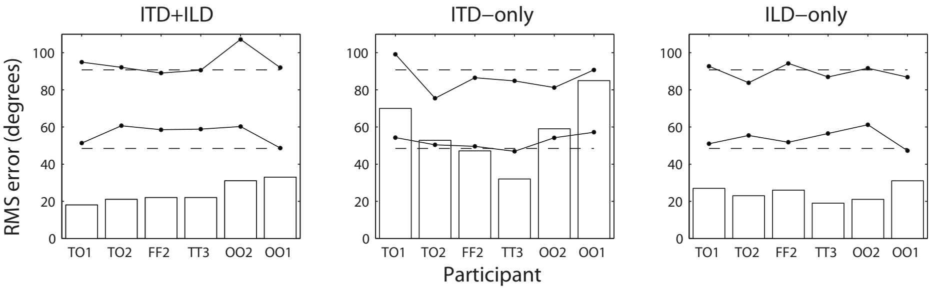

Fig. 2. Bar graphs of the RMS error scores for each participant for the three direct connect testing conditions. Lower scores indicate better performance. The dots connected with solid lines indicate the upper and lower bounds for the 99.2% confidence interval (α corrected for multiple comparisons) for random guessing corrected for the response bias of each participant. For reference, the upper and lower bounds for the 99.2% confidence interval for unbiased chance is shown as dashed lines, calculated as in Grantham *et al.* (2007).

To control for familywise error, a Bonferroni correction was used, setting α to 0.0083. The resulting confidence interval was defined as the range that encompassed 99.2% of the RMS error scores resulting from this simulation (marked by dots connected with solid lines in Fig. 2). Any participant whose RMS error score fell below the lower line of the confidence interval shown in Fig. 2 demonstrated a significant ability to use ITD cues. For comparison, chance, defined using the method of Grantham *et al.* (2007) but with $\alpha=0.0083$, is also presented (confidence interval based on 10,000 randomly generated target-response sets: 48.4° and 90.7°; dashed lines in Fig. 2).

Comparison of the ITD-only scores to the biased random guessing confidence intervals (Fig. 2, middle panel) revealed that two participants performed significantly better than chance when response biases were taken into account (FF2 and TT3), indicating that some of the CI users had a significant ability to localize using interaural temporal cues only.

4. Discussion

This study examined the relative contribution of ITD and ILD cues for bilateral CI users' sound localization. The effects of these cues were independently measured using generic HRTFs designed for each type of CI processor. These HRTFs were verified by comparing each participant's RMS error scores for DC (using the HRTFs) and SF testing. These comparisons revealed similar means and no significant difference between DC and SF testing (Fig. 1).

Comparison of the RMS error scores across the three DC conditions revealed identical mean performance in the ITD+ILD and the ILD-only conditions, and significantly poorer performance in the ITD-only condition (Fig. 2). This pattern of poorer performance in the ITD-only condition was found for every participant and is consistent with the findings using indirect measures (e.g., van Hoesel and Tyler, 2003; Schoen *et al.*, 2005; Grantham *et al.*, 2007; Poon *et al.*, 2009). Despite ILD cues having a primary role, two participants were able to localize significantly better than chance in the ITD-only condition, even when response biases were taken into account (Fig. 2, middle panel).

A closer examination of Fig. 2 suggests that there was a complex interaction between ITD and ILD cues. For example, participants TO1 and OO1 were the two worst performers in both the ITD-only and the ILD-only conditions, yet TO1 was the best performer and OO1 was the worst performer for the ITD+ILD condition.

In summary, this study directly compared the contributions of ITD and ILD cues for bilateral CI users' localization, using the same measure, localization in terms of RMS error, to directly compare the two. The results demonstrated a strong reliance on ILD cues, although the interaction between ITD and ILD cues was complex. The results also indicated significant localization abilities when only using ITD cues for two participants, indicating that some bilateral CI users are sensitive to ITD cues, although further studies are needed to determine how widespread such sensitivity is across CI users. This pattern of results is quite different than that seen with individuals with unimpaired acoustic hearing, for whom ITD cues play a larger role than ILD cues for broadband sounds (e.g., Macpherson and Middlebrooks, 2002).

The results also suggest that improved temporal information may help some CI users. In current clinical practice, a variety of factors reduce the availability of temporal cues including the use of processing strategies that reduce temporal information, poor place pitch matching across interaural electrode pairs, and a lack of synchronization between the two processors. Given the evidence provided above that at least some CI users are sensitive to ITD cues, modifications to current practices that result in a more faithful transmission of temporal information may significantly improve bilateral performance.

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