Cochlear implant patients' localization using interaural level differences exceeds that of untrained normal hearing listeners

Justin M. Aronoff[a)]
Communication and Neuroscience Division, House Research Institute, 2100 West 3rd Street,
Los Angeles, California 90057
jaronoff@hei.org

Daniel J. Freed
EarLens Corporation, 200 Chesapeake Drive, Redwood City, California 94063
dfreed@earlenscorp.com

Laurel M. Fisher
Clinical and Translation Science Division, House Research Institute, 2100 West 3rd Street,
Los Angeles, California 90057
lfisher@hei.org

Ivan Pal
Compreval, Inc., 3 Spinnaker Court, Grayslake, Illinois 60030
ivan.compreval@gmail.com

Sigfrid D. Soli
Communication and Neuroscience Division, House Research Institute, 2100 West 3rd Street,
Los Angeles, California 90057
ssoli@hei.org

Abstract: Bilateral cochlear implant patients are unable to localize as well as normal hearing listeners. Although poor sensitivity to interaural time differences clearly contributes to this deficit, it is unclear whether deficits in terms of interaural level differences are also a contributing factor. In this study, localization was tested while manipulating interaural time and level cues using head-related transfer functions. The results indicate that bilateral cochlear implant users' ability to localize based on interaural level differences is actually greater than that of untrained normal hearing listeners.

PACS numbers: 43.66.Pn, 43.66.Qp, 43.66.Ts [JL]
Date Received: February 2, 2012 **Date Accepted:** March 12, 2012

1. Introduction

Bilateral cochlear implant (CI) patients are unable to localize sounds as well as normal hearing (NH) listeners (Grantham *et al.*, 2007; Majdak *et al.*, 2011). NH listeners rely on interaural time differences (ITDs) and interaural level differences (ILDs) to localize sounds. However, bilateral CI users have considerable difficulty using ITDs to localize (Aronoff *et al.*, 2010), indicating that their localization abilities are primarily or exclusively based on ILDs.

Despite relying primarily on ILDs, studies that have measured ILD sensitivity (in terms of just-noticeable-differences) with acoustically presented stimuli have found that CI users' ILD sensitivity is worse than that of NH listeners (Grantham *et al.*,

---

[a)] Also at: Neurobiology Department, University of Southern California, Los Angeles, CA 90089. Author to whom correspondence should be addressed.

2008; Laback *et al.*, 2004). This suggests that CI users may also have a deficit in terms of ILD-based localization. Alternatively, CI users' relative inability to localize using ITDs would result in extended localization experience relying primarily on ILDs. This in turn may have yielded better ILD-based localization abilities than is seen with untrained NH listeners. The goal of the current study was to compare NH and CI ILD-based localization abilities.

2. Methods

2.1 Participants

Fifteen bilateral CI users were tested using their clinical settings. For the participants using a Freedom processor (Cochlear, Centennial, CO), noise canceling programs and auto-sensitivity, which are separately added in the clinical settings, were disabled. Table 1 provides details on the participants. Forty-two normal hearing listeners with pure tone thresholds $\leq$ 25 dB hearing level (HL) from 0.25 to 8 kHz also participated in this experiment. Localization performance for five of the bilateral CI users was reported in Aronoff *et al.* (2010).

Table 1. Characteristics of the CI participants. ACE = Advanced Combination Encoder; SPEAK = Spectral Peak coding; CIS = Continuous Interleaved Sampling; HDCIS = High Definition Continuous Interleaved Sampling; FSP = Fine Structure Processing.

	Processor		Strategy		Length of use (years)	
Etiology (patient report)	Left	Right	Left	Right	Left	Right
Ototoxic	Cochlear Freedom	Cochlear Freedom	ACE	ACE	7	11
Ototoxic	Cochlear Freedom	Cochlear Freedom	ACE	ACE	0.5	0.5
Unknown	Cochlear Freedom	Cochlear Freedom	ACE	SPEAK	1	14
Progressive/ hereditary	Cochlear Freedom	Cochlear Freedom	SPEAK	ACE	16	0.5
Progressive	Cochlear Freedom	Cochlear Freedom	ACE	ACE	4	2
Hereditary/ ototoxic	Cochlear Freedom	Cochlear Freedom	ACE	ACE	1	1
Progressive	AB Harmony[a]	AB Harmony[b]	HiRes/ Fidelity 120	HiRes/ Fidelity 120	4	0.5
Progressive	AB Harmony[b]	AB Harmony[b]	HiRes/ Fidelity 120	HiRes/ Fidelity 120	2	5
Ototoxic	AB Harmony[b]	AB C1[b]	HiRes/ Fidelity 120	CIS	2	5
Unknown	Med-El Tempo+	Med-El Tempo+	HDCIS	HDCIS	7	7
Mumps/ measles	Med-El Opus 2	Med-El Opus 2	HDCIS	HDCIS	1	1[a]
Ménière's	Med-El Opus 2	Med-El Opus 2	HDCIS	HDCIS	2	.5
Progressive	Med-El Opus 2	Med-El Opus 2	HDCIS	HDCIS	6	6
Ménière's	Med-El Tempo+	Med-El Opus 2	CIS+	FSP	7	1
Unknown	Med-El Tempo+	Med-El Opus 2	CIS+	FSP	7	3

[a] This participant originally was implanted on the right side three years before testing, but device channels started turning on and off unpredictably within three months, and the device was replaced approximately one year before testing.

[b] Participants used the AB Tmic microphone for everyday listening.

2.2 Stimuli

Participants' localization performance was tested using the source azimuth localization test (SALT; Aronoff *et al.*, 2010; Chan *et al.*, 2008), which consists of a broadband impulsive gunshot sound at one of twelve locations. The gunshot sound was chosen because it contains energy across a wide range of frequencies, providing both ITD and ILD cues. For the CI users, the stimuli were presented through the processor's auxiliary input using head-related transfer functions (HRTFs) specific to the type of processor they used in their everyday life. Processor-specific automatic gain control was applied to all signals, either by custom-built software (for Med-El's Tempo+, Durham, NC) or by the processor itself. The stimuli were presented over headphones for the NH listeners. The HRTFs were previously validated by demonstrating comparable performance for sound field and HRTF-based SALT (Aronoff *et al.*, 2010; Chan *et al.*, 2008). The NH listeners were each tested with two sets of HRTFs such that there were data from 12 NH listeners for each processor-specific HRTF (see Table II in Aronoff *et al.*, 2011 for a list of the sets of HRTFs tested with each participant). As a reference, data from 12 NH listeners were also collected using an acoustic hearing HRTF based on recordings from the microphone in the Zwislocki coupler of a Knowles Electronics Manikin for Acoustic Research (Itasca, IL). Versions of the HRTFs were created that preserved the ITDs, the ILDs, or both from the original HRTFs. For each HRTF, the ITD version preserved the phase response of the original HRTF, with the magnitude response for both ears replaced by the magnitude response derived from the right ear HRTF for a source at 180° (i.e., back center). The ILD version preserved the magnitude response of the original HRTF, with the phase response replaced for both ears by the phase response derived from the right ear HRTF for a source at 180°.

2.3 Procedures

Testing followed the same procedure as in Chan *et al.* (2008) and Aronoff *et al.* (2010). Participants were asked to locate a stimulus presented from one of 12 locations. Locations were chosen that were behind the head because it is more crucial in everyday life to be able to localize sounds behind the head based solely on auditory cues than it is to localize sounds in front of the listener, where there is often a visual cue that can be used to help localization. The locations were spaced 15° apart, ranging from 97.5° to 262.5°. All locations were 1 m away from the listener. 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 from which the stimulus originated by verbally indicating the number corresponding to the perceived location. Participants were provided with a diagram that divided the space behind the head into twelve numbered segments, with a stimulus location centered in each segment. Prior to testing in each condition, participants were familiarized with the stimulus locations by listening to the stimulus presented at each of the 12 locations, once in ascending and once in descending order. The location of each stimulus was indicated to the participant using the diagram described above. During familiarization, a reference stimulus was presented immediately prior to each target stimulus. This reference stimulus was located at 90° when familiarizing in the ascending order and at 270° when familiarizing in the descending order. After familiarization, participants were presented with a practice test that included each location presented in a random order. After completing the practice, the participants proceeded to the test. Neither the practice nor the test contained reference stimuli, and no feedback was provided. For the practice and test (but not for familiarization), roving was applied to prevent participants from localizing based on the overall loudness of the stimulus. The presentation level was roved by scaling the stimulus to the HRTF-specific root mean square (RMS) level for the right ear for a randomly selected location. This resulted in roving amounts ranging from 8.9 dB [Advanced Bionics (AB) (Valencia, CA) Tmic HRTF] to 17.2 dB (Freedom HRTF, which uses a directional microphone), depending on the HRTF used. For the practice and test, the target was presented twice at a given location prior to the participant indicating the perceived location of the stimulus. The number of stimuli presented during the test was determined by the participant's localization performance, calculated based on the first block of 24 stimuli (Chan *et al.*, 2008). Participants who, at minimum, were able to distinguish adjacent groups of three locations with an accuracy of at least 75% in the first block were presented with a second block of 24 stimuli. If the required level of accuracy was not achieved in the first block, no additional blocks were tested and the participant's score was calculated based on their performance on the first block. Otherwise, the participant's score was calculated based on their performance combined across the first and second block. The final test score was determined by calculating the RMS localization error, in degrees, based on all responses.

3. Results

Robust statistical techniques and measures were adopted to minimize the potential effect of any outliers or non-normality in the data (for more detail, see the Appendix in Aronoff *et al.*, 2011). RMS error for the CI listeners was analyzed using a percentile bootstrap analysis based on 20% trimmed means. Because different CI listeners used different microphones corresponding to different HRTFs, CI performance was compared to an NH weighted 20% trimmed mean, calculated by weighting the NH 20% trimmed mean for each HRTF (presented in Table 2) by the number of CI users in this study using that particular HRTF. Consistent with previous research (Grantham *et al.*, 2007; Majdak *et al.*, 2011), this analysis indicated that the CI users' binaural localization was significantly poorer than that of the typical NH listener ($p < 0.0001$; CI 20% trimmed mean: 27°; NH weighted trimmed mean: 20°; all scores indicate RMS error and lower scores indicate better performance; see Fig. 1).

Although poor ITD-based localization likely contributed to the CI users' binaural deficit, it is not clear if reduced ILD-based localization also played a role. To determine whether the CI users had poor ITD- and ILD-based localization compared to NH listeners, localization performance with the ITD and ILD HRTFs was analyzed using a percentile bootstrap analysis based on 20% trimmed means. As expected, CI users' ITD-based localization was significantly poorer than that of the typical NH listener ($p < 0.0001$; CI 20% trimmed mean: 62°; NH weighted trimmed mean: 24°; see Fig. 1). In contrast, the analysis of ILD-based localization indicated that CI users were significantly better than the typical NH listener ($p < 0.01$; CI 20% trimmed mean: 28°; NH weighted trimmed mean: 37°; see Fig. 1). This was the case even if CI performance was compared to that of NH listeners using the acoustic hearing HRTF ($p < 0.02$; NH 20% trimmed mean: 34°). These results suggest that bilateral CI users have exceptional localization abilities using ILDs.

4. Discussion

The CI users' ILD-based localization performance was particularly striking, reflecting performance above that of the NH listeners. This may reflect how the signal is

Table 2. Trimmed means of RMS error in degrees for the NH listeners for each HRTF. The standard deviation, calculated using Sn (see the Appendix in Aronoff *et al.*, 2011) is shown in parentheses.

HRTF	ITD + ILD	ITD	ILD
Acoustic hearing	24.0 (8.4)	25.8 (10.7)	34.4 (8.3)
AB (Tmic)	17.1 (4.8)	22.1 (4.8)	39.6 (7.2)
Freedom	20.8 (9.5)	24.3 (9.5)	34.0 (9.5)
Tempo+	18.0 (6.0)	21.9 (4.8)	32.3 (10.7)
Opus 2	20.9 (6.0)	23.3 (4.8)	38.3 (9.5)
Tempo+/Opus 2	22.1 (6.0)	25.1 (3.6)	43.5 (8.4)

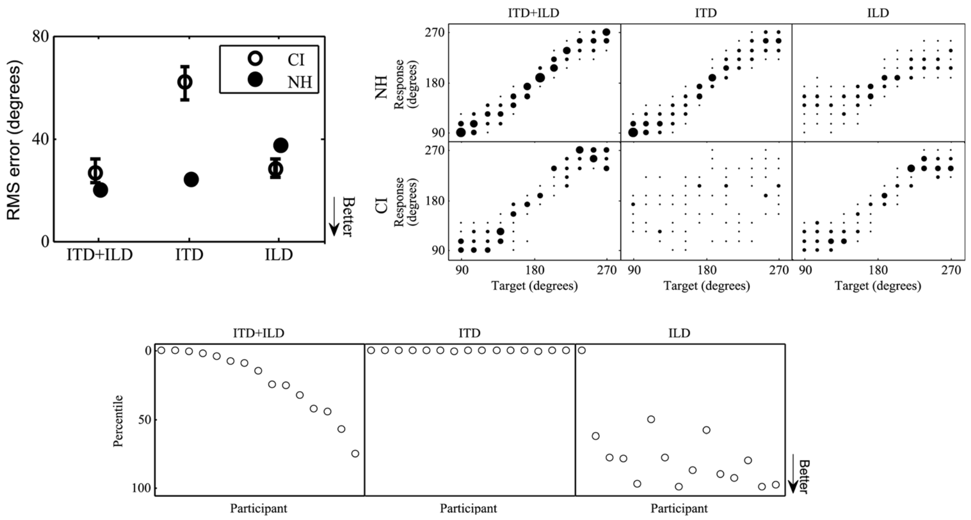

Fig. 1. In the top left panel, localization scores in terms of RMS error are provided for CI listeners and NH listeners. Each data point represents the trimmed mean for the CI users and the weighted trimmed mean for the NH listeners. Error bars indicate 95% confidence intervals for the trimmed means based on bootstrap analyses. Lower scores indicate better performance. Response patterns are shown in the top right panel. In the bottom panel, performance for each CI user is presented. Participants are ordered based on performance using the ITD + ILD HRTFs. To facilitate comparison across different processors, scores are presented as percentiles based on a normal distribution with a mean and standard deviation matching the processor-specific NH data presented in Table 2. Lower scores indicate better performance. Results suggest that CI users' binaural localization deficit largely reflects a deficit for using ITD cues, alongside exceptional performance using ILD cues.

processed by the cochlear implant, possibly resulting in magnified ILD cues. However, the results from Grantham *et al.* (2008) and Laback *et al.* (2004), indicating that CI users have worse ILD sensitivity when using speech processors compared to NH listeners, would suggest that this is not the case. Alternatively, CI users' excellent ILD-based localization may reflect differences in the perceptually available information since the HRTFs with only ILDs preserved may sound similar to the ITD + ILD HRTFs for CI users, given their minimal access to ITDs when using clinical processors. However, one CI user was able to localize relatively well with ITD cues [the bilateral Tempo+ (Med-El, Durham, NC) user had an ITD-based localization RMS error score of 33°], yet her ILD-based localization (RMS error score of 24°) was still better than that of the typical NH listener using any of the HRTFs. Another explanation may be that CI users have learned to better use ILD cues as a result of their minimal access to ITD cues, much as patients with high frequency hearing loss make better use of low frequency information (Hornsby *et al.*, 2011). This would suggest that, with proper training, NH listener's ILD-based localization may be comparable to or exceed that of the CI users.

Despite excellent localization using ILDs, the results also indicated that the CI users' ILD-based localization did not compensate for their inability to use ITD cues. Consistent with previous studies (e.g., Grantham *et al.*, 2007; Majdak *et al.*, 2011), when both ITD and ILD cues were combined, CI users did not perform as well as the typical NH listener. This suggests that CI users' difficulty using ITD cues with clinical processors is significantly limiting their ability to localize sounds. As such, improving CI users' localization may require improving ITD sensitivity. There are a number of ways that may be accomplished, such as by using low pulse rates (van Hoesel *et al.*, 2009), or reducing interaural mismatches in terms of place of stimulation (Poon *et al.*, 2009). Conversely, given CI users' impressive ILD-based localization, it may be possible to improve localization by enhancing ILDs.

5. Conclusions

Previous studies have indicated that bilateral CI users' ILD sensitivity is worse than that of NH listeners. However, that deficit does not translate into a comparable deficit in ILD-based localization. Instead, the results of this study indicate that CI users' ability to localize using ILD cues is better than that of untrained NH listeners.

Acknowledgments

We thank our participants for their time and effort. We also thank Advanced Bionics, Cochlear Ltd., and Med-El for providing equipment and expertise for this study, and John Wygonski for hardware development. This work was supported by NIH Grant Nos. R44DC005759 (S.D.S.) and T32DC009975 (J.M.A.).

References and links

Aronoff, J. M., Freed, D. J., Fisher, L., Pal, I., and Soli, S. D. (**2011**). "The effect of different cochlear implant microphones on acoustic hearing individuals' binaural benefits for speech perception in noise," Ear Hear. **32**(4), 468–484.

Aronoff, J. M., Yoon, Y.-S., Freed, D. J., Vermiglio, A. J., Pal, I., and Soli, S. D. (**2010**). "The use of interaural time and level difference cues by bilateral cochlear implant users," J. Acoust. Soc. Am. **127**(3), EL87–EL92.

Chan, J. C., Freed, D. J., Vermiglio, A. J., and Soli, S. D. (**2008**). "Evaluation of binaural functions in bilateral cochlear implant users," Int. J. Audiol. **47**(6), 296–310.

Grantham, D. W., Ashmead, D. H., Ricketts, T. A., Labadie, R. F., and Haynes, D. S. (**2007**). "Horizontal-plane localization of noise and speech signals by postlingually deafened adults fitted with bilateral cochlear implants," Ear. Hear. **28**(4), 524–541.

Grantham, D. W., Ashmead, D. H., Ricketts, T. A., Haynes, D. S., and Labadie, R. F. (**2008**). "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. **29**(1), 33–44.

Hornsby, B. W. Y., Johnson, E. E., and Picou, E. (**2011**). "Effects of degree and configuration of hearing loss on the contribution of high- and low-frequency speech information to bilateral speech understanding," Ear. Hear. **32**(5), 543–555.

Laback, B., Pok, S.-M., Baumgartner, W.-D., Deutsch, W. A., and Schmid, K. (**2004**). "Sensitivity to interaural level and envelope time differences of two bilateral cochlear implant listeners using clinical sound processors," Ear. Hear. **25**(5), 488–500.

Majdak, P., Goupell, M. J., and Laback, B. (**2011**). "Two-dimensional localization of virtual sound sources in cochlear-implant listeners," Ear. Hear. **32**(2), 198–208.

Poon, B. B., Eddington, D. K., Noel, V., and Colburn, H. S. (**2009**). "Sensitivity to interaural time difference with bilateral cochlear implants: Development over time and effect of interaural electrode spacing," J. Acoust. Soc. Am. **126**(2), 806–815.

van Hoesel, R. J., Jones, G. L., and Litovsky, R. Y. (**2009**). "Interaural time-delay sensitivity in bilateral cochlear implant users: Effects of pulse rate, modulation rate, and place of stimulation," J. Assoc. Res. Otolaryngol. **10**(4), 557–567.