Effects of Noise and Reverberation on Virtual Sound Localization for Listeners With Bilateral Cochlear Implants

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Objective: This study investigated the effects of both noise and reverberation on the ability of listeners with bilateral cochlear implants (BCIs) to localize and the feasibility of using a virtual localization test to evaluate BCI users.

Design: Seven adults with normal hearing (NH) and two adults with BCIs participated. All subjects completed the virtual localization test in quiet and at 0, −4, −8 dB signal-to-noise ratio in simulated anechoic and reverberant environments. BCI users were also tested at +4 dB signal-to-noise ratio. The noise source was at 0°. A three-word phrase was presented at 70 dB SPL from nine simulated locations in the frontal horizontal plane (±90°).

Results: Results revealed significantly poorer localization accuracy for BCI users than NH listeners in all conditions. Significant reverberation effects were observed for BCI users but not listeners with NH.

Conclusion: Noise and reverberation have a significant effect on BCI users, and their localization ability can be evaluated using these virtual tests.

(Ear & Hearing 2011;32;1–●)

INTRODUCTION

Typical listening environments contain noise and reverberation, which degrade the binaural cues used for sound localization by listeners with normal hearing (NH) and impaired hearing (IH) (Hartmann 1983; Lorenzi et al. 1999a,b). There is a variety of approaches to address the difficulties individuals encounter in these situations. For patients with severe to profound sensorineural hearing loss for whom hearing aids offer little or no benefit, cochlear implants (CIs) have been shown to be an effective rehabilitative method (Brown & Balkany 2007). However, sound source localization is a problem that continues to be faced by CI users. Previous localization studies of CI users have focused on performance in quiet. Results indicate that bilateral cochlear implants (BCIs) help restore spatial hearing to some extent (Schön et al. 2005), and speech is localized more accurately than noise signals (Grantham et al. 2007).

To our knowledge, there has been only one study investigating the effects of noise on localization in BCI listeners. Van Hoesel et al. (2008) recruited four BCI users to locate a click train (100 and 500 Hz) in noise (at 0° or 90°) in the sound field in an anechoic chamber at 0 dB signal-to-noise ratio (SNR). The signals were presented from one of seven speakers mounted in the frontal horizontal plane (±90°, radius 1.1 m). Results showed that root mean square localization errors (RMSLEs) were larger when the noise was located at 90° azimuth than at 0° azimuth, in agreement with Lorenzi et al. (1999a,b). Two other studies have included reverberation as a variable when measuring localization in BCI users. Neuman et al. (2007) evaluated localization in a real room with a reverberation time (RT_{60}) of 0.4 secs but did not include an anechoic room. Thus, reverberation effects were not investigated. In contrast, Verschuur et al. (2005) presented stimuli via loudspeakers in an anechoic chamber and added reverberation to the stimuli. Results indicated better localization accuracy for speech stimuli (reverberant and nonreverberant) than nonspeech stimuli (pink noise, 1 kHz beep, and transient); however, reverberation time and effects of reverberation were not reported. In addition, none of these studies systematically explored the effects of varying SNR on localization for BCI users. Therefore, this study was designed to evaluate the individual and combined effects of noise and reverberation on localization of BCI users.

Most previous research on sound localization of listeners with CIs has been conducted in a free field (Grantham et al. 2007). One study used a nontraditional approach, earphone delivery of stimuli, to evaluate binaural processing of BCI users (Grantham et al. 2008). They obtained reliable data and confirmed that it is possible to study binaural processing in BCI users with signals presented via earphones. However, there have been no studies of individuals with BCIs using virtual, spatial stimuli, although virtual localization has been shown to be a sensitive tool for evaluating children and adults with NH (Besing & Koehnke 1995a,b) and IH (aided and unaided) (Koehnke & Besing 1997). The advantage of this approach is that it eliminates many issues encountered in sound field testing such as head movement, difficulty controlling reverberation, and calibration. Therefore, this study was also designed to confirm the feasibility of using virtual localization tests with BCI users.

In this study, we used the Spatial Localization in Quiet (SLIQ) and Spatial Localization in Noise Test (SPLINT) developed by Besing and Koehnke to investigate the effects of noise and reverberation on the ability of listeners with BCIs to localize speech (Besing & Koehnke 1995a; Strother et al. 1998). Information obtained in this study extends our understanding of the effects of noise and reverberation on localization in BCI users. It may also be useful for modeling performance of BCI users in different noise and/or reverberation situations and for improving the design of CI processing strategies to optimize binaural benefit for BCI users in everyday listening situations.

SUBJECTS AND METHODS

Subjects

Seven adults with NH (age 23 to 54 yrs) and two adults with BCIs were recruited. The background information for the BCI

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TABLE 1. Background information for BCI users

Subject	Age, Gender	CI Device	CI Strategy	Age at Implantation	BCI Experience	Age Received Hearing Aids	Hearing Aid Experience	Etiology and Onset of Hearing Loss
1	60 yrs, F	ABC Harmony R + L	HiRes 120 R + L	L: 49 yrs R: 59 yrs	8 mos	L: 24 yrs R: 24 yrs	L: 8 yrs R: 25 yrs	Unkown; age 20 yrs
2	65 yrs, M	ABC HiRes 90k R + L	HiRes 120 R + L	L: 64 yrs R: 53 yrs	6 mos	L: 17 yrs R: 18 yrs	L: 36 yrs R: 26 yrs	Unknown; age 10 yrs

ABC, Advanced Bionics Corporation.

subjects is provided in Table 1. Listeners with NH had pure-tone thresholds of 25 dB HL or better at octave frequencies from 250 to 8000 Hz. None of the subjects had a history of neurological pathology.

Stimuli and Listening Conditions

The SPLINT virtual localization test developed by Besing and Koehnke (1995a) was used in this study. In the no-noise condition, a variation (the SLIQ) was used. To simulate the sound field conditions, KEMAR was used to record head-related transfer functions (HRTFs) in anechoic and reverberant (RT_{60} = 0.2–0.4 secs) rooms for each ear and each sound source location (Burkhard & Sachs 1975). The HRTFs were measured using Zwislocki couplers (Knowles, DB100) with ER-11 1/2″ microphones and preamplifiers (Etymotic Research). Please refer to Besing and Koehnke (1995a) for further details of HRTF measurement.

The same HRTFs were used to process the stimuli for both groups of subjects (NH and BCI). When recording the HRTFs, an equalization filter was used to compensate for KEMAR's ear canal response (Killion 1979). During the experiment, subjects obtained their own canal resonance. They may have also received some pinna cues because the Sennheiser earphones used to present the stimuli are circumaural. However, this likely varied among the subjects depending on the size of their pinna relative to the earphones. Both BCI users in this study had T-mics, which were placed at the entrance of their ear canals likely preserving some pinna resonance (with the limitations imposed by the earphones). However, due to the microphone location, they did not receive the same ear canal contribution as the subjects with NH.

The signal, a three-word phrase, was presented from nine simulated locations in the frontal horizontal plane (±90°), 22.5° apart. The stimuli were processed for each source location for each ear in anechoic and reverberant environments. The RT_{60} varied from 0.2 to 0.4 secs across frequency. At 0°, the signal level was 70 dB SPL or 30 dB SL, whichever was more comfortable for each subject; the level at each ear for sources at other locations varied due to the head-shadow effect. Speech-spectrum noise was presented from a simulated location of 0°; its level was changed to achieve different SNRs. Five noise conditions (no noise, +4, 0, −4, and −8 dB SNRs) were tested in each environment.*

Procedure

Before the experiment, subjects with NH had pure-tone and acoustic immittance testing to verify NH sensitivity and middle ear function. Subjects with BCIs wore their processors set as they are routinely used and completed a loudness balance measure to ensure equal loudness between ears. Their hearing was also tested in the sound field with their BCIs on to estimate the appropriate signal presentation level. All subjects had about 10 mins of training to familiarize them with the localization test.

During the experiment, the subjects were seated in a quiet, sound-treated room and presented with sounds via circumaural earphones (Sennheiser HD 265). The SLIQ and SPLINT were administered to the subjects at the different SNRs in both environments in random order. A single-interval, nine-alternative, forced-choice identification procedure with feedback was used to measure localization ability. Each run had 27 trials, three at each of the nine source locations. Within a run of 27 trials, SNR and reverberation were held constant and source location varied randomly. Each condition was repeated twice unless the two response RMSLEs differed by more than 11.25°. In this case, a third run was completed. Subjects indicated the perceived location of the sound source by clicking the mouse on the appropriate visual image on the computer monitor. It took approximately 2 hrs for each subject to complete all measures.

RESULTS

RMSLE in degrees was calculated. Multivariate analysis of variance (MANOVA) was used to determine the effects of noise and reverberation on localization performance for each group of subjects and to compare the groups. The bar graph in Figure 1a shows the RMSLE in degrees in the anechoic environment. It indicates that both listeners with BCIs had significantly poorer localization accuracy than listeners with NH (p = 0.0008) in all conditions. The across listening condition analysis showed a marginally significant difference (p = 0.0449), suggesting that at least one listening condition was significantly different from the others. However, there was no significant interaction between listening condition and group (p = 0.436). Post hoc Tukey Honestly Significant Difference (α = 0.05) indicates significant performance difference between the quiet and −8 dB SNR condition for NH subjects. For BCI subjects, this analysis was not completed due to limited data; but because the MANOVA results indicate no significant difference between the effects of SNR on NH and BCI performance, it is possible further data would show that localization of the BCI subjects is significantly different in quiet and at −8 dB SNR. Results from more subjects are needed to confirm this.

Figure 1b is similar to Figure 1a for the reverberant environment. It also shows a significant difference between groups (p < 0.0001) and across listening conditions (p =

*Note that listeners with NH were not tested at +4 dB SNR, because Strother et al. (1998) had demonstrated that localization performance of NH subjects did not begin to decrease until the SNR was below 0 dB in the anechoic and reverberant environments used in the SLIQ and SPLINT.

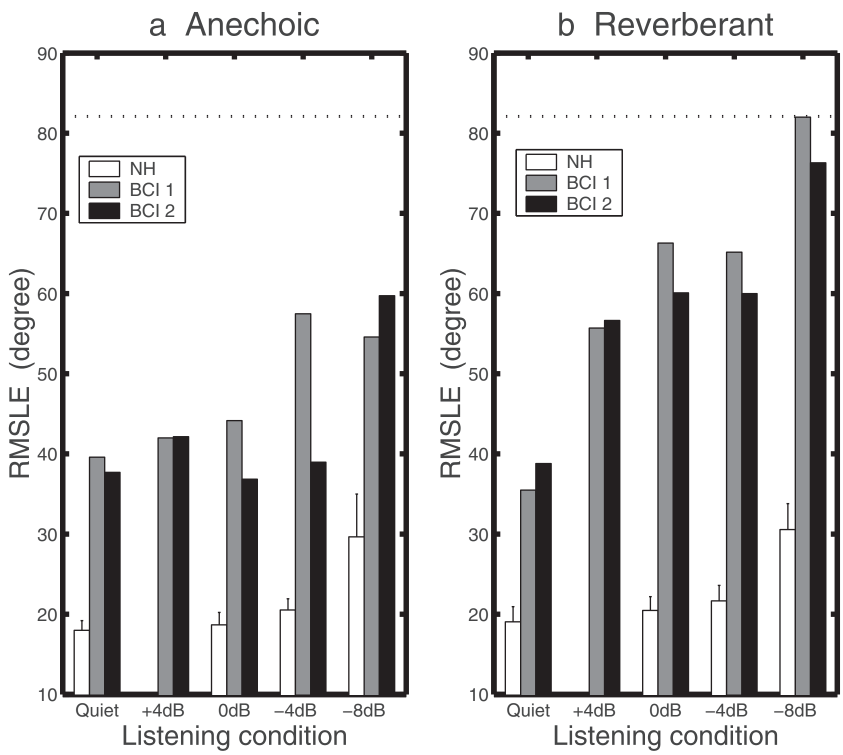

Fig. 1. Sound source localization data in anechoic (a) and reverberant (b) environments. The RMSLE in degrees is indicated on the y axis versus the listening conditions on the x axis. Chance performance is indicated by the dashed line at 82°. Average results for the NH subjects are indicated by the unfilled bars, and individual BCI users are indicated by the filled bars; gray bars for BCI subject 1 and black bars for BCI subject 2. SEs are indicated for each condition for subjects with NH. NH, normal hearing; BCI, bilateral cochlear implant.

0.00004). However, unlike the anechoic environment, there was a significant interaction between listening condition and group ($p = 0.0014$). Tukey's Honestly Significant Difference for the NH group data indicates a significant difference between quiet and the −8 dB SNR condition. Due to the small number of subjects, BCI data could not be analyzed statistically; the figure reveals a large increase in RMSLE from quiet to +4 dB SNR and from −4 SNR to −8 dB SNR.

To investigate the effects of reverberation on localization performance, data were further analyzed using paired *t* tests. Figure 2a shows the RMSLE in degrees for NH subjects under different test conditions in both anechoic and reverberant

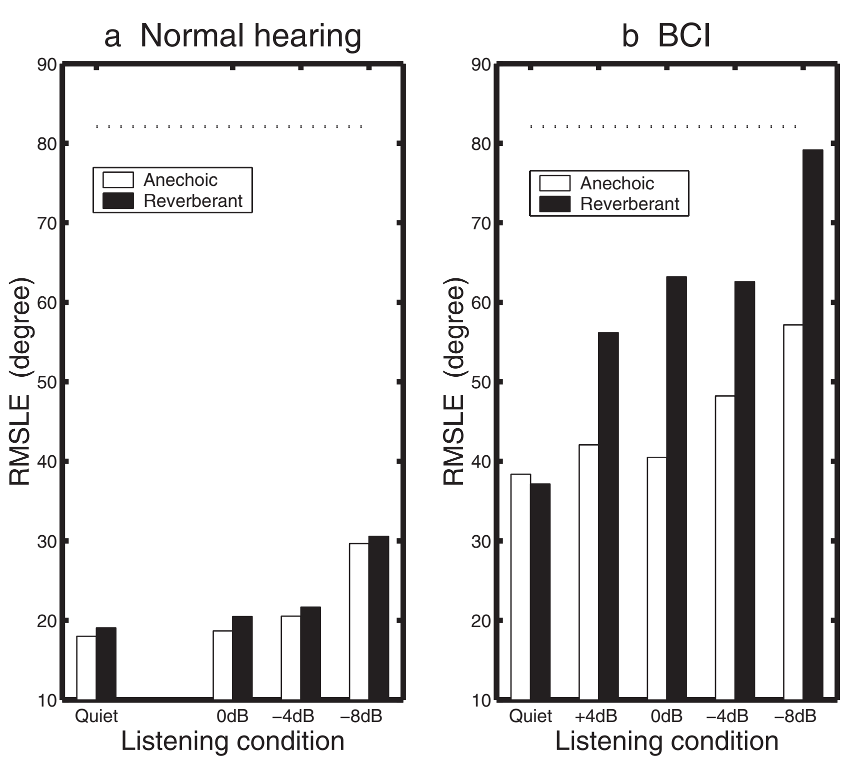

Fig. 2. Sound source localization data in two environments for listeners with NH (a) and BCIs (b). The RMSLE in degrees is indicated on the y axis as a function of the listening conditions. Chance performance is indicated by the dashed line at 82°. The unfilled bars represent data for the anechoic environment, and filled bars represent data for the reverberant environment. NH, normal hearing; BCI, bilateral cochlear implant.

environments. There is no significant effect ($p = 0.3171$) of reverberation; in other words, RMSLE of NH subjects is not affected by the 0.2 to 0.4 secs RT_{60}. In contrast, Figure 2b shows a significant difference in RMSLE ($p = 0.0014$) between environments, indicating that this reverberation time did affect localization for BCI users.

DISCUSSION AND CONCLUSION

In summary, the results of this study reveal that listeners with BCIs have significantly poorer localization accuracy than listeners with NH in both virtual environments in quiet and in noise. For subjects with NH, localization performance did not decrease until the SNR reached −8 dB in both environments. These results are consistent with those reported by Lorenzi et al. (1999a) and Strother et al. (1998). BCI users had a pattern of performance similar to NH subjects in the anechoic environment. However, in the reverberant environment, RMSLEs of the BCI users started to decrease at +4 SNR. The results in quiet for BCI users were consistent with those obtained in a real sound field by Neuman et al. (2007). For the 0 dB SNR noise condition, the RMSLEs in this study were higher than those measured by Van Hoesel et al. (2008). This may be due to the relatively short BCI experiences (less than a year, see Table 1) of the subjects in this study compared with the study by Van Hoesel et al. and/or because in the present study subjects listened through KEMAR's ears. Tyler et al. (2006) showed that localization performance in quiet stabilized after a year of BCI experience. It is interesting that the relatively short reverberation time of 0.2 to 0.4 sec had a significant effect on the RMSLEs of BCI users but no effect on listeners with NH. In addition, the results of this study indicate that for BCI users, the combined effect of noise and reverberation on localization is greater than the effect of noise or reverberation alone.

This is the first reported study in which the effects of noise and reverberation have been investigated on the same group of BCI subjects, and the performance of BCI users has been measured on a virtual localization task. Overall, these initial data indicate that the SLIQ and SPLINT are appropriate for measuring binaural performance in listeners with BCIs and are sensitive to differences in localization ability of listeners with NH and BCIs. In addition, the clear effect of reverberation on the performance of BCI users is important to consider when designing CI processing strategies and developing CI rehabilitation plans to optimize binaural benefit for BCI users. This study provides preliminary data for a limited number of subjects and reverberation times. Based on these results, we are designing a more comprehensive study to further investigate the effects of noise and reverberation on localization performance for BCI users.

ACKNOWLEDGMENTS

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Received March 2, 2010; accepted February 21, 2011.

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