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Effects of Reverberation on Sound Localization for Bilateral Cochlear Implant Users

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Abstract

The purpose of this study was to examine the effects of reverberation on the ability of listeners with bilateral cochlear implants (BCIs) to localize speech in anechoic and reverberant environments. Two specific research questions were addressed: (1) how do listeners with BCIs localize sounds in different environments compared to listeners with normal hearing (NH)? and (2) at what reverberation time (RT_{60}) does localization performance begin to decline for both groups of subjects? Six adults with BCIs and ten with NH participated. All subjects completed a virtual localization test in simulated anechoic and reverberant environments (0.0, 0.2, 0.6, and 0.9 s RT_{60}) in quiet. A three-word phrase was presented at 70 dBSPL from nine simulated source locations in the frontal-horizontal plane (± 90°). Root-mean-square localization error (RMSLE) in degrees was calculated. Results revealed localization accuracy significantly decreased as reverberation time increased for both groups of subjects. Listeners with BCIs had significantly poorer localization accuracy than listeners with NH in all conditions. Their RMSLE changed from 32° in anechoic condition to 60° in RT_{60} 0.9s condition, while corresponding change for listeners with NH was only from 17° to 22°. In addition, localization performance of listeners with BCIs started to decrease at a shorter reverberation time (RT_{60} 0.6s) compared to those with NH (RT_{60} 0.9s). In conclusion, reverberation significantly degraded localization performance, with a greater influence on listeners with BCIs than listeners with NH. In addition, bilateral experience is likely to help listeners with BCIs achieve a better localization outcome over time. It is important to apply the information obtained in this study to optimize binaural benefit for listeners with BCIs in everyday listening situations.

Keywords: Reverberation; Sound localization; Bilateral cochlear implants

Introduction

Cochlear implants have been shown to provide remarkable hearing benefits to people with severe-to-profound sensorineural hearing loss who receive little or no benefit from hearing aids [1]. However, due to the limitations of current signal processing strategies and implant compression circuits, binaural cues (interaural time and level cues) that are important for accurate sound localization, are not fully preserved by the CI devices [2]. Even with two devices, listeners with bilateral cochlear implants (BCIs) have difficulty localizing sounds in typical listening environments, and have poorer than normal localization performance [2,3].

Reverberation is part of natural listening environments. Excessive reverberation affects localization and speech perception performance by masking the stimuli and/or altering timing cues of the stimuli. Studies have revealed adverse effects of reverberation on listeners with normal hearing (NH). Specifically, their localization performance was consistently poorer in a reverberant room than in an absorbent room [4] and localization accuracy of continuous broadband noise decreased significantly with increasing RT_{60}/ RT_{30} [5,6]. Sound localization is crucial for both communication and safety; therefore, it is important to understand the effect of reverberation on the ability of listeners with BCIs to locate sound sources.

There have only been a few studies that included reverberation as a variable to examine localization in listeners with BCIs. Neuman et al. [7] investigated the benefit of binaural implantation on sound localization in a large classroom with a RT_{60} of 0.4 sec. The results showed a BCI benefit to sound localization compared to unilateral cochlear implant (UCI), but the study did not vary the RT_{60} or test in an anechoic room, so the effect of reverberation in their study cannot be quantified. In another study by Verschuur et al. [8], various stimuli including speech in the sound-field, with and without simulated reverberation, were used to examine the binaural advantage of BCIs for localization. The reverberation time of the room was not specified; the authors only reported that localization performance was significantly more accurate for speech, including both reverberant and non-reverberant speech, than for non-speech stimuli. An effect of reverberation was not reported in this study [8].

To our knowledge, there have been only two studies that have examined the effect of reverberation on localization performance of listeners with BCIs. In an earlier study [3] seven listeners with NH and two with BCIs listened to a three-word phrase at various SNRs in a simulated anechoic and a simulated reverberant environment (RT=0.2s). Results revealed significantly poorer localization accuracy for listeners with BCIs than listeners with NH in all conditions, and a significant reverberation effect was observed for listeners with BCIs but not for listeners with NH. Similarly, Kerber and Seeber [9] in 2013 recruited seven listeners with BCIs who listened to noise pulses in an anechoic and a simulated reverberant room (RT_{60}=0.4s). Their results

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indicated significantly poorer localization accuracy in a reverberant room than in an anechoic environment.

Neither of these studies [3,9] systematically investigated the effects of varying reverberation time on sound localization for listeners with BCIs. Therefore, in this study, we included more listeners with BCIs and added more and longer reverberation times to investigate how reverberation affects localization performance for listeners with BCIs. The same virtual localization procedure [10] used in the preliminary study was applied to address two specific questions: (1) how do listeners with BCIs localize sounds in reverberant environments compared to listeners with NH; and (2) at what reverberation time (RT_{60}) does localization performance begin to decline for both groups of subjects?

Methods

Subjects

Two groups of age matched subjects participated in this study: ten listeners with NH and six postlingually deafened listeners with BCIs. Table 1 provides the background information for the subjects with BCIs. All of them were adult native English speakers, age ≥ 18 years. Two of the subjects had sudden hearing loss due to Meniere's Disease, and four of them had gradual hearing loss with unknown etiology. None of the subjects had a history of neurological pathology. All subjects with normal hearing have pure tone thresholds of 25 dB HL or better at the octave frequencies from 250 Hz through 8000 Hz.

Subject #	Age & Gender	CI device and processor	CI strategy	Age at implantation	BCI experience	Etiology and onset of hearing loss
1	62 years, F	ABC* HiRes 90k Harmony L + R	HiRes 120 L + R	L: 49 yrs R: 59 yrs	26 months	Unknown; age 20 yrs
2	65 years, M	ABC* HiRes 90k Harmony L + R	HiRes 120 L + R	L: 64 yrs R: 53 yrs	24 months	Unknown; age 10 yrs
3	52 years, F	CC* CI24RE(CA) Freedom L + R	ACE L + R	L: 50 yrs R: 51 yrs	18 months	Unknown; age 31 yrs
4	69 years, F	CC* CI24RE(CA) Freedom L + R	ACE L + R	L: 67 yrs R: 67 yrs	31 months	Bacterial Meningitis age 67 yrs
5	49 years, F	CC* L: CI24RE(CA) R: CI24R(CS) Freedom	ACE L + R	L: 46 yrs R: 38 yrs	27 months	Unknown; age 15 yrs
6	53 years, M	CC* CI24RE(CA) Freedom L + R	L: ACE R: CIS``	L: 52 yrs R: 51 yrs	14 months	Meniere's Disease; age 42 yrs
*ABC=Advanced Bionics Corporation; CC=Cochlear Corporation						

Table 1: Background information for BCI users.

Stimuli and listening conditions

Stimuli were presented simultaneously to both ears through circumaural headphones (Sennheiser HD 265). The signal, a three-word phrase, "Mark the spot", was presented from nine simulated locations in the frontal horizontal plane from -90° to +90° in 22.5° steps. At 0° azimuth the signal level was 70 dB SPL; the level at each ear for sources at other locations varied due to the head-shadow effect. The stimuli were processed for each source location for each ear in each listening environment (quiet anechoic and quiet reverberant). Localization ability was assessed in quiet at four RT_{60s} (0 s, 0.2 s, 0.6 s, and 0.9 s) for both groups of subjects. Van Hoesel, Ramsden, and O'Driscoll [11] found that signal presentation level decreases localization ability of listeners with BCIs due to activation of the automatic gain control (AGC). Therefore, to avoid possible activation by the experimental stimuli, the AGC was turned off before the experiment and turned back on when the subjects completed the study.

Signal processing

Before presentation to the listeners the stimuli were processed to simulate different listening conditions. Rychtarikova et al. [6] found comparable localization performance when using virtual stimuli processed using different types of impulse responses. Impulse responses for the anechoic environment and the RT_{60}=0.2 s environment were measured using KEMAR in an actual room as described in Besing and Koehnke [10]. Note that the RT_{60}=0.2 s is the averaged reverberation time across octave bands. For RT_{60} of 0.6 s and 0.9 s environments, Matlab^{TM} was used to generate head-related transfer functions (HRTFs) for each ear and each sound source location [12] to simulate the sound-field conditions. DADiSP software was used to convolve the HRTFs with the phrase Mark the Spot in order to generate the virtual localization stimuli. During signal processing, the stimuli were filtered by HRTFs separately for each ear and each sound source location, and then presented to each ear via headphones. Figure 1 shows the simulated room size and speaker arrangement. The room size and arrangement are the same for all listening environments including AN, RT 0.2 s, 0.6 s, and 0.9 s. Further details can be found in Koehnke and Besing [13] and Zheng et al. [3].

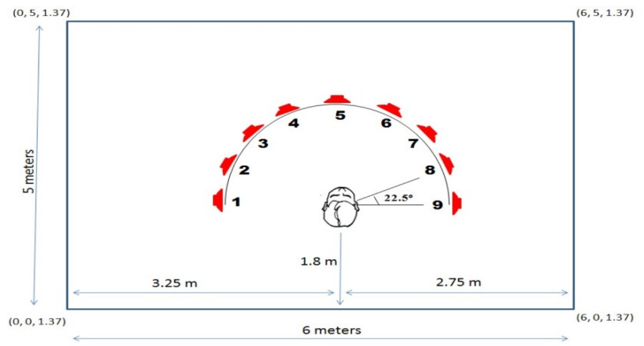

Figure 1: Simulated room size and speaker montage.

Procedure

For subjects with NH, a pure-tone air conduction test and an acoustic immittance screening were conducted first to make sure hearing sensitivity and middle ear function were normal.

During the experiment all subjects with BCIs wore their processors set as they were routinely used with the exception of the AGC setting. These settings were obtained using standard clinical fitting procedures, which involved device mapping one ear at a time, loudness matching across the electrode array within the ear, and loudness balancing across ears. At our facility, loudness balance was re-checked formally for each CI user to ensure equal-loudness between ears. Then, a sound-field hearing test was administered in a sound-treated room to measure warble-tone thresholds for each subject with each cochlear implant (CI-left/CI-right) in order to estimate the appropriate signal presentation level when wearing both implants.

Prior to testing, all subjects were familiarized with the experimental procedure by presenting the stimuli randomly from each of the nine simulated sound source locations with feedback for two listening conditions (Quiet/AN and Quiet/RT0.2).

During the experiment the subjects were seated in a quiet, sound-treated room, and presented with sounds via circumaural earphones (Sennheiser HD 265). The virtual localization test was administered to the subjects in a random order for the different reverberation conditions. A single-interval, nine-alternative, forced-choice identification procedure with feedback was used to measure localization ability. The subjects indicated the perceived location of the virtual sound source by choosing the appropriate visual image shown on the computer monitor.

For each subject, there were a total of 4 conditions (anechoic and 3 RTs). Each run in each condition had 27 trials, three for each of the nine source locations. Each condition was repeated twice unless the root-mean-square localization error (RMSLE) between two runs differed by more than 11.25°. In this case a third run was completed and the two runs with the closer RMSLE were used for further data analysis. Each run of 27 trials took about 2-3 minutes. Breaks were arranged between tests. For each subject, it took about two hours to complete the entire experiment including the hearing test, implant adjustment, training, and virtual localization tests.

Results

RMSLE in degrees was calculated to illustrate the deviation of subject's response from the actual sound location, as

$$\sqrt{\frac{\sum\left(x_i - x_0\right)^2}{n}}$$

Where x_i is the actual location of the sound source in degrees, x_0 is the subject response location in degrees, and n is the number of possible responses.

Multivariate analysis of variance (MANOVA) and post-hoc Tukey Honestly Significant Difference (HSD) were used to determine the effects of reverberation on localization performance for each group of subjects and to compare the performance between groups. The bar graph in Figure 2 shows the average RMSLE in degrees for listeners with NH and listeners who use BCIs in anechoic and reverberant environments. Group comparison indicates that listeners with BCIs had significantly poorer localization accuracy than listeners with NH ($p<0.0001$) in all conditions. Their RMSLE changed from 32° in anechoic condition to 60° in RT_{60} 0.9 s condition, while corresponding change for listeners with NH was only from 17° to 22°.

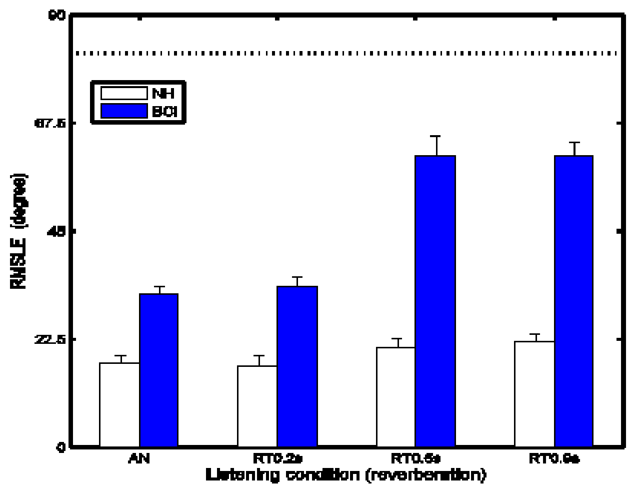

Figure 2: Sound source localization in anechoic and reverberant environments for listeners with normal hearing (NH) and bilateral cochlear implants (BCIs). The RMSLE in degrees is indicated on the y-axis versus the listening conditions on the x-axis. Chance performance is indicated by the dashed line at 82°. Average results for the subjects with NH are indicated by the white bars, and average results for listeners with BCIs are indicated by the blue bars. Standard errors are indicated for each condition for each group of subjects.

The across listening condition analysis for both groups of subjects showed a significant difference ($p<0.0001$), suggesting that at least one listening condition was significantly different from the others for each group of subjects. Post-hoc Tukey HSD ($\alpha=0.05$) indicates a significant performance difference between the AN and RT_{60} 0.9 sec conditions for subjects with NH, and between AN and RT_{60} 0.6 s and 0.9 sec conditions for listeners who use BCIs. That is, the RMSLE was significantly larger in the RT_{60} 0.9 s condition than in the AN

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condition for listeners with NH, and significantly larger in the RT_{60} 0.6 s and 0.9 s conditions than in the AN condition for listeners with BCIs.

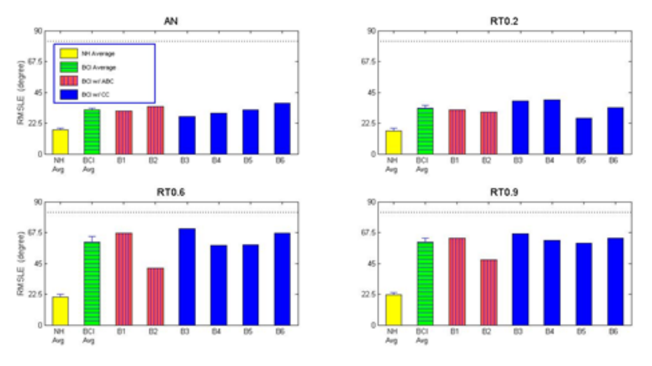

Figure 3: Sound source localization in anechoic and reverberant environments. The RMSLE in degrees is indicated on the y-axis versus the listening conditions on the x-axis. Chance performance is indicated by the dashed line at 82°. Average results for the NH subjects are indicated by the yellow bars, and average results for the BCI users are indicated by the green + horizontal line bars. Standard errors are indicated for each condition for both groups of subjects. Individuals with ABC devices are indicated by the red + vertical line bars and individuals with CC devices by blue bars. NH=Normal Hearing; BCI=Bilateral Cochlear Implant; AN=Anechoic; B1-6=BCI subject 1-6; ABC=Advanced Bionics Corporation; CC=cochlear corporation.

Individual localization performance of listeners with BCIs, data is plotted in Figure 3. This figure shows RMSLE in degrees in different listening environments (AN, RT_{60} 0.2 s, 0.6 s and 0.9 s) for each listener with BCIs compared to the average data and the average data of listeners with NH. It indicates clearly poorer localization accuracy for listeners with BCIs than listeners with NH in all listening environments. In addition, all listeners with BCIs had similar localization performance in AN and RT_{60} 0.2 s environments, but localization accuracy decreased significantly in both RT_{60} 0.6 & 0.9s environments. However, no clear performance difference among listeners with BCIs was observed with exceptions of subject #5, whose localization accuracy is relatively better in RT_{60} 0.2 s condition, and subject #2, whose localization accuracy was clearly better than others in RT_{60} 0.6 s and 0.9 s conditions.

Results obtained in this study were also compared with those in our previous study [3] so that the effect of experience for listeners with BCIs was investigated. Two of the BCI subjects in this study also participated in our previous study, except at the time of the present study they had more BCI experience than in the previous study. Specifically, they were 24/26 months post implantation in the current study, versus 6/8 months post implantation in the 2011 study. In addition, the AN and RT_{60} of 0.2 s listening environments were the same for both studies. Figure 4 shows the average RMSLE in degrees for listeners with BCIs in anechoic and RT_{60}=0.2 s reverberant environments in both preliminary and current studies. There is a clear improvement of localization performance with increased BCI experience in both listening conditions, and the improvement was greater in the anechoic environment than in the reverberant environment.

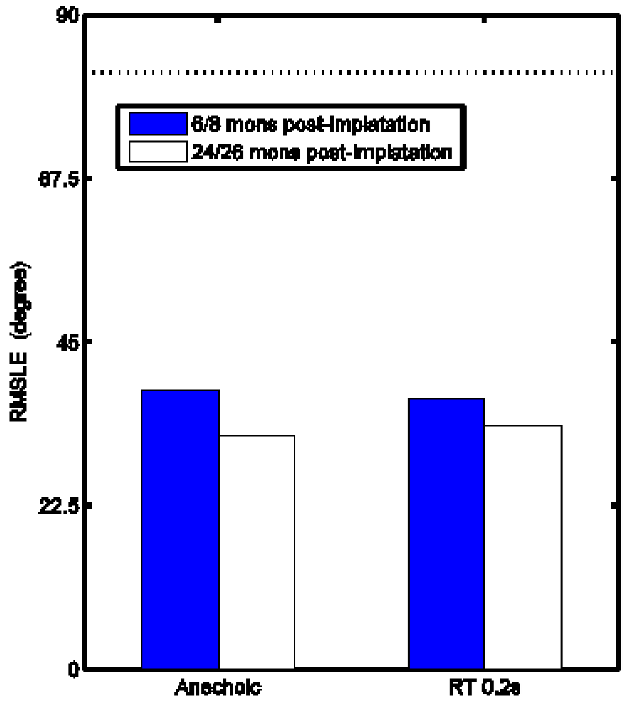

Figure 4: The effect of listening experience on sound source localization RMSLE data from Zheng et al. and the current study in quiet in the anechoic and RT60=0.2 sec reverberant environments for two listeners with BCIs. The RMSLE in degrees for localization at 6/8 months or 24/26 months post implantation is indicated on the y-axis versus the listening conditions on the x-axis. Chance performance is indicated by the dashed line at 82°. BCI=Bilateral Cochlear Implant; AN=Anechoic; RT=Reverberation Time.

Discussion

Localization performance was assessed in simulated anechoic and reverberant environments for listeners with NH and those who use BCIs. Results reveal a significant effect of reverberation on both groups of subjects. Localization accuracy decreased as reverberation time increased, which is consistent with previous reports by Giguere and Abel [4], Hartmann [5], and Zheng et al. [3]. Compared to listeners with NH, listeners who use BCIs had significantly poorer localization performance in both anechoic and reverberant environments. In addition, their localization accuracy was poorer at a shorter reverberation time (RT_{60} 0.6 s) than listeners with NH (RT_{60} 0.9 s). The reverberation time at which localization began to degrade in listeners with BCIs in this study was a little longer than that found by Kerber and Seeber [9] (RT_{60} 0.4 s). This could be because the stimulus (a three-word-phrase) used in this study was easier to identify than the stimulus (noise pulses) used by Kerber and Seeber. According to Kerber and Seeber [9], Speech signals contain more waveform envelope information than noise signals, which thus provides some timing cues that may improve localization performance in a reverberant environment. In addition, studies have demonstrated that speech signals are localized more accurately than noise signals by listeners with BCIs [8,14,15].

Interestingly, similar to our previous study [3], there was no effect of reverberation on sound localization of listeners who use BCIs for the RT_{60}=0.2 s compared to the anechoic condition. It would be interesting to compare our result with Kerber and Seeber findings [9]; their data revealed a significant adverse effect of reverberation on listeners with BCIs for RT_{60}=0.4 s in quiet. This could be because of the relatively shorter reverberation time used in the current study (RT_{60}=0.2-0.4 s as a function of frequency) than in their study (RT_{60}=0.4 s at all frequencies). The uniformly longer reverberation time may have resulted in more degraded sound localization ability. In addition, individual differences may account for the different findings of the two studies. There were limited numbers of subjects who use BCIs involved in both studies (this study: six; Kerber and Seeber: seven); in this study the listeners who use BCIs were fairly homogeneous who had normal or close to normal hearing sensitivity with excellent speech understanding ability in quiet when wearing their devices and had fairly consistent localization performance across subjects (Figure 3). Excellent speech understanding ability as measured in the subjects in our study may reflect better ability to process timing cues in the speech envelope. This may result in an improvement in localization in the reverberant environment [16-18].

In additional to measuring localization in individuals who use BCIs, Kerber and Seeber examined subjects sensitivity to ITD and ILD, the cues thought to underlie accurate localization. This sensitivity to ITDs in the speech envelope may improve localization ability in reverberant environments. This may explain why listeners who use BCIs are not affected by short reverberation times when localizing in quiet environments.

Two of the subjects who use BCIs in the present study also participated in our previous investigation. We compared results obtained in this study to their previous performance to investigate the effect of experience on localization in listeners who use BCIs. In the previous study subjects had 6 and 8 months BCI experience; at the time of this study the same subjects had 24 and 26 months experience. As shown in Figure 3, both subjects showed clear improvement in both anechoic and reverberant environments. This is consistent with the results of Tyler et al. [15]. This further confirms BCI users' ability to use binaural cues, and suggests that with more experience and possibly focused auditory training listeners with BCIs can achieve improved binaural processing. Interestingly, the localization performance improvement was greater in the anechoic environment than in the reverberant environment. This suggests further that with longer experience and/or training, users with BCIs may achieve better performance in more adverse listening environments.

Conclusion

This is the first reported study to investigate the effect of increasing reverberation time on localization in listeners with BCIs. Results revealed localization accuracy significantly decreased as reverberation time increased. Listeners with BCIs had significantly poorer localization accuracy than listeners with NH in both anechoic and reverberant environments. In addition, localization performance of listeners with BCIs started to decrease at a shorter reverberation time (RT_{60} 0.6 s) compared to those with NH (RT_{60} 0.9 s). In conclusion, reverberation significantly degraded localization performance, with a greater influence on listeners with BCIs than listeners with NH. In addition, bilateral experience is likely to help listeners with BCIs achieve a better localization outcome over time.

The clear effects of reverberation provide useful information concerning the binaural processing ability of listeners with NH and with BCIs. The data obtained in this study for listeners with NH will be useful for comparison in future evaluations of localization ability not only in individuals with BCIs, but also in individuals with bilateral hearing aids or bi-modal CI/hearing aid. The data obtained for listeners with BCIs provides concrete information regarding the specific reverberation time at which the localization ability of these listeners begins to degrade. This information should be useful for refining CI processing strategies and developing CI rehabilitation strategies to optimize binaural benefit for users with BCIs in everyday listening situations and improve their quality of life.

In this study we only describe results for localization in quiet. However, a typical listening environment includes both noise and reverberation. In addition, the experience effect observed in this study suggests more experience and/or training might improve localization ability in more adverse environments. Further study has been undertaken to investigate the combined effect of noise and reverberation on localization in listeners with NH and with BCIs. These data will be described in a separate paper.

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