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Localization and interaural time difference (ITD) thresholds for cochlear implant recipients with preserved acoustic hearing in the implanted ear

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Abstract

The purpose of this study was to investigate horizontal plane localization and interaural time difference (ITD) thresholds for 14 adult cochlear implant recipients with hearing preservation in the implanted ear. Localization to broadband noise was assessed in an anechoic chamber with a 33-loudspeaker array extending from −90 to +90°. Three listening conditions were tested including bilateral hearing aids, bimodal (implant + contralateral hearing aid) and best aided (implant + bilateral hearing aids). ITD thresholds were assessed, under headphones, for low-frequency stimuli including a 250-Hz tone and bandpass noise (100–900 Hz). Localization, in overall rms error, was significantly poorer in the bimodal condition (mean: 60.2°) as compared to both bilateral hearing aids (mean: 46.1°) and the best-aided condition (mean: 43.4°). ITD thresholds were assessed for the same 14 adult implant recipients as well as 5 normal-hearing adults. ITD thresholds were highly variable across the implant recipients ranging from the range of normal to ITDs not present in real-world listening environments (range: 43 to over 1600 μs). ITD thresholds were significantly correlated with localization, the degree of interaural asymmetry in low-frequency hearing, and the degree of hearing preservation related benefit in the speech reception threshold (SRT). These data suggest that implant recipients with hearing preservation in the implanted ear have access to binaural cues and that the sensitivity to ITDs is significantly correlated with localization and degree of preserved hearing in the implanted ear.

1. Introduction

Minimally traumatic surgical techniques and atraumatic electrodes have led to an increasing number of individuals with preserved acoustic hearing in the implanted ear(s). Cochlear implant (CI) recipients with hearing preservation have binaural hearing in the low-to-mid frequency range. Binaural hearing should allow for access to interaural time difference (ITD) cues, which are known to be most prominent for frequencies below 1500 Hz (e.g.,

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Yost, 2000). In contrast, access to interaural level difference (ILD) cues requires audibility for frequencies above approximately 1500 Hz (e.g., Yost, 2000) *in both ears*. Given that most current hearing preservation CI users are unilaterally implanted (but see Dorman et al., 2013), ILD cues are not available, as bilateral acoustic hearing for most patients does not extend beyond 750–1000 Hz.

Because interaural time differences (ITDs) are most prominent in the low-to-mid frequency range, hearing preservation CI patients should have access to binaural timing cues, which could be beneficial for speech understanding in noise and reverberation. A number of studies have documented the efficacy of hearing preservation for significantly improving speech understanding in semi-diffuse noise (Dunn et al., 2010; Dorman and Gifford, 2010; Gifford et al., 2010, 2013; Rader et al., 2013) and reverberant speech (Gifford et al., 2013). Indeed, Gifford et al. (2013) showed that some hearing preservation CI recipients had access to ITDs and that ITD thresholds for a 250-Hz signal were significantly correlated with the degree of speech recognition benefit afforded by the preserved hearing in the implanted ear. The ITD thresholds for a 250-Hz signal, however, were generally poorer than that observed for individuals with normal hearing with some thresholds approaching ITDs that do not physically exist in real-world listening environments (Gifford et al., 2013). Thus it is unclear to what extent ITDs are preserved with hearing preservation cochlear implantation and what role ITD cues play in the underlying benefit for speech understanding in diffuse noise.

For hearing preservation CI users who theoretically have access to ITDs, localization abilities should be better than that demonstrated by unilateral CI users or individuals with bimodal hearing as the latter two groups would have little-to-no access to ITD cues (Grantham et al., 2007). Research has shown that hearing preservation CI patients do in fact exhibit significantly better localization abilities when using the acoustic hearing in the implanted ear (Dunn et al., 2010; Dorman et al., 2013). Dunn et al. (2010) assessed horizontal-plane localization for 11 hearing preservation CI patients who were recipients of the Nucleus Hybrid S8 short-electrode implant. Localization was assessed with an 8-loudspeaker array placed in a 108° arc using everyday sounds as the target stimuli. The 11 participants were tested in three bilateral listening conditions including bilateral hearing aids (HAs), bimodal (CI + contralateral HA), and best aided (CI + bilateral HAs, termed ‘combined’). Dunn et al. (2010) found significantly better localization in the bilateral HA and combined conditions as compared to the bimodal condition. Further, there was no difference between localization obtained in the bilateral HA and combined conditions. This last point is of considerable interest as the use of a unilateral CI sound processor did not disrupt localization abilities.

It is of interest to compare the localization performance of hearing preservation CI patients (as reported by Dunn et al., 2010), and that of bilateral CI recipients (e.g., Litovsky et al., 2004; van Hoesel and Tyler, 2003; van Hoesel, 2004; Grantham et al., 2007). In general, the hearing preservation CI users would have access to ITD cues but little or no access to ILD cues, while it is generally accepted that the bilaterally implanted CI users utilize ILD cues but have little or no access to ITD cues (e.g., Grantham et al., 2007). It turns out that performance of bilateral CI patients depends on the span of the loudspeaker array employed: For studies that have employed loudspeaker spans similar to that employed by Dunn et al.

(2010) (e.g., 108° – van Hoesel, 2004; van Hoesel and Tyler, 2003), rms error was smaller (performance better) than that reported by Dunn et al. (2010). However, for studies that employed larger loudspeaker spans (145°–180° – Litovsky et al., 2004; Grantham et al., 2007), error scores tended to be higher (performance worse) than that reported by Dunn et al. (2010). Grantham et al. (2007) attributed the poorer performance with the wider loudspeaker spans to the fact that the ILD cues became ambiguous for sources beyond ±60°, leading to a deterioration in performance for these extreme azimuths. Whether loudspeaker span has a similar effect for hearing preservation CI patients, who presumably use primarily ITD cues, remains to be investigated.

The localization experiment conducted by Dunn et al. (2010) used everyday sounds with varying temporal and spectral characteristics. The use of a broadband noise is most generally the stimulus of choice for localization experiments as it allows for precise specification of spectral and temporal characteristics and thereby greater experimental control across conditions. Thus the localization data as described by Dunn et al. (2010), while describing functional localization for everyday sounds, were obtained in a dramatically different test environment than the majority of localization experiments currently in the literature.

Another consideration for the localization abilities described by Dunn et al. (2010) for hearing preservation patients is that the 11 short-electrode recipients had relatively symmetrical hearing with a low-frequency pure tone average (125, 250 and 500 Hz) of approximately 50 and 35 dB HL in the implanted and non-implanted ears, respectively. Though this is not unexpected as short-electrode recipients tend to have lower (i.e. better) preoperative thresholds and better hearing preservation than long electrode implant recipients (Gantz, 2013, but see Erixon et al., 2012), there are a number of hearing preservation CI recipients who have significantly poorer hearing in both ears as well as greater asymmetry.

The purpose of this study was to investigate horizontal plane localization and ITD thresholds for hearing preservation CI patients with both long and short electrodes using the same experimental protocol as used by Grantham et al. (2007, 2008) for bilateral CI recipients. The primary hypotheses were that 1) like reported by Dunn et al. (2010), hearing preservation CI users with different devices and varying insertion depths will exhibit significantly better localization in the best aided condition using the CI plus bilateral HAs as compared to the bimodal hearing configuration, and 2) localization error for hearing preservation CI users will be significantly correlated with ITD threshold.

2. Experiment 1: horizontal plane localization

2.1. Participants

Participants were 14 adult unilateral CI recipients with hearing preservation in the implanted ear. The mean age of the participants was 58.8 years with a range of 46–80 years. Participants were required to have at least 6 months experience with the CI prior to enrollment. The mean number of years of experience with the CI was 3.5 with a range of 0.6–7.4 years. Participants were implanted with 4 MED-EL and 10 Cochlear devices with a breakdown as follows: 1 Nucleus CI24RCA, 1 Nucleus CI512, 1 Nucleus CI24RE(CA), 1 Nucleus Hybrid S12, 3 Nucleus Hybrid S8, 3 Nucleus Hybrid L24, 2 MED-EL Sonata H (standard), and 2 MED-EL CONCERT FLEX24. The implanted electrode length ranged from 10 to 31 mm. Though insertion depth is not the most functional descriptor of effective cochlear coverage as lateral wall and perimodiolar electrode arrays have different courses, we did not have access to angular insertion depth for the current study sample. All participants had a full insertion of their electrode array; that is, none of the electrode arrays had been partially inserted. Table 1 displays demographic, device, and hearing loss information for the individual subjects. In addition, Table 1 displays the degree of hearing preservation related benefit in the speech reception threshold (SRT), in dB, as reported in our earlier publication (Gifford et al., 2013).

All Nucleus implant recipients used Autosensitivity (ASC) in their preferred everyday program. ASC is a front-end processing strategy designed to adjust the sensitivity of the microphone based on the noise floor of the incoming signal. With ASC enabled, the microphone sensitivity is reduced if the ambient noise level exceeds 57 dB. This ensures that speech peaks exceed the long-term average noise spectrum by at least 15 dB before infinite compression sets in. When ASC is not active, the incoming signal is infinitely compressed for input levels ≥65 dB SPL. The use of ASC for all Nucleus implant recipients is relevant so that the participants’ sound processors did not infinitely compress the experimental stimuli used in the current study. It is further relevant as all Nucleus implant recipients were making use of ASC in their preferred program and thus the performance noted here was directly applicable to the participants’ everyday use of the implant processor.

Subject inclusion criteria required postoperative audiometric thresholds 80 dB HL or better at 250 Hz in the implanted ear. Fig. 1A and B displays the audiometric thresholds in the implanted and non-implanted ears obtained on the date of testing. The low-frequency pure tone averages (125, 250, and 500 Hz) were 55.0 and 41.4 dB HL in the implanted and non-implanted ears, respectively. Table 1 shows postoperative low-frequency pure tone average (LF PTA) in the implanted ear as well as the degree of hearing loss resulting from implantation.

The participants’ hearing aids were verified with real-ear measures prior to commencing testing. Hearing aids were verified to match NAL-NL1 (Dillon et al., 1998) target audibility. Hearing aids that were undershooting target audibility by more than 5 dB at one or more frequencies were reprogrammed to match NAL-NL1 targets.

2.2. Test environment and stimuli

Localization was assessed in a lighted anechoic chamber. The participant was seated in a comfortable chair in the center of the chamber and instructed to sit upright facing forward. Thirty-three stationary loudspeakers (Meyers Sound MM4) were situated in a horizontal arc placed at ear level. Speakers were positioned at a distance of 1.95 m from the listener, extending from −90- to +90° azimuth (Fig. 2). Nine of the thirty-three loudspeakers were used for stimulus presentation as indicated by the filled speakers in Fig. 2. The 9 active loudspeakers extended from −78° to +78°. The frequency response of the speakers was within ±5 dB over the frequency range 160–10,000 Hz.

The stimulus was a Gaussian noise burst, bandpass filtered from 100 to 8000 Hz to encompass the frequency range transmitted by CI sound processors. The stimulus duration was 200 ms, including 10-ms $\cos^2$ ramping. A fresh stimulus was generated for each trial and presented at a nominal calibrated level of 70 dB SPL. The level for each stimulus presentation was randomly varied over a 4-dB range about 70 dB SPL to help avoid the use of monaural intensity cues.

2.3. Methods

We used the same modified source identification protocol (e.g., Rakerd and Hartmann, 1985) as described in Grantham et al. (2012). The participant was seated in the center of the chamber facing the center of the loudspeaker array (see Fig. 2). Each run involved 54 stimulus presentations, 6 via each of the 9 active loudspeakers, in a randomized manner. Before each presentation, the subject turned his or her head toward the midline (speaker #17). After the presentation, the subject was allowed to move his or her head to look at the loudspeaker labels, and s/he called out the number of the loudspeaker that s/he believed presented the signal. The experimenter sat in an adjacent control room monitoring the experiment via both audio and video transmission and entered the participants' responses via computer keypad. After response entry there was a 500 ms pause, after which the stimulus for the next trial was presented. The subject was unaware that only nine of the loudspeakers were used so that valid responses ranged from 1 to 33. Feedback was not provided.

Prior to experimentation, each participant was provided with several practice runs lasting approximately 20–30 min (approximately 4 runs). Data collection did not begin until the experimenter judged that the subject fully understood the task.

The order of conditions (bilateral HA, bimodal, and best aided) was determined so that that the presentation order for bimodal and best-aided conditions was alternated from one listener to the next. Thus approximately half of the participants were presented with bimodal before best aided and the other half were presented with best aided before bimodal.

Three runs were completed for each listening condition, such that there were a total of 18 responses for each of the nine loudspeakers. The measure of performance was taken as the overall rms error (difference between stimulus and response azimuth), computed across the nine stimulus positions. Localization data were collected within a single test session lasting approximately 90 min including a brief break.

Study data were collected and managed using REDCap electronic data capture tools hosted at Vanderbilt University (Harris et al., 2009). REDCap (Research Electronic Data Capture) is a secure, web-based application designed to support data capture for research studies, providing: 1) an intuitive interface for validated data entry; 2) audit trails for tracking data manipulation and export procedures; 3) automated export procedures for seamless data downloads to common statistical packages; and 4) procedures for importing data from external sources. All research activities associated with this project had been granted approval by the Vanderbilt University Institutional Review Board.

2.4. Results and discussion

Individual and mean localization results are shown in Fig. 3. The bimodal, bilateral HA, and best-aided conditions are represented by black, white, and gray bars, respectively. Though there was considerable variability noted across listeners, mean localization rms error was 60.2, 46.1, and 43.4° for the bimodal, bilateral HA, and best-aided conditions. A one-way repeated measures analysis of variance (ANOVA) revealed a significant main effect of listening condition [$F_{(2,13)} = 9.5$, $p < 0.001$]. Post-hoc analysis using an all-pairwise multiple comparison procedure with the Holm–Sidak statistic revealed significant difference between bimodal and best-aided conditions ($t = 4.0$, $p = 0.001$) and between bimodal and bilateral HA ($t = 3.5$, $p = 0.004$), but no difference between bilateral HA and best-aided ($t = 0.6$, $p = 0.58$).

Individual localization responses are shown in Fig. 4 for the bimodal (filled circles) and best-aided condition (unfilled circles). As shown in Fig. 3, these individual data highlight the fact that localization accuracy was better for the best-aided condition, or the implant plus bilateral hearing aids, as compared to the bimodal condition. For most listeners in the bimodal condition, there was a localization bias to the side of the cochlear implant, independent of source position. Two obvious exceptions to this rule were subjects 11 and 13 both of whom exhibited localization bias to the non-implanted ear in the bimodal condition. Both subjects were recipients of the Nucleus Hybrid device. Subject 11 had a Hybrid-L24 implant and better hearing in the implanted ear than the non-implanted ear. Because of this, this subject’s bimodal condition included a higher starting frequency for the implant than the subjects with poorer hearing preservation in the implanted ear. Thus it is likely the case that this subject perceived greater loudness in the non-implanted ear biasing responses to that side. Subject 13 was the recipient of a Nucleus Hybrid S12 and had some of the best low-frequency hearing of all the participants (mild hearing loss through 750 Hz in both ears). For this reason, like subject 11, the starting frequency for the implant was the highest of all subjects (1188 Hz). Thus in the bimodal listening condition, the hearing aid bandwidth was actually greater than the implant resulting in greater loudness on the side of the non-implanted ear.

The pattern of results reported here is equivalent to that reported by Dunn et al. (2010) for short-electrode recipients using an everyday sounds localization task. That is, the best-aided and bilateral HA conditions yielded significantly better localization than the bimodal condition, though performance in all conditions was worse than obtained for individuals with normal hearing (<10° error, e.g., Grantham et al., 2012). The current data, however, revealed much poorer localization as compared to Dunn et al. (2010). Average localization thresholds, in overall rms error, as reported by Dunn et al. (2010) were approximately 42° for bimodal, 25° for bilateral HA, and 28° for the best-aided condition. We believe that there are several possible reasons for the differences in localization across studies. One possibility is related to the different loudspeaker spans employed. As has been shown to be the case with bilaterally implanted CI users (see Grantham et al., 2007), performance for hearing-preservation CI users is better when the span is relatively short (108° in the Dunn et al. study) than when it spans the entire hemifield (present study). Evidently, hearing preservation CI users were not able to take maximum advantage of ITD cues for sources in the periphery (i.e., beyond about ±60°), thereby yielding larger error scores when a wide array of loudspeakers is employed. As noted earlier, this result is parallel to the situation faced by bilaterally implanted CI users, for whom ILD cues become ambiguous for sources in the periphery. Another possible explanation for the poorer performance in this study than what was reported by Dunn et al. (2010) is that several participants in this study had higher levels of asymmetric hearing loss. Although the localization task was conducted with aided listening conditions, some asymmetries likely remained. Asymmetric hearing loss may cause the perceived location of a stimulus to shift towards the ear with lower (i.e. better) thresholds, thus potentially decreasing localization accuracy.

3. Experiment 2: ITD thresholds

3.1. Introduction

The mean localization errors for the bilateral CI users in Grantham et al. (2007) and the hearing preservation CI users in the current study were 30.8 and 43.0°, respectively. It should be noted that in both of these studies a wide loudspeaker span was employed (near 180°). Though a number of factors may be responsible for the differences in performance across the groups, the most likely factor contributing to the differences noted across the subject groups was the cue used for localization across the bilateral CI and hearing preservation CI patients. Individuals with bilateral CIs have access to ILDs, but not ITDs. Conversely, individuals with hearing preservation CI have access to ITDs, but not ILDs. As shown by Grantham et al. (2007), approximately half of the bilateral CI users demonstrated ILD thresholds comparable to normal-hearing listeners. Furthermore, Grantham et al. (2007) showed that localization for the bilateral CI users were significantly better when using just ILD cues (high-pass noise) as compared to ITD cues (low-pass noise). Despite the availability of some low-frequency hearing in the hearing preservation participants, it is possible that they cannot take maximum advantage of ITD cues to localize well in the horizontal plane. Thus the purpose of experiment 2 was to obtain ITD thresholds for low-frequency stimuli and to relate these thresholds to localization error for the 12 hearing preservation patients in the current study.

3.2. Participants

The same 14 CI users with hearing preservation from Experiment 1 also participated in Experiment 2. In addition, 5 participants with normal hearing (NH) were also run for comparison purposes. The 5 NH listeners (3 male, 2 female) with normal hearing ranged in age from 27 to 31 years with a mean of 29.2 years.

3.3. Test environment and stimuli

The two stimuli used were a 250-Hz tone and a bandpass noise (100–900 Hz) representing the limited audible spectrum for the hearing preservation patients. For each stimulus, the duration was 200 ms with 10-ms $\cos^2$ ramping. Signals were output at a sampling rate of 50,000 Hz via a 2-channel Tucker–Davis digital-to-analog converter (DD1). The overall level was 90 dB SPL for both stimuli which corresponded to a spectrum level of 61 dB SPL for the bandpass noise. Stimuli were calibrated prior to experimentation for each subject using a Fluke 8050A digital multimeter.

3.4. Methods

Testing was completed under Sennheiser HD 250 II headphones using the participants' native acoustic hearing without the hearing aids or CI sound processor. An adaptive two-interval forced-choice procedure was used, in which the stimulus was presented bilaterally in each of the two intervals, separated by 400 ms. In the first interval, an ITD was presented favoring one side, and in the second interval an ITD of the same magnitude favored the other side, with the order randomized across trials. Participants responded by pressing a button on a response box indicating a lateral position change for which the sequence of two sound images moved (left-to-right or right-to-left). Correct answer feedback was given via LEDs on the response box.

A two-down one-up stepping rule was used to track 70.7% correct performance (Levitt, 1971). The starting ITD was set to 900 μs during practice so that the listener could clearly identify the lateral position changes. The nominal ITD of 900 μs was split equally between the intervals—450 μs favoring the left ear in one interval and 450 μs favoring the right ear in the other interval. For listeners unable to discriminate the position changes with a 900-μs ITD, the initial ITD was arbitrarily set between 1600 and 4000 μs. Following completion of approximately 6 practice runs (approximately 25 min), the step size was chosen for each participant individually to promote an efficient threshold track based on the ITD thresholds obtained during practice; however, starting ITD values that worked for the majority of the implanted participants were in the range of 200–400 μs. The initial step size was used for the first two reversals of the threshold track and decreased thereafter. A run was terminated following eight reversals with threshold comprising the mean ITD for the final six reversals. Three threshold runs were completed for each stimulus and the threshold was computed as the mean of the three threshold tracks. Data were collected during a single test session lasting approximately 60 min including a break, but not counting practice.

For 9 of the 14 CI participants, quiet thresholds were also obtained for each stimulus type in the left and right ears. Time did not allow for determining quiet threshold for the other 5 participants. Quiet thresholds were completed so that we could quantify the sensation level (SL), in dB, of the 90-dB-SPL overall level in each ear. Quiet thresholds were not completed for the 5 NH listeners. Rather a hearing screening was completed to verify hearing within the normal range.

3.5. Results and discussion

Quiet thresholds, in dB SPL, for each stimulus are shown in Table 2 with the corresponding sensation level (SL) in dB SL for the 90-dB-SPL overall level used for determining ITD thresholds. Because time did not allow for quiet threshold estimation for participants 5, 6, 8, 9 and 12, reference equivalent threshold sound pressure level (RETSPL, ANSI S3.6, 2010) for insert earphones (ER-3A) were used to estimate the listeners' thresholds for the 250-Hz signal. To estimate SPL thresholds for the 100–900-Hz signal, HL thresholds for 125, 250, 500, and 750 Hz were converted to SPL and averaged. The estimates of SPL thresholds are shown in Table 2, enclosed in parentheses, next to the abbreviation for *did not test* (DNT).

The range of SLs for the implanted ear was 10.6–60.3 dB SL for 250 Hz and 2.1–50.5 dB SL for 100–900 Hz. The range of SLs for the non-implanted ear was 12.1–82.8 dB SL for 250 Hz and 9.8–62.9 dB SL for 100–900 Hz. Due to high quiet thresholds for the stimuli used in testing for participant 1 for 100–900 Hz and participant 4 for both stimuli, ITD thresholds could not be obtained for these listeners. Further, ITDs were attempted for participant 5 at 100–900 Hz; however, he reported that he could barely hear the signal in the non-implanted ear, and thus testing ceased for this reason. Based on the estimated SPL threshold for 100–900 Hz, the 90-dB-SPL level for the stimulus would have been at threshold and thus testing would not have yielded valuable ITD threshold information. ITD thresholds were ultimately successfully tracked for 10 of the 14 CI participants. ITD thresholds for participants 5 and 11 were arbitrarily set to 1600 μs to reflect the difficulty with the task and to capture the poor ITD detection performance for these listeners.

Individual and mean ITD thresholds for the NH listeners are shown in Table 3. Mean thresholds were 81.6 and 21.2 μs for the 250-Hz signal and 100- to 900-Hz band, respectively. Fig. 5A and B displays individual and mean ITD thresholds, in microseconds, rank ordered by participant performance for 250 Hz and 100–900 Hz, respectively. Fig. 5C and D displays ITD thresholds for the CI participants as a function of overall rms localization error for 250 Hz and 100–900 Hz, respectively. In each figure, the dotted horizontal line represents the mean ITD threshold for the 5 NH listeners. Subjects 1 and 4 had quiet thresholds for the stimuli resulting in sensation levels less than 10 dB for at least one ear. Thus these subjects lateralized all stimuli to the side with a greater sensation level. Two additional subjects (5 and 11) were unable to track ITD thresholds even after 90 min of training and experimentation as the threshold tracks varied between termination without a tracked threshold or were highly variable with resulting thresholds ranging from 1600 to over 4000 μs. These participants reported that they struggled with the task and were never certain that they could detect a lateral position change. Thus ITD thresholds are plotted in Fig. 5A and B for 10 listeners. The best ITD thresholds exhibited by the CI subjects overlapped with performance for the NH listeners. Conversely, the poorest ITD thresholds were orders of magnitude poorer than the NH listeners and in fact, were representative of ITDs that do not exist in the real world.

As observed with localization in Experiment 1, there was considerable variability in ITD thresholds across the CI subjects. As shown in Fig. 5C and D, ITD thresholds were significantly correlated with localization. Pearson correlation coefficients were 0.73 and 0.80 for the 250-Hz and 100–900-Hz signals, respectively. Correlations were performed using only those data from subjects able to track threshold. This suggests that, as hypothesized, localization for the hearing preservation patients was related to the listeners' ITD cues.

Pearson correlation analyses were also completed for ITD thresholds as a function of absolute threshold for the 250-Hz and 100–900-Hz signals in the implanted ear, non-CI ear, and the degree of asymmetry (in dB) in absolute thresholds across ears. There was no correlation between absolute threshold for the implanted ear and ITD thresholds for either 250 Hz ($p = 0.39$) or 100–900 Hz ($p = 0.64$). Similarly, there was no correlation between absolute threshold for the non-implanted ear and ITD thresholds for either 250 Hz ($p = 0.79$)

or 100–900 Hz ($p = 0.77$). As shown in Fig. 6A and B, however, there was a significant correlation between the degree of interaural asymmetry, in dB, across the implanted and non-implanted ears and ITD thresholds at both 250 Hz and for 100–900 Hz. There was not, however, a correlation between localization and asymmetry, in dB. This is likely due to the fact that localization was measured with the listeners' hearing aids, which likely tempered the effects of asymmetry.

Fig. 7A and B displays the degree of hearing preservation related benefit in the SRT, in dB, as reported in Gifford et al. (2013) as a function of ITD threshold at 250 Hz and 100–900 Hz, respectively. Fig. 7C displays the degree of hearing preservation related benefit in the SRT, in dB, as a function of localization rms error. For Fig. 7A–C, there is a trend that those exhibiting the lowest (i.e. best) ITD thresholds and rms error are also those exhibiting the greatest degree of hearing preservation related benefit for speech understanding in diffuse noise. This relationship was statistically significant for ITD thresholds at 250 Hz ($p = 0.0066$), 100–900-Hz noise ($p = 0.024$) and localization rms error ($p = 0.029$). Thus there is a relationship between localization, ITD threshold, and benefit from hearing preservation for speech understanding in complex, semi-diffuse noise. Conversely, however, as shown in Fig. 7D and E, there was no correlation between the hearing preservation related benefit in the SRT and the degree of hearing asymmetry across ears. Because speech understanding was assessed in the best-aided condition, the use of the hearing aids likely mitigated the effects of hearing asymmetry.

Multiple regression was completed for the dependent variable *degree of hearing preservation benefit*, in dB (Table 1), and independent variables asymmetry at 250 Hz, asymmetry for 100- to 900-Hz noise, ITD thresholds at 250 Hz, ITD threshold at 100–900 Hz, and localization error. The ITD values for those unable to complete the task were not included in the analysis. The results of the regression analysis were such that the dependent variable, *degree of hearing preservation benefit*, can be predicted from a linear combination of the independent variables ($F_{(5)} = 56.6$, $p = 0.0037$). Not all of the independent variables were necessary to account for the ability to predict hearing preservation benefit. Indeed there were two variables that significantly contributed to the model which included asymmetry at 250 Hz ($p = 0.005$) and asymmetry at 100–900 Hz ($p = 0.045$).

4. General discussion

Cochlear implantation with minimally traumatic surgical techniques and atraumatic electrodes can result in significant preservation of acoustic hearing in the implanted ear. In theory, this affords CI users with hearing preservation access to binaural cues present in the low-to-mid frequency region. The dominant binaural cues present in this range are ITDs, which are known to be important for spatial hearing and speech understanding in noise. The results presented here agree well with past research (e.g., Dunn et al., 2010) showing significantly better localization abilities for hearing preservation CI patients with bilateral HAs alone or the CI plus bilateral HAs—as compared to the bimodal hearing configuration in which the CI is paired only with a contralateral HA.

The current results also demonstrate that hearing preservation CI users have access to ITD cues and that the patients' ITD thresholds are significantly correlated with localization performance. These results suggest that ITD cues are the driving underlying mechanism for localization abilities in hearing preservation CI users. Of course, another possibility is that the current CI users were using ITDs *and* ILDs present in the lower-frequency region. Though ILDs are typically considered high-frequency cues, ILDs are present for lower frequency stimuli though much smaller in magnitude (≤2 dB, e.g., Yost and Dye, 1988). This possibility was not directly assessed in the present study and thus begs further investigation. Another consideration with respect to the correlation between ITD thresholds and localization is related to the stimulus delivery differences between ITD and localization testing. Because the subjects were using headphones without hearing aids for ITD threshold estimation, any low-frequency ILDs due to asymmetrical hearing loss could have affected the measurement of ITDs. This has the potential to make ITD thresholds appear to be larger than they actually are. Thus, a larger asymmetry would result in larger ITD thresholds, leading to a correlation due entirely to the experimental design. Thus further investigation is warranted for ITD estimation with stimulus presentation levels at equal SL across ears.

There was considerable variability in the range of ITD thresholds for the CI subjects in the present study. ITD thresholds were found to be significantly correlated with the degree of asymmetry between acoustic thresholds across ears. This is not unexpected given past research in this area. Bronkhorst and Plomp (1989) demonstrated less ITD-related benefit in the speech reception threshold for listeners with asymmetrical hearing losses across ears. In fact, the degree of deficit related to hearing asymmetry was approximately 2.0–2.5 dB as compared to listeners with symmetric hearing loss and normal hearing, respectively. The degree of asymmetry is not only related to localization and ITDs. Indeed, the results of a multiple regression analysis revealed that degree of hearing preservation related benefit in the SRT, in dB, as reported in Gifford et al. (2013) was best explained by the degree of asymmetry at 250 Hz and for the 100- to 900-Hz noise. Because most hearing preservation patients have relatively symmetrical hearing preoperatively, this suggests that individuals with the greatest degree of preserved hearing will 1) have greater symmetry in postoperative audiometric thresholds, 2) better access to ITDs, 3) better localization abilities, and 4) better speech understanding in complex listening environments. Clearly, the degree of preserved hearing in the implanted ear is critical for both speech understanding in diffuse noise and as reported here, the spatial hearing abilities.

5. Summary and conclusion

In a previous study, we demonstrated a significant correlation between the degree of hearing-preservation related improvement in speech understanding and ITD thresholds (Gifford et al., 2013). In the current study, we found significant correlation between ITD thresholds and localization performance.

The conclusions that can be drawn from past and current results are that CI recipients with the greatest degree of hearing preservation will have:

- greater access to ITD cues (Gifford et al., 2013; present study)

- better speech understanding in diffuse noise (Dorman and Gifford, 2010; Dunn et al., 2010; Gifford et al., 2010, 2013; Rader et al., 2013)
- better speech understanding in the presence of reverberation (Gifford et al., 2013)
- better localization abilities (Dunn et al., 2010; Dorman et al., 2013; present study)

It is clear that hearing preservation is efficacious for speech understanding in complex listening environments and spatial hearing; however, it is not yet clear how much hearing preservation is necessary for said benefit. This is an important research question as it could influence preoperative clinical decision-making and patient counseling. There may be a range of preoperative audiometric thresholds that are best suited to hearing preservation surgery and atraumatic electrodes and a criterion threshold beyond which no expected benefit from preserved hearing would be expected.

In conclusion, the current dataset showed that hearing preservation in the implanted ear affords access to ITD cues and that the magnitude of ITD preservation was significantly correlated with localization, speech recognition in semi-diffuse noise, and symmetry of auditory thresholds. Based on the results of the current study, however, we cannot definitively state that ITDs are the sole underlying mechanism for the hearing preservation related benefit observed for improved localization and speech understanding. We can, however, conclude that CI users with hearing preservation have access to ITDs and that the residual availability of these cues significantly and positively affects localization and speech understanding in diffuse noise.

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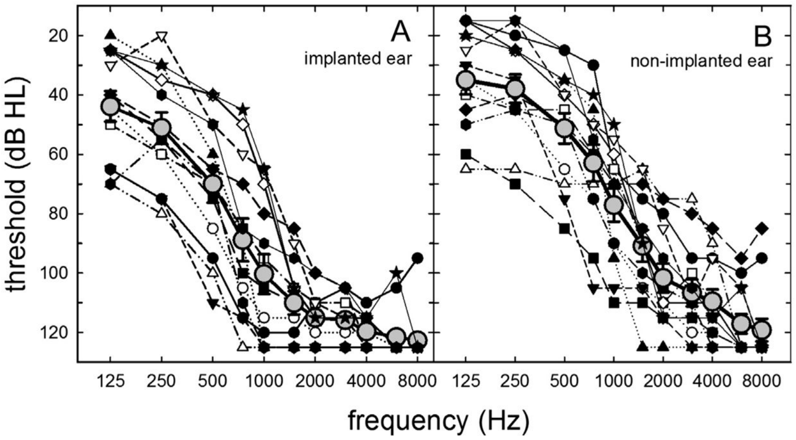

Fig. 1.

Individual and mean (large shaded circles) unaided audiometric thresholds, in dB HL, for the implanted ears (A) and the non-implanted ears (B). Error bars represent ±1 SEM.

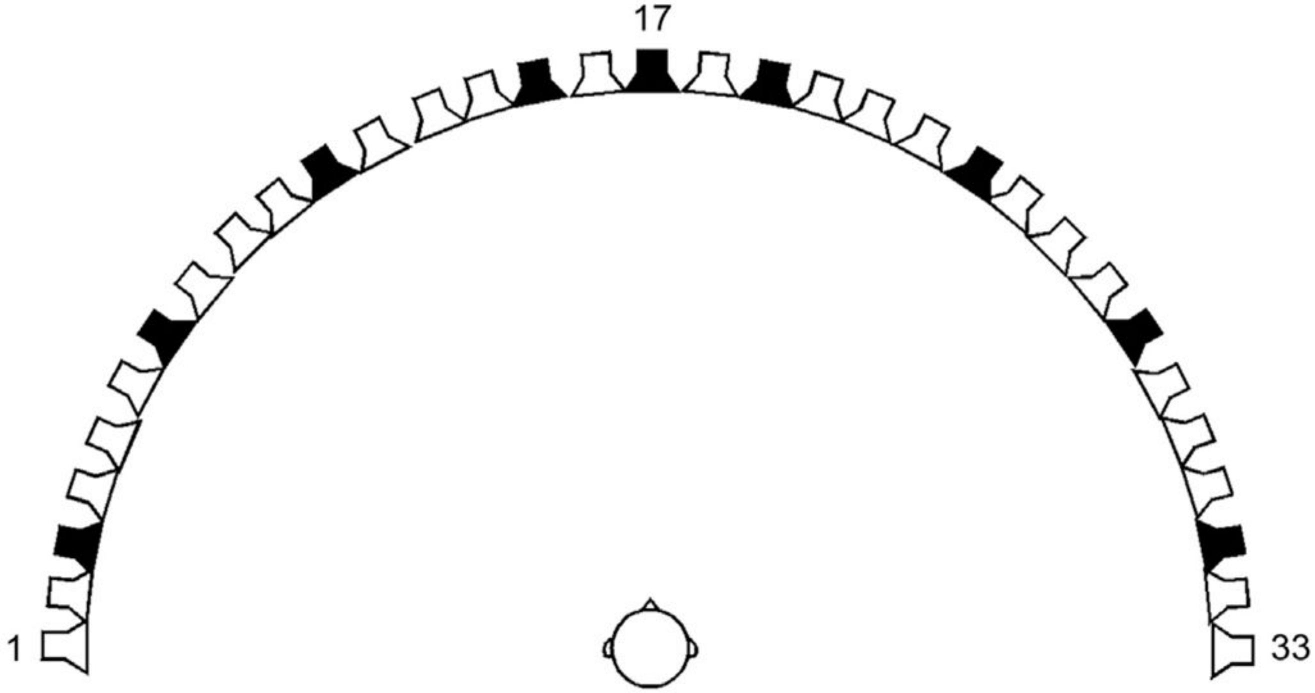

Fig. 2.

Loudspeaker arrangement in anechoic chamber. Filled symbols show the “active” loudspeakers; open symbols indicate “dummy” loudspeakers. Loudspeakers were labeled 1–33 (numbers 1, 17, and 33 are shown here).

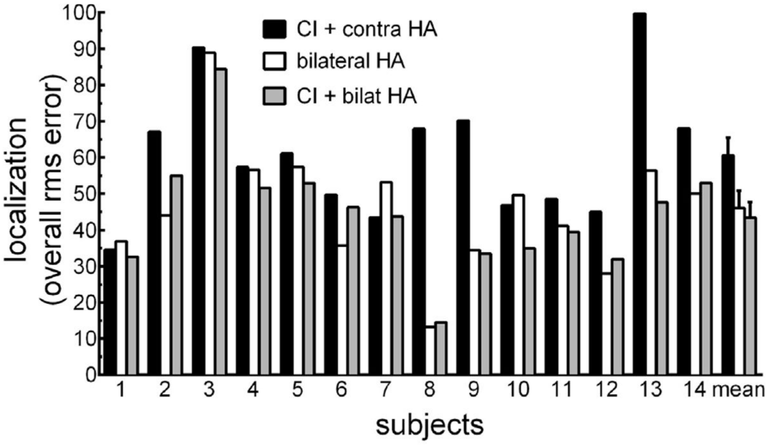

Fig. 3.

Individual and mean localization thresholds, in overall rms error, for the 14 hearing preservation CI subjects in the bimodal (CI + contra HA), bilateral HA, and best-aided (CI + bilateral HA) conditions. Error bars represent ±1 SEM.

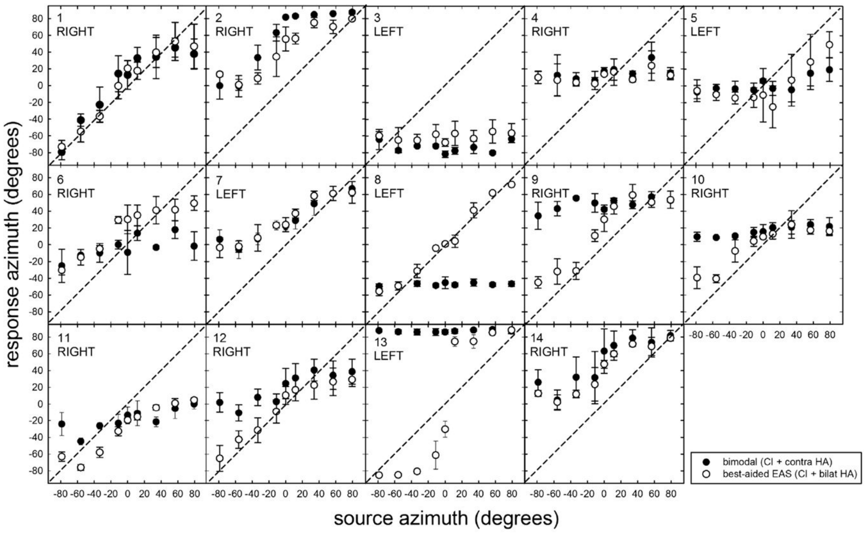

Fig. 4.

Localization responses for individual subjects in the bimodal (filled circles) and best-aided conditions (unfilled circles). Each individual panel specifies the participant number and the implanted ear.

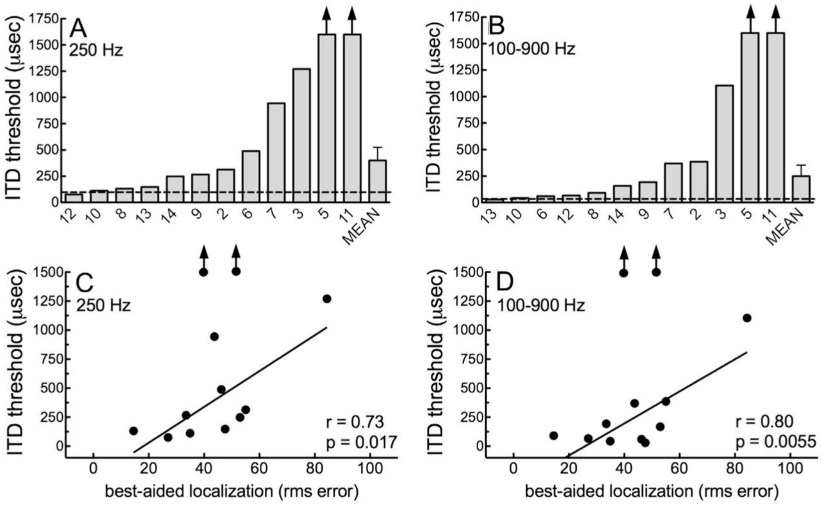

Fig. 5.

Individual and mean ITD thresholds, in microseconds, for (A) 250 Hz and (B) 100–900 Hz bandpass noise. ITD thresholds are also shown as a function of rms localization error in the best-aided condition, for (C) 250 Hz and (D) 100–900 Hz. For (A) and (B) means were calculated only for those participants who had a tracked threshold. Regression analysis did not include results for the listeners with normal hearing nor the data points representing those participants unable to track ITD thresholds.

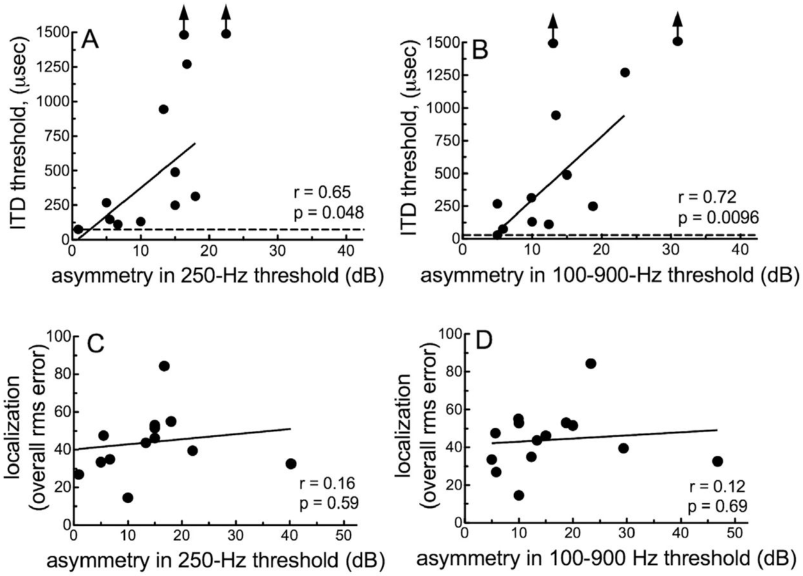

Fig. 6.

ITD thresholds for (A) 250 Hz and (B) bandpass noise (100–900 Hz) as a function of the magnitude of interaural asymmetry, in dB, for quiet thresholds.

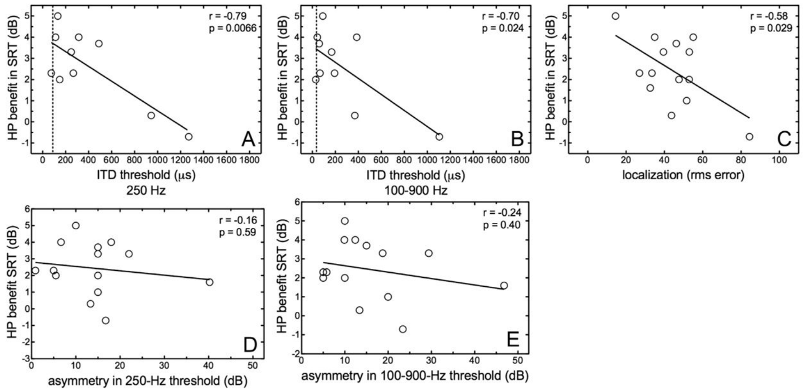

Fig. 7.

Hearing preservation (HP) related benefit in the speech reception threshold (SRT), in dB, as function of (A) ITD thresholds at 250 Hz, (B) ITD thresholds for 100–900 Hz bandpass noise, (C) localization in the best-aided condition, (D) asymmetry at 250 Hz, and (E) asymmetry for 100–900 Hz bandpass noise.

Table 1

Subject demographic information including age at testing, years of CI experience, device type, processor, insertion depth, long or short electrode, postoperative low-frequency pure tone average (LF PTA) in dB HL in the CI ear, degree of hearing loss (dB) for the LF PTA in the CI ear (as a result of surgery), interaural asymmetry (in dB) in unaided audiometric thresholds across ears (CI ear–non-CI ear), degree of hearing preservation (HP) related benefit in the SRT (dB) as reported in Gifford et al. (2013). The mean values for interaural asymmetry, in dB, are shown for 125, 250 and 500 Hz. Interaural asymmetry was calculated as CI ear–non-CI ear. Thus a negative value indicates that the threshold in the CI ear was lower (i.e. better) than the non-CI ear.

Subject	Age	Years CI experience	Device	Processor	Insertion depth (mm)	Postop LF PTA (dB HL) in CI ear	Hearing loss (dB) in LF PTA	Interaural asymmetry for 125, 250 and 500 Hz (CI ear)–(non-CI ear)	Hearing preservation (HP) benefit in SRT (dB)
1	54	1.4	Nucleus CI512	CP810	18	28.3	50.0	50, 55, 70	1.6
2	58	7.4	Nucleus CI24RCA	CP810	18	42.5	20.8	10, 15, 20	4.0
3	46	5.9	Nucleus Hybrid S8	Hybrid SP	10	23.3	60.0	35, 40, 35	−0.7
4	76	0.6	MED-EL Sonata H	Opus2	31	78.3	5.0	5, 15, 30	1.0
5	61	1.7	MED-EL Sonata H	Opus2	31	46.7	10.0	−20, −15, −10	2.0
6	67	0.8	MED-EL FLEX24	Opus2	24	41.7	18.3	10, 15, 25	3.7
7	69	4.8	MED-EL FLEX 24	Opus2	24	42.5	9.2	−5, 10, 15	0.3
8	54	6.7	Nucleus Hybrid S8	Hybrid SP	10	33.3	0.0	10, 10, 0	5.0
9	62	6.2	Nucleus Hybrid S8	Hybrid SP	10	26.7	10.0	0, 5, 25	2.3
10	80	2.2	Nucleus Hybrid L24	Hybrid SP	16	16.7	16.7	5, 5, 10	4.0
11	48	2.8	Nucleus Hybrid L24	Hybrid SP	16	51.7	13.3	−20, −10, −20	3.3
12	46	2.4	Nucleus Hybrid L24	Hybrid SP	16	28.3	7.2	10, 15, 25	2.3
13	44	2.1	Nucleus Hybrid S12	Hybrid SP	10	31.7	5.0	5, 5, 5	2.0
14	54	4.4	Nucleus CI24RE (CA)	CP810	18	30.0	6.7	20, 20, 20	3.3
MEAN	58.5	3.5	N/A	N/A	18.0	34.5	19.3	14.6, 16.8, 22.1	2.4
STDEV	11.3	2.3	N/A	N/A	7.2	15.9	19.7	13.7, 14.1, 16.8	1.6

Table 2

Quiet thresholds, in dB SPL, for the stimuli used in Experiment 2 and the corresponding sensation level (SL), in dB SL, for the 90-dB-SPL overall level used for determining ITD thresholds. Because time did not allow quiet threshold tracking for participants 5, 6, 8 and 9, reference equivalent threshold sound pressure level (RETSPL, ANSI S3.6, 2010) for insert earphones (ER-3A) were used to estimate the listeners' thresholds for the 250-Hz signal. To estimate SPL thresholds for 100–900 Hz, HL thresholds for 125, 250, 500, and 750 Hz were converted to SPL and averaged. Thus the estimated SPL thresholds are shown in parentheses next to did not test (DNT).

Subject	**Quiet threshold, overall level (dB SPL)**				**Sensation level (SL) of ITD stimuli (dB SL)**			
	250 Hz		**100–900 Hz**		**250 Hz**		**100–900 Hz**	
	CI ear	**Non-CI ear**	**CI ear**	**Non-CI ear**	**CI ear**	**Non-CI ear**	**CI ear**	**Non-CI ear**
1	83.4	33.2	87.9	41.1	6.6[a]	56.8	2.1[a]	48.9
2	79.4	61.4	77.7	67.8	10.6	28.6	12.3	22.2
3	24.0	7.3	57.7	34.3	66.0	82.8	32.3	55.7
4	>90	77.9	>90	70.4	N/A	12.1	N/A	19.6
5	DNT (70.5)	DNT (80.5)	DNT (81.3)	DNT (90.0)	19.5	9.5	8.7	0.0[a]
6	DNT (75.5)	DNT (60.5)	DNT (80.0)	DNT (61.3)	14.5	29.4	10.0	28.7
7	52.6	65.9	55.8	69.2	37.4	24.1	34.2	20.8
8	DNT (50.5)	DNT (40.5)	DNT (50.0)	DNT (42.5)	39.5	49.5	40.0	47.5
9	DNT (45.5)	DNT (40.5)	DNT (63.8)	DNT (45.0)	44.5	49.5	26.2	45.0
10	29.7	23.0	39.5	27.1	60.3	67.0	50.5	62.9
11	39.8	73.0	50.8	80.2	50.2	17.0	39.2	9.8
12	DNT (45.5)	DNT (25.5)	DNT (63.8)	DNT (41.3)	44.5	64.5	26.3	48.8
13	57.2	50.8	51.2	47.3	32.8	39.2	38.8	42.7
14	DNT (76.5)	DNT (61.5)	DNT (79.0)	DNT (70.3)	13.5	28.5	11.0	19.7
MEAN	57.9	50.1	64.5	56.3	34.6	39.9	27.5	36.3
STDEV	20.0	22.3	15.2	18.8	18.5	22.3	14.1	16.8

[a] Because participants 1, 4, and 5 had such a high threshold for the 100–900 Hz stimulus in at least one ear, ITDs could not be measured for this stimulus.

Table 3

Shown here are individual and mean ITD thresholds, in microseconds, for the 250-Hz signal and 100- to 900-Hz band of noise.

	ITD threshold (μs)	
	250 Hz	**100–900 Hz**
NH1	76.7	17.0
NH2	113.3	47.2
NH3	90.0	19.7
NH4	90.6	12.8
NH5	37.2	9.2
MEAN	81.6	21.2
STDEV	16.8	8.6