Auditory motion tracking ability of adults with normal hearing and with bilateral cochlear implants

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Adults with bilateral cochlear implants (BiCIs) receive benefits in localizing stationary sounds when listening with two implants compared with one; however, sound localization ability is significantly poorer when compared to normal hearing (NH) listeners. Little is known about localizing sound sources in motion, which occurs in typical everyday listening situations. The authors considered the possibility that sound motion may improve sound localization in BiCI users by providing multiple places of information. Alternatively, the ability to compare multiple spatial locations may be compromised in BiCI users due to degradation of binaural cues, and thus result in poorer performance relative to NH adults. In this study, the authors assessed listeners' abilities to distinguish between sounds that appear to be moving vs stationary, and track the angular range and direction of moving sounds. Stimuli were bandpass-filtered (150–6000 Hz) noise bursts of different durations, panned over an array of loudspeakers. Overall, the results showed that BiCI users were poorer than NH adults in (i) distinguishing between a moving vs stationary sound, (ii) correctly identifying the direction of movement, and (iii) tracking the range of movement. These findings suggest that conventional cochlear implant processors are not able to fully provide the cues necessary for perceiving auditory motion correctly.

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I. INTRODUCTION

In realistic complex auditory environments, sound localization is a fundamental and important perceptual ability. This has been studied extensively in listeners with normal hearing (NH). In many studies, stationary sound sources are presented from discrete locations, and listeners respond by indicating the perceived location of the target sound, with data consisting of a statistical measure of average localization error such as root-mean-square (RMS) error (Hawley *et al.*, 1999; Lorenzi *et al.*, 1999; Makous and Middlebrooks, 1990; Nopp *et al.*, 2004; Schoen *et al.*, 2005; Wightman and Kistler, 1989). NH listeners are generally excellent at localizing sounds along the horizontal plane; in particular with broadband sounds, RMS errors are generally below 10°.

When input to one ear is removed and monaural deafness is simulated, NH listeners' performance on sound localization tasks drop significantly, demonstrating the importance of binaural inputs for accurate sound localization (Blauert, 1997; Macpherson and Middlebrooks, 2002; Middlebrooks and Green, 1991; Wightman and Kistler, 1997). Benefits that occur from binaural input have been considered in the context of clinical intervention with listeners who are deaf and hard of hearing. For example, in recent years there have been a growing number of patients who receive cochlear implants (CIs) in both ears. With this increase, evidence has demonstrated that patients with bilateral cochlear implants (BiCIs) generally perform significantly better on tasks of sound localization when using two implants compared with a single implant (van Hoesel and Tyler, 2003; Litovsky *et al.*, 2009). Experiments conducted in the laboratory have utilized relatively standard configurations of locations in the frontal hemifield. For instance, Grantham *et al.* (2007) tested 22 adults with BiCIs with targets presented in azimuth, and locations spanning from $-80°$ to $+80°$ with 10° separation between locations. Mean RMS errors were ∼30° for BiCI users, compared to 6.7° for NH adults. Kerber and Seeber (2012) tested 10 adults with BiCIs, with target locations also spanning $-80°$ to $+80°$ in azimuth. The median RMS errors were 27.58° for adult BiCI users compared to 5.11° for NH adults. In a recent study, Jones *et al.* (2014) tested 10 BiCI users using target locations spanning $-90°$ to $+90°$ in azimuth, and 10° separation. BiCI users had a mean RMS error of 27.9° and 8.2° for NH adults. These three examples of studies conducted with different groups of patients in different laboratories show that there is clear consistency in the findings of sound localization ability for stationary sound sources among BiCI users, and the gap in performance relative to young NH adults. One of the factors that differentiates BiCI users from NH listeners is that clinical processors are not coordinated and discard temporal fine structure. Thus, access to interaural time differences (ITDs) in the signal fine structure is limited. In contrast, BiCI users appear to have access to interaural level differences (ILDs) and use those cues to localize (Aronoff *et al.*, 2010; Grantham *et al.*, 2008). There are some efforts being made to improve signal processing of bilateral devices,

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however, the outcomes from those efforts remain to be fully demonstrated (e.g., Brown, 2014, 2018; Churchill *et al.*, 2014; Laback and Majdak, 2008; Thakkar *et al.*, 2018).

Experiments on stationary sound source localization have become somewhat standard in assessing spatial hearing in BiCI users. However, this condition is not representative of many auditory stimuli that occur in everyday situations, for example, when listeners need to track auditory objects that are in motion, such as other individuals (e.g., children in play spaces) or moving vehicles. In addition, dynamic changes in location are perceived when listeners move in relation to objects in the environment. In these situations, NH listeners are able to perceive source locations in a consistent manner by compensating for self-motion (Brimijoin and Akeroyd, 2014; Yost *et al.*, 2015). The present study assessed the ability to perceive motion of an auditory stimulus and to identify locations associated with start- and end-points of the stimulus.

Some early studies on perceiving moving sound sources in NH adults have focused on estimating angular thresholds for detecting sound movement. Harris and Sergeant (1971) placed a loudspeaker on a cart that was physically pulled by a moving apparatus to elicit auditory motion. A white noise stimulus was gated on when the cart traversed midline (0° in azimuth) and the smallest amount of movement needed to identify the direction of the moving sound source was estimated as the minimum audible angle (MAA). NH adults were tested in binaural and monaural conditions with a lower MAA reported in the binaural condition, suggesting binaural hearing improves motion detection. Grantham (1986) tested the ability to discriminate a moving sound from a stationary sound. Movement was simulated using amplitude panning between two loudspeakers in azimuth (−15° to +15°). The minimum audible movement angle (MAMA) was evaluated as the smallest amount of movement required for subjects to reliably discriminate a moving sound from a stationary sound. Approximately 5° of movement was needed for reliable discrimination. Furthermore, Perrott and Marlborough (1989) assessed the importance of auditory motion cues for localizing the start- and end-point of the moving sound, a feature that we implemented in the present study.

Interesting observations have also been made when factors such as duration, distance, and speed are roved and made unreliable. For instance, Carlile and Best (2002) found that duration and distance are relied on more so than speed; when those cues are unreliable, listeners tend to rely on speed (velocity), however, listeners are less sensitive to speed than to the other cues. A fascinating and growing literature on auditory motion has emerged in recent years, focusing on issues that listeners face in the real world. Auditory motion perception involves a complicated interaction between sensory, motor, and perceptual systems, including also proprioceptive feedback due to head motion and self-locomotion. Many of the studies on these topics are reviewed by Carlile and Leung (2016). Interestingly, the authors underscore the dearth of knowledge on auditory motion perception in people with hearing loss.

In the present study, we measured the abilities of adults with BiCIs and NH to track auditory motion. Stationary and moving sounds were interleaved, and subjects were asked (1) to indicate whether the sound was stationary or moving, and (2) if the sound was moving then identify the direction and range of motion. We hypothesized that having to track a moving sound may lead to poorer spatial hearing performance in BiCI users because they do not receive spatial cues with fine grained resolution.

II. METHODS

A. Listeners

Twenty subjects in total were recruited for testing. Ten post-lingually deafened BiCI adults travelled to the University of Wisconsin–Madison for testing and received a stipend as payment for their time. Biographical data for individual BiCI subjects is provided in Table I. All BiCI listeners used Cochlear (Sydney, Australia) Nucleus devices, programmed with the Advanced Combination Encoder (ACE) sound coding strategy. ACE uses a peak-picking strategy to select the 8 out of 22 channels with the greatest spectral energy within a brief time window.

Ten NH adults (eight females and two males, mean age = 23.4 yr) indicated by audiometric thresholds less than or equal to 20 dB at octave frequencies between 250 and 8000 Hz in both the right and left ears with no asymmetries of more than 10 dB at any frequency. One of the NH adults was the first author. The remaining NH adults were students at the University of Wisconsin–Madison and were paid for their participation. Note that NH subjects are labeled with the letter "N" and BiCI subjects using the letter "B."

TABLE I. Demographic and CI information of listeners.

ID	Age at testing	Sex	Years Between 1st and 2nd CI	Years of BiCI use	Internal processor (L/R)	External Processor (L/R)
B1	64	F	2	8	CI24RE/CI24RE	Freedom/Freedom
B2	76	M	6	6	CI24R/CI24RE	N6/N5
B3	69	F	5	10	CI24M/CI24RE	N5/N6
B4	65	F	3	10	CI24RE/CI24RE	N5/N5
B5	58	F	6	7	CI24RE/CI24R	N6/N6
B6	57	F	1	6	CI24RE/CI24RE	Freedom/Freedom
B7	53	M	3	3	CI24RE/CI24RE	N5/N5
B8	22	M	Simultaneous implantation	4	CI512/CI512	N5/N5
B9	75	F	1	4	CI24RE/CI512	N5/N5
B10	20	M	3	4	CI512/CI24RE	N5/N5

Experimental protocols were within standards set by the National Institutes of Health and approved by the University of Wisconsin–Madison's Human Subjects Institutional Review board.

B. Equipment

Binaural recordings and subsequent testing were completed in the same sound-treated booth. The sound booth had internal dimensions of $2.90 \times 2.74 \times 2.44$ m (Acoustic Systems, RS 254 S, Austin, TX) and included additional acoustic-absorbing foam inside the walls to reduce reflections ($t_{60} \approx 40$ ms). The computer software MATLAB (Mathworks Inc., Natick, MA) was used to create and run the auditory motion experiment. A Tucker-Davis Technologies (Alachua, FL) System3 controlled an array of 37 stationary loudspeakers (Cambridge SoundWorks, North Andover, MA) positioned in azimuth, in the frontal hemisphere, with a radius of 1.2 m, separated by 5°, and spanned from −90° to +90°. A dark acoustically transparent curtain was used to conceal the loudspeaker array from the subjects.

C. Stimuli

Auditory stimuli consisted of white noise tokens sampled at 48 kHz and calibrated to an output of 60 dBA sound pressure level using a sound level meter (System 824, Larson Davis, Depew, NY). The white noise tokens were bandpass filtered using a fourth-order Butterworth filter that spanned a frequency range (150–6000 Hz) like that of the Nucleus processors that were used by the BiCI subjects. To simulate auditory motion, vector based amplitude panning was applied to the stimuli which resulted in sound source that traversed the loudspeaker array and appeared to be moving (Pulkki, 1997). To account for individual loudspeaker differences, inverse filters were created for each loudspeaker (Epain *et al.*, 2010) and applied to the stimulus to be presented from each loudspeaker. The frequency response $E(k)$ of the inverse filters was calculated as

$$E(k) = \min\left\{\frac{1}{|C(k)|},\ \beta(k)e^{-i\angle C(k)}\right\},$$

where k is the frequency index, $C(k)$ is the N-point Fast Fourier Transform of the loudspeaker impulse response, and $\beta(k)$ is the maximum amplitude of the inverse filter at a particular frequency. For our inverse filters, $N = 512$ and $\beta = 0$, 0, 2, 3, 5, 10, 20, 20, 0, 0 at $k = 0$, 500, 750, 1000, 3000, 5000, 10 000, 16 000, 18 000, and 24 000 Hz. All loudspeakers in the horizontal array were calibrated to ensure that each individual loudspeaker had a flat frequency spectrum (within 3 dB between 500 Hz and 16 kHz) after the application of the inverse filter.

D. Binaural recordings

Stimuli for this experiment consisted of binaural recordings made on KEMAR (Knowles Electronics Manikin for Acoustic Research, G.R.A.S Sound & Vibration, Holte, Denmark). Binaural recordings, as opposed to freefield testing, was used because we intend on conducting future studies to understand the influence of binaural cues and CI processing on auditory motion perception. The use of binaural recordings will facilitate cue manipulation and offline vocoder processing for future studies, as well as ease of comparison of results against the benchmark data obtained in this study. However, we acknowledge that the use of non-individualized binaural recordings may lead to slightly poorer localization performance, especially in NH listeners, and removes head movement as a cue for completing the task.

Binaural recordings were made by placing microphones (HeadZap binaural microphones, AuSim, Mountain View, CA) into the ear canal of KEMAR. A three-point laser system was used to position KEMAR in the center of the loudspeaker array. One laser was pointed at the nose from 0°, while the other two lasers were placed at −90° and +90°, to ensure the ears of KEMAR were at the height of the loudspeakers.

Stimuli for the binaural recording were white noise tokens (see Sec. II C). A new noise token was generated for each recording. Stationary sound source recordings were made at 19 target locations across the horizontal loudspeaker array (−90° to +90° in 10° intervals). For the moving sound sources, the end points of the trajectory were matched to the same 19 target locations as the stationary sounds.

E. Testing procedure

Listeners sat on a height-adjustable chair located in the same position as that of the KEMAR during recordings. The same three-point laser system approach mentioned previously was used to ensure listeners were positioned in the same location as the KEMAR manikin used for the binaural recordings. Stimuli were presented to NH adults via circumaural headphones (Sennheiser HD600, Wedemark, Germany) and to BiCI users via auxiliary input ports on their clinical CI sound processors. Subjects sat facing a touchscreen monitor (ELO 1517L, Milpitas, CA) that was used to control stimulus presentation and to capture the response during each trial. Each block of trials consisted of interleaved stationary and moving sounds at a fixed stimulus duration (500, 1000, or 2000 ms). The moving sounds within each block spanned different angular ranges (10°, 20°, or 40°). After stimulus presentation, an image representing the loudspeaker array appeared on the touch-screen, and the listener responded by marking the perceived trajectory of the stimulus. Subjects could respond in one of two ways: (1) If a stationary sound was perceived, the subject made a single press at a location on the screen corresponding to the perceived location of the sound (see Fig. 1). In this case, a small blue rectangle would appear on the screen where the press had been made and that location was converted to an angle corresponding to the location. (2) If a moving sound was perceived, the subject drew a line on the screen to denote the range and direction of the perceived sound source motion. From these responses we inferred the perceived angular positions, range, and direction of motion. Stimuli were presented 10 times for a stationary sound, and 10 times for each moving sound (10 presentations left-moving and 10 presentations right-moving). It should be noted that due to limitations of the speaker array, some moving sound

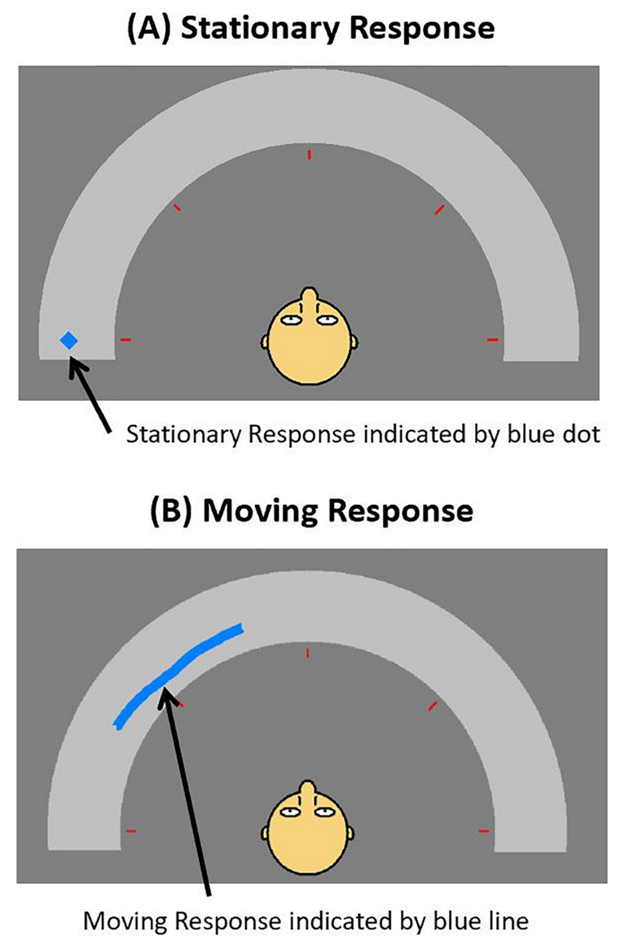

FIG. 1. (Color online) Graphical user interface (GUI) used to obtain listener responses. A stationary and moving sound was indicated by a small blue rectangle (A) or a line (B) on the GUI, respectively.

trajectories are not possible (e.g., a rightward moving sound to the leftmost speaker). Hence, the number of trials varied based on angular range. Table II shows all simulated auditory motion conditions and the number of trials associated with each angular range.

F. Data analyses

Several metrics were used to analyze the data for each subject:

(1) Identification of sound movement: data were analyzed with respect to the proportion of trials identified moving. For this analysis, sensitivity (d') and bias criterion (c) were calculated for each listener to understand their ability to discriminate the perceived motion of a sound source and their response biases (Macmillan and Creelman, 2005).

(2) Direction of movement: trials with moving sound sources that were correctly identified as moving were analyzed to determine if the *direction* of motion was correctly identified to the right vs left. For this analysis as well, sensitivity (d') and bias criterion (c) were calculated for each listener to understand their ability to discriminate the direction of auditory motion and their response biases (Macmillan and Creelman, 2005).

(3) RMS errors: for stationary sounds, the RMS error was computed as the average difference between target and response locations; for moving sounds, the RMS was calculated twice: start-point RMS error was computed based on the difference between the starting location of the moving sound and the angle corresponding to the participant's start-point response, and end-point RMS error was computed based on the difference between the ending location of the moving sound and the angle corresponding to the participant's end-point response.

(4) Tracking range of perceived motion: for moving sound source trials where the listener correctly identified the sound as moving and in the correct direction, these trials were analyzed to quantify a listener's ability to track the angular range of the moving sound source.

TABLE II. Summary of auditory motion conditions.

Angular range of movement (°)	Angular velocity (°/sec)	Duration (ms)	Number of Trials
Stationary (0)	0	500	190
10	20	500	180 left, 180 right
20	40	500	170 left, 170 right
40	80	500	150 left, 150 right
Stationary (0)	0	1000	190
10	10	1000	180 left, 180 right
20	20	1000	170 left, 170 right
40	40	1000	150 left, 150 right
Stationary (0)	0	2000	190
10	5	2000	180 left, 180 right
20	10	2000	170 left, 170 right
40	20	2000	150 left, 150 right

G. Statistical analyses

Initially, all data were analyzed using a mixed-effects three-way, analysis of variance with a Greenhouse–Geisser correction for sphericity. However, Levene's test indicated significant differences in across-group variance ($p < 0.05$). Hence, non-parametric statistical methods were used to analyze the data using the software MATLAB version 2015b (Mathworks Inc., Natick, MA). For between group comparisons, Kruskal–Wallis tests were conducted to assess main effects. For within group comparisons, Friedman's test was conducted to assess main effects and where significant differences were found, *post hoc* comparisons were conducted using Wilcoxon signed-rank tests with a Bonferroni correction. Binary outcome responses (metrics number 1–2 previously mentioned) were modeled using generalized linear (logistic) mixed-models (GLMM) with the lme4 package (Bates *et al.*, 2014) in R (version 3.1.3, R Core Team, 2015). For Metric 1, the model was constructed using the participant's response when reporting a sound source correctly or incorrectly as the outcome variable. For example, trials with a stationary target presented would be assessed based on how many stationary responses were reported by the listener. An individual model was constructed for each angular range condition (stationary, 10°, 20°, and 40°) within each stimulus duration (500, 1000, and 2000 ms), where group membership (BiCI and NH) was defined as a fixed-effect, and individual differences were modeled by a random intercept for each participant. For Metric 2, similar models were constructed using the same predictors but the outcome variable was the participant's response when reporting the direction of a moving sound correctly.

III. RESULTS

A. Discriminating between a stationary and moving sound source

Figure 2 shows individual data (top panels) and group means [±standard deviation (SD)] (bottom panels) for proportions of trials identified as moving for each stimulus duration (500, 1000, and 2000 ms) and angular range condition (stationary, 10°, 20°, and 40°). Visual inspection of the data suggests that variability in performance seems much larger for the BiCI group when compared to the NH group when (1) the sound source was not moving and (2) in the farthest moving angular range condition (40°). Both groups had large variability in their responses in short moving angular range conditions (10° and 20°). Because there are both floor and ceiling effects the variability was not statistically analyzed.

On average, for the stationary sound source condition, BiCI users reported a stationary sound source as moving more often than the NH group (greater than 50% of trials for BiCI vs less than 10% for NH). When considering the effect of duration, results from the GLMM for the stationary condition revealed a significant effect of group at each duration [500 ms: $\chi^2(1) = 19.53$, $p < 0.001$; 1000 ms: $\chi^2(1) = 29.64$, $p < 0.001$; 2000 ms: $\chi^2(1) = 30.113$, $p < 0.001$]. When considering the effect of angular range, on average, the BiCI group appeared to have reported a larger amount of moving responses than the NH group for the 10° angular range condition (compare bottom panels for the 10° angular range condition). Results from the GLMM for the 10° angular range condition revealed a significant effect of group at a duration of 1000 ms [$\chi^2(1) = 6.16$, $p = 0.01$] and 2000 ms [$\chi^2(1) = 7.15$, $p = 0.007$], but not for 500 ms [$\chi^2(1) = 1.34$, $p = 0.24$]. For the 20° angular range condition, on average, both groups of listeners performed similarly when reporting the sound source as moving (compare bottom panels for the 20° angular range condition). Results from the GLMM for the 20° angular range condition revealed no significant effect of group at each duration [500 ms: $\chi^2(1) = 2.57$, $p = 0.10$; 1000 ms: $\chi^2(1) = 0.01$, $p = 0.90$; 2000 ms: $\chi^2(1) = 0.43$, $p = 0.51$]. For the 40° angular range condition, on average, the BiCI group reported fewer sound sources as moving compared to the NH group (compare bottom panels for the 40° angular range condition). Results from the GLMM for the 40° angular range condition revealed a significant effect of group at each duration [500 ms: $\chi^2(1) = 35.34$, $p < 0.001$; 1000 ms: $\chi^2(1) = 20.08$, $p < 0.001$; 2000 ms: $\chi^2(1) = 12.58$, $p < 0.001$]. These results indicate that BiCI users were more likely to report a sound source as moving at a short angular range (10°) for stimulus durations of 1000 and 2000 ms than NH listeners (67% of trials for BiCI vs 30% for NH listeners), but were poorer than the NH group when the angular range was 40° (79% of trials for BiCI vs 98% for NH listeners) and in the stationary condition (35% of trials for BiCI vs 92% for NH listeners).

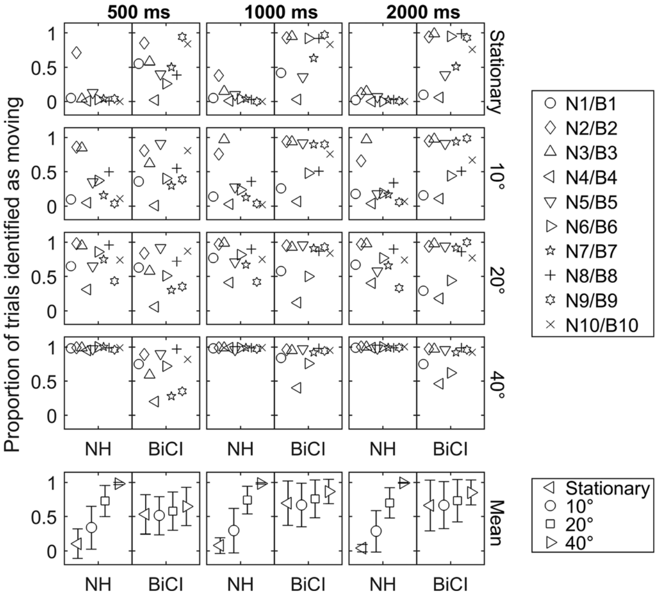

FIG. 2. Each subplot is shown in a similar manner (left panels = NH; right panels = BiCI) for the proportion of sound sources reported as moving, for each stimulus duration (500, 1000, and 2000 ms) and angular range condition (stationary, 10°, 20°, and 40°). The top panels show individual data from each group. Each individual subject is represented by their own emblem as seen in the legend to the right of the plots. The bottom panels show the group means. Each individual symbol represents each stimulus duration as seen in the legend at the bottom right of the figure. All error bars show standard deviation.

An important trend that was seen across the BiCI group was the general tendency to report the sound source as moving in the stationary condition, regardless of stimulus duration. This suggests a general inability to discriminate between whether the sound was stationary or moving. To quantitatively analyze this trend, sensitivity (d') was

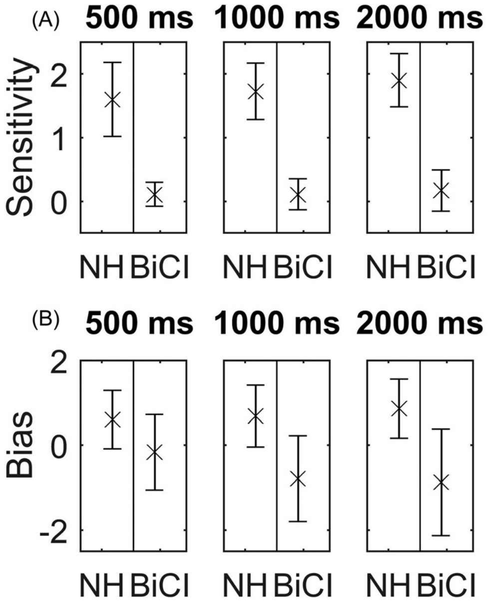

FIG. 3. Each subplot is shown in a similar manner (left panels = NH; right panels = BiCI) for each stimulus duration tested (500, 1000, and 2000 ms). (A) shows the group means for sensitivity when discriminating a moving sound source from a stationary sound source. (B) shows the group means for response bias of a moving sound source compared to a stationary sound source. All error bars show SD.

calculated to assess a listener's ability to discriminate a sound source as moving or stationary. Figure 3(A) shows the mean ($\pm$SD) sensitivity (d') measure of each group, in each duration, for discriminating the motion of a sound source. On average, NH adults had better sensitivity between discriminating a sound source as stationary vs moving compared to BiCI users. Kruskal–Wallis tests for all possible comparisons, when duration was held constant, revealed the BiCI group was significantly poorer than the NH group (all p-values < 0.001). In addition, Fig. 3(B) shows the mean ($\pm$ SD) for bias criterion (c), which was calculated to assess if a listener was biased toward identifying a sound source as stationary or moving. Kruskal–Wallis tests for all possible comparisons, when duration was held constant, revealed the BiCI group was significantly poorer than the NH group (all p-values < 0.005). These data suggest that the BiCI group was poorer at discriminating the motion of a sound source and more biased toward stating that a sound was moving (vs stationary) compared to the NH group.

B. Discriminating the direction of a moving sound source

Figure 4 shows a listener's ability to correctly report the direction of a moving sound source. While it should be noted that the number of trials for each individual listener varies due to performance differences, on average the total number of trials identified as moving by the two groups of listeners were similar when pooled across all conditions (21 430 in BiCI vs 20 971 in NH listeners). For BiCI users, variability appears to be larger compared to the NH adults in all stimulus conditions (compare top panels). Because there are both floor and ceiling effects the variability was not statistically analyzed. When comparing group means within each duration for each moving angular range condition, the BiCI group had fewer correct responses compared to the NH group (compare bottom panels). Results from the GLMM revealed a significant effect of group at each duration for 10° [500 ms: $\chi^2(1) = 66.11$, $p < 0.001$; 1000 ms: $\chi^2(1) = 83.83$, $p < 0.001$; 2000 ms: $\chi^2(1) = 58.75$, $p < 0.001$], 20° [500 ms: $\chi^2(1) = 108.23$, $p < 0.001$; 1000 ms: $\chi^2(1) = 101.3$, $p < 0.001$; 2000 ms: $\chi^2(1) = 135.95$, $p < 0.001$], and 40° [500 ms: $\chi^2(1) = 70.89$, $p < 0.001$; 1000 ms: $\chi^2(1) = 119.81$, $p < 0.001$; 2000 ms: $\chi^2(1) = 124.6$, $p < 0.001$]. These results indicate that the BiCI group was significantly poorer at correctly reporting the direction of a moving sound source than the NH group. Furthermore, to assess a listener's discrimination ability, sensitivity (d') and bias criterion (c) was calculated for discrimination ability of the direction of a moving sound source.

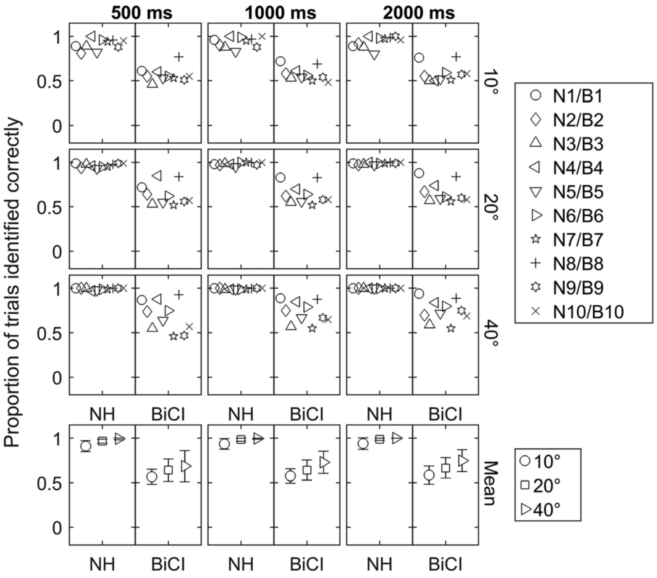

FIG. 4. Each subplot is shown in a similar manner (left panels = NH; right panels = BiCI) for the proportion of moving sound sources reported moving in the correct direction, for each stimulus duration (500, 1000, and 2000 ms) and moving angular range condition (10°, 20°, and 40°). The top panels show individual data from each group. Each individual subject is represented by their own emblem as seen in the legend to the right of the plots. The bottom panels show the group means. Each individual symbol represents each stimulus duration as seen in the legend at the bottom right of the figure. All error bars show SD.

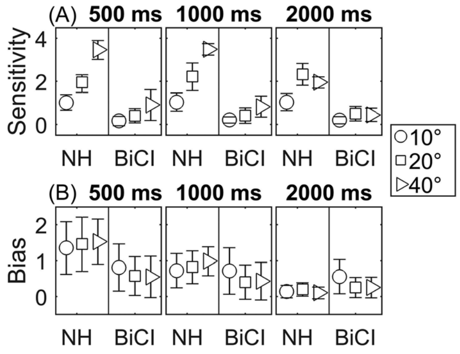

FIG. 5. Each subplot is shown in a similar manner (left panels = NH; right panels = BiCI) for each stimulus duration (500, 1000, and 2000 ms). Each individual symbol represents each moving angular range condition (10°, 20°, and 40°) as seen in the legend at right of the figure. (A) shows the group means for sensitivity when discriminating between a left-moving sound source compared to a right-moving sound source. (B) shows the group means for response bias toward a left-moving sound source compared to a right-moving sound source. All error bars show SD.

Figure 5(A) shows the mean ($\pm$ SD) sensitivity (d') measure of each group when discriminating the direction of a sound source. On average, NH adults had better sensitivity when discriminating the direction of a moving sound source compared to the BiCI users. Kruskal–Wallis tests for all possible comparisons, when duration was held constant, revealed the BiCI group was significantly poorer than the NH group (all p-values < 0.001; Bonferroni-corrected $\alpha = 0.016$). In addition, Fig. 5(B) shows the mean ($\pm$ SD) for bias criterion (c), which was calculated to assess if a listener was biased toward left- or right-moving responses. On average, BiCI users appeared to be less biased toward left-moving responses than NH adults in the 10° angular range condition, but biases were comparable across the longer angular range conditions (20° and 40°). Kruskal–Wallis tests for all possible comparisons, when duration was held constant, revealed the BiCI group was not significantly different than the NH group (all p-values > 0.019; Bonferroni-corrected $\alpha = 0.016$). These data suggest that the BiCI group had significantly poorer sensitivity when discriminating the direction of a moving sound source compared to NH adults, but that the BiCI group was not more biased than the NH group toward a specific directional response.

C. Sound localization

1. Stationary sound source localization

Figure 6(A) shows mean RMS errors (±SD) from the angular range condition with sound sources that are stationary (compare within "stationary" subplot), for the BiCI and NH groups. Individual RMS error data for BiCI and NH listeners are included in Appendixes A (Table III) and B (Table IV), respectively. For each duration, Kruskal–Wallis tests were conducted to compare RMS errors between groups, revealing significantly higher RMS errors in BiCI users compared with NH adults for all comparisons (all p-values < 0.001; Bonferroni-corrected $\alpha = 0.016$). Friedman's test revealed that stimulus duration did not significantly affect RMS errors within each group [BiCI: $\chi^2(2) = 2.4$, $p = 0.3$; NH: $\chi^2(2) = 1.4$, $p = 0.5$].

2. Moving sound source start-point localization

Figure 6(B) shows average RMS errors for locating the start-point of a moving sound. Between groups, start-point RMS errors were higher in the BiCI group compared with the NH group, as confirmed with Kruskal–Wallis tests for all possible comparisons, when each duration was held constant (all p-values < 0.001; Bonferroni-corrected $\alpha = 0.016$).

For the BiCI group [compare within each BiCI subplot in Fig. 5(B)], there was no significant difference in RMS error across stimulus durations, as confirmed by Friedman's tests within each angular range [10°: $\chi^2(2) = 2.6$, $p = 0.27$; 20°: $\chi^2(2) = 4.2$, $p = 0.12$; 40°: $\chi^2(2) = 0.8$, $p = 0.67$]. However, when comparing RMS errors for the different angular ranges within each stimulus duration, Friedman's tests revealed significant effects for all three durations [500 ms: $\chi^2(2) = 15.2$, $p < 0.001$; 1000 ms: $\chi^2(2) = 13.4$, $p < 0.001$; 2000 ms: $\chi^2(2) = 11.44$, $p = 0.003$]. *Post hoc* analyses revealed that at all durations, RMS errors were significantly higher at 40° compared to the two smaller moving angular ranges (all p-values < 0.014; Bonferroni-corrected $\alpha = 0.016$), with no significant differences between 10° and 20°. Although the difference was only a few degrees, the significant findings suggest that locating the start-point of a moving sound source at the largest angular range (40°) may have been more difficult, regardless of stimulus duration.

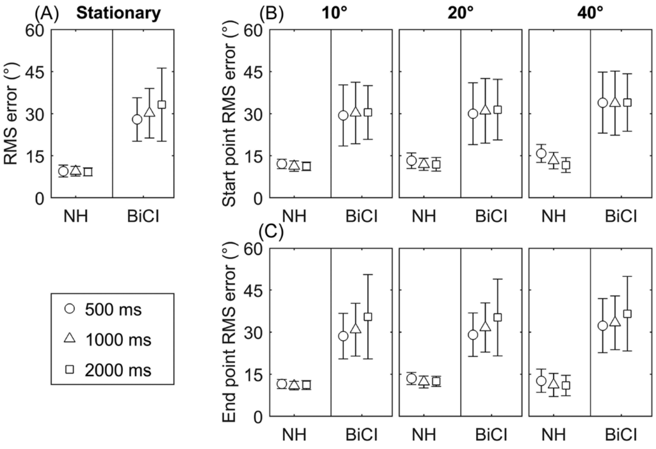

FIG. 6. Each subplot is shown in a similar manner (left panels = NH; right panels = BiCI) where a symbol represents each stimulus duration (500, 1000, and 2000 ms) as seen in the legend in the bottom left of the plot. In (A), the mean RMS error of the stationary sound source condition is plotted. In (B) and (C) the mean RMS errors of the start and end-points of each moving sound source condition (10°, 20°, and 40°) are shown, respectively. All error bars show SD.

In the NH group, there was a decrease in start-point RMS error with increasing duration, most noticeable for the 40° angular range. Friedman's test revealed no significant effect of stimulus duration for the 10° range [$\chi^2(2) = 3.8$, $p = 0.15$], but significant differences were found for the larger angular ranges [20°: $\chi^2(2) = 7.4$, $p = 0.02$); 40°: $\chi^2(2) = 20$, $p < 0.001$]. *Post hoc* analyses revealed that at the 20° angular range, RMS error at the 500 ms duration stimulus was significantly higher compared with 1000 and 2000 ms ($p = 0.01$ and $p = 0.006$, respectively; Bonferroni-corrected $\alpha = 0.016$). At the 40° angular range, the RMS error in the 2000 ms duration was significantly lower than the other stimulus durations ($p = 0.002$ for all comparisons; Bonferroni-corrected $\alpha = 0.016$). Friedman's Test on RMS errors within each duration revealed a significant effect of angular range at 500 ms [$\chi^2(2) = 14.6$, $p < 0.001$], but no significant effect at 1000 and 2000 ms [$\chi^2(2) = 5$, $p = 0.08$; $\chi^2(2) = 0.8$, $p = 0.67$, respectively]. *Post hoc* analyses at the 500 ms stimulus duration revealed that the RMS error at the 40° angular range was significantly higher than that of 10° and 20° ($p = 0.002$ and $p = 0.006$, respectively; Bonferroni-corrected $\alpha = 0.016$).

3. Moving sound source end-point localization

Figure 5(C) shows mean (±SD) RMS errors for locating the end-point of the trajectory. RMS errors were higher in the BiCI group compared with the NH group, as confirmed by Kruskal–Wallis tests for all possible comparisons, when duration was held constant (all p-values < 0.001; Bonferroni-corrected $\alpha = 0.016$).

In the BiCI group, within each angular range, RMS errors increased with longer durations. Friedman's test found a significant effect at 20° [$\chi^2(2) = 7.4$, $p = 0.03$], but not at 10° [$\chi^2(2) = 6.2$, $p = 0.05$] or 40° [$\chi^2(2) = 1.4$, $p = 0.5$]. *Post hoc* analyses for the 20° angular range revealed that RMS errors were significantly lower at 500 ms compared to 1000 and 2000 ms ($p = 0.01$ for both comparisons, Bonferroni-corrected $\alpha = 0.016$). Friedman's test at each stimulus duration revealed a significant effect of angular range for 500 ms [$\chi^2(2) = 7.4$, $p = 0.025$], but no significant differences were found at 1000 and 2000 ms [$\chi^2(2) = 5.6$, $p = 0.06$; and $\chi^2(2) = 0.2$, $p = 0.091$, respectively]. *Post hoc* analyses for 500 ms revealed a higher RMS error at 40° than 10° and 20° ($p = 0.01$ and $p = 0.006$, respectively; Bonferroni-corrected $\alpha = 0.016$). In summary, the BiCI data suggest that significant effects were only found at a short stimulus duration (500 ms), and localization ability of the end-point is poorest at the largest angular range of 40° compared to the smaller angular ranges of 10° and 20°.

In the NH group, Friedman's test on the RMS errors at each angular range found no effect of stimulus duration at 10° [$\chi^2(2) = 0.2$, $p = 0.9$] and 20° [$\chi^2(2) = 3.8$, $p = 0.14$]. There was a significant effect at 40° [$\chi^2(2) = 12.2$, $p = 0.002$]; *post hoc* analyses revealed a higher RMS error at 500 ms compared to 1000 and 2000 ms ($p = 0.002$ and $p = 0.003$, respectively; Bonferroni-corrected $\alpha = 0.016$). Within each stimulus duration, RMS errors varied slightly with angular range. Friedman's test at each duration revealed a significant effect of angular range at 500 ms [$\chi^2(2) = 13.4$, $p < 0.001$] and 2000 ms [$\chi^2(2) = 10.4$, $p = 0.006$], but no significant difference was found for 1000 ms [$\chi^2(2) = 6.2$, $p = 0.05$]. *Post hoc* analyses revealed that at the 500 and 2000 ms stimulus durations, the RMS error at 10° was lower than that of 20° ($p = 0.002$; Bonferroni-corrected $\alpha = 0.016$). The data suggest that in NH adults, lower end-point RMS errors were found for the shortest angular range of 10° at stimulus durations of 500 and 2000 ms.

4. Comparing stationary and end-point localization

We considered the possibility that a moving sound may improve the sound localization ability of subjects who are fitted with BiCIs, if a moving sound provides multiple reference points for accurately locating the end-point of the stimulus. RMS errors were compared for stationary vs end-point stimuli in the conditions with moving sources [compare Figs. 5(A) and 5(C)]. In the BiCI group, RMS errors were lower in the stationary condition compared to the end-point of a moving sound source, and this was true for each of the angular range conditions tested. Friedman's test comparing RMS errors within each stimulus duration revealed significant effects of angular range at 500 ms [$\chi^2(3) = 10.2$, $p = 0.017$] and 1000 ms [$\chi^2(3) = 11.16$, $p = 0.011$], but not for 2000 ms [$\chi^2(3) = 5.28$, $p = 0.15$]. *Post hoc* analyses revealed that at the 500 ms stimulus duration, the RMS error was significantly lower in the stationary condition compared to the end-point of a moving sound source at 40° ($p = 0.014$; Bonferroni-corrected $\alpha = 0.016$); at 1000 ms, the RMS error was significantly lower in the stationary condition compared to the end-point for moving sound sources of 20° ($p = 0.014$; Bonferroni-corrected $\alpha = 0.016$) and 40° ($p = 0.004$; Bonferroni-corrected $\alpha = 0.016$). The effects were not significant for 10° vs stationary, regardless of stimulus duration. Overall, the BiCI group did not improve in localization ability of the end-point of a moving sound when compared to a stationary sound source.

Within the NH group, Friedman's test comparing RMS errors within each stimulus duration revealed a significant effect of angular range for all durations [500 ms: $\chi^2(3) = 22.2$, $p < 0.001$; 1000 ms: $\chi^2(3) = 16.68$, $p < 0.001$; 2000 ms: $\chi^2(3) = 20.28$, $p < 0.001$]. *Post hoc* analyses revealed that for the 500 ms duration, the RMS error of the stationary condition was significantly lower than all end-point localization errors of moving sound source conditions (all p-values $= 0.14$; Bonferroni-corrected $\alpha = 0.016$). For 1000 and 2000 ms, the RMS error of the stationary sound source condition was significantly lower than the end-point RMS errors for moving sound sources of only 10° and 20° (all p-values $= 0.003$; Bonferroni-corrected $\alpha = 0.016$). This suggests that a NH listener's localization ability of a stationary sound source is generally better than that of the end-point of a moving sound source with a short angular range.

5. Comparing stationary and start-point localization

Conversely, listeners reported their responses after listening to the target sound source and were able to perceive the end-point as well as the start-point if the target sound source was moving. To fully understand if localization ability was different when a moving sound source was introduced, we also compared the RMS errors between the start-point of a moving sound with that of a stationary sound [compare Figs. 5(A) and 5(B)]. In the BiCI group the RMS error of the stationary condition appears to be slightly lower than the RMS errors for the start-point of all moving sound conditions. Friedman's test comparing RMS errors within each stimulus duration revealed a significant effect of angular range for all durations [500 ms: $\chi^2(3) = 14.04$, $p = 0.003$]; 1000 ms: $\chi^2(3) = 10.44$, $p = 0.02$; 2000 ms: $\chi^2(3) = 9.06$, $p = 0.03$]. *Post hoc* analyses revealed no significant differences when comparing the RMS error of the stationary condition with the start-point RMS error of a moving sound for all durations. Overall, for the BiCI group, there was no difference in their ability to localize the start-point of a moving sound when compared to a stationary sound source.

Within the NH group, Friedman's test comparing RMS errors within each stimulus duration revealed a significant effect of angular range for all durations [500 ms: $\chi^2(3) = 23.4$, $p < 0.001$; 1000 ms: $\chi^2(3) = 17.17$, $p < 0.001$; 2000 ms: $\chi^2(3) = 18.48$, $p < 0.001$]. *Post hoc* analyses revealed that within each duration, the RMS error of the stationary condition was significantly lower than each start-point RMS error of all moving sound source conditions (all p-values < 0.003; Bonferroni-corrected $\alpha = 0.016$). This suggests that a NH listener's localization ability of a stationary sound source is better than that of the start-point of a moving sound source.

D. Extent of perceived motion

Figure 7 shows the ability of a listener to track how far a moving sound source traversed the horizontal plane. A subject's motion tracking response was accurate if they were near the target angular range presented, shown as solid horizontal lines in the top panels of Fig. 7. Between groups (compare between each NH and BiCI bottom subplot), as the sound source traversed a larger angular range, both groups increased their performance but the NH group seemed to have less variability compared to the BiCI group. Kruskal–Wallis tests revealed no significant differences between the BiCI and NH groups at a duration of 500 ms. However, the BiCI group reported angular ranges that were significantly higher than the NH group for a stimulus duration of 1000 ms at angular ranges of 10° [$\chi^2(1) = 7.0$, $p = 0.008$; Bonferroni-corrected $\alpha = 0.016$] and 20° [$\chi^2(1) = 6.61$, $p = 0.01$; Bonferroni-corrected $\alpha = 0.016$] and at 2000 ms for all possible comparisons of each angular range (all p-values < 0.001; Bonferroni-corrected $\alpha = 0.016$).

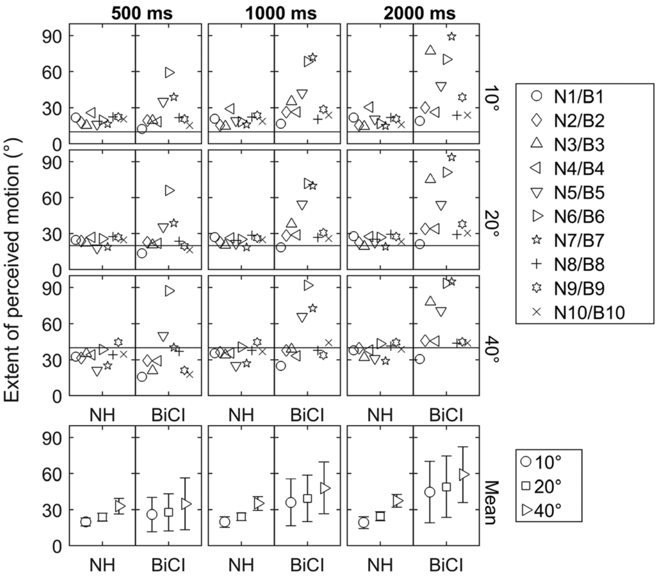

FIG. 7. Each subplot is shown in a similar manner (left panels = NH; right panels = BiCI) where a symbol represents each stimulus duration (500, 1000, and 2000 ms) as seen in the legend in the bottom left of the plot. In (A), the mean RMS error of the stationary sound source condition is plotted. In (B) and (C) the mean RMS errors of the start and end-points of each moving sound source condition (10°, 20°, and 40°) are shown, respectively. All error bars show SD.

Within the BiCI group, when comparing the means for each angular range (compare within each bottom BiCI subplot), motion tracking responses increased as duration increased. Friedman's test found a significant effect of stimulus duration at all angular ranges [10°: $\chi^2(2) = 16.2$, $p < 0.001$; 20°: $\chi^2(2) = 18.2$, $p < 0.001$, and 40°: $\chi^2(2) = 15.2$, $p < 0.001$]. *Post hoc* analyses revealed that all combinations of comparisons for each stimulus duration were significant (all p-values < 0.001; Bonferroni-corrected $\alpha = 0.016$). These data suggest that BiCI users increased their range of perceived motion responses as the duration increased. Furthermore, Friedman's test found a significant effect of angular range at all stimulus durations [500 ms: $\chi^2(2) = 16.8\, p < 0.001$; 1000 ms: $\chi^2(2) = 12.8$, $p = 0.002$; and 2000 ms: $\chi^2(2) = 16.8$, $p < 0.001$]. *Post hoc* analyses for 500 and 1000 ms showed the 40° angular range was larger than 10° or 20° (all p-values $= 0.002$; Bonferroni-corrected $\alpha = 0.016$). At 2000 ms, all combinations of comparisons for 10°, 20°, and 40° were significant (all p-values < 0.01; Bonferroni-corrected $\alpha = 0.016$). These data suggest that BiCI users were able to distinguish between tracking sound sources that traversed different angular ranges movement, specifically at the longest duration of 2000 ms.

Within the NH group, when comparing the effect of stimulus duration within each angular range (compare within each NH bottom subplot), motion tracking responses were similar for angular ranges of 10° and 20° across all durations, but a slight increase occurred when the sound source was moving at 40°. Friedman's test found a significant effect of duration at 40° [$\chi^2(2) = 8.6$, $p = 0.014$], but not for 10° [$\chi^2(2) = 4.2$, $p = 0.13$] or 20° [$\chi^2(2) = 2.6$, $p = 0.27$]. *Post hoc* analyses at the 40° angular range condition revealed the stimulus duration of 500 ms was significantly lower than 1000 and 2000 ms (all p-values $= 0.01$; Bonferroni-corrected $\alpha = 0.016$). When comparing within each stimulus duration, the motion tracking response of the NH group increased as the angular range increased. Friedman's test found a significant effect of angular range at all stimulus durations [500 ms: $\chi^2(2) = 20$, $p < 0.001$; 1000 ms: $\chi^2(2) = 182$, $p < 0.001$; 2000 ms: $\chi^2(2) = 18.2$, $p < 0.001$]. *Post hoc* analyses revealed all combinations of comparisons of each angular range, for each duration, were significant (all p-values $= 0.014$; Bonferroni-corrected $\alpha = 0.016$). These analyses suggest that NH adults were able to distinguish between tracking a short moving sound source (10°) and longer moving sound sources (20° and 40°), regardless of stimulus duration.

IV. DISCUSSION

The ability to perceive and track a moving sound is important for functioning in everyday listening situations, for example, tracking a moving vehicle to avoid danger, or tracking changes in the location of important sound sources in educational settings and in social situations. The current study assessed the ability of adults to perform on three aspects of sound motion tracking on the horizontal plane: (1) discriminating whether sounds are moving or stationary; (2) if perceived as moving, then discriminating the direction of movement; and (3) finally, tracking the range of sound movement. Performance was compared between stationary and dynamic conditions, for listeners with BiCIs and NH.

Results from this study suggest three main novel findings. First, within the BiCI group, the ability to report whether a sound source is moving vs stationary was highly variable. In addition, performance was best for the majority of participants in the conditions with the greatest movement. NH listeners were excellent at knowing when sounds are stationary; for moving sounds, they were near perfect at all durations if the movement is as large as 40°, and within group there was more variability for smaller angular movements. Second, if they correctly reported sounds as moving, NH listeners could then report the correct direction of movement with near perfect accuracy, being slightly worse at 10° than larger angles, with no effect of stimulus duration. BiCI users performed worse on the same conditions compared with NH listeners, and performance had more inter-subject variability, even at large angular ranges and longer stimulus durations. The third novel finding involves the measure of tracking auditory motion. Our data showed that BiCI users had significantly larger response trajectories compared to NH adults, generally overshooting the actual range of sound movement, especially for longer stimulus durations of 1000 and 2000 ms. Overall, as has been previously shown, BiCI users were worse than NH adults at localizing a stationary sound source (e.g., Grantham *et al.*, 2007; Litovsky *et al.*, 2009). Finally, all of the measures generally show that BiCI users have greater variability across subjects than NH listeners. However, because there are both floor and ceiling effects the variability was not statistically analyzed.

A. Auditory motion tracking abilities

NH listeners were able to discriminate between sound sources that were either stationary or moving; however, BiCI users performed significantly worse compared with NH listeners. As concluded by Perrott and Marlborough (1989), the continuity of a moving sound source is an important auditory motion cue. NH adults were likely able to take advantage of this cue, aiding in their performance to discriminate the movement of a sound source as well as the direction of movement. On the contrary, BiCI users were more biased toward reporting a sound source as moving compared to NH adults. This may be due to the fact that, even when sound sources are stationary, the processing by bilateral devices does not provide listeners with a perception of consistent stationary sources. Our subjects with BiCIs were fitted with a clinical sound processing strategy that uses a frame-wise, peak-picking approach to encode the acoustic signal into electrical stimulation. It is likely that even if the motion of a sound source was identified correctly as moving by a BiCI user, the direction of the movement could be difficult to discern. In particular, because the sound encoding is done independently by each processor, the peaks picked on each CI may not necessarily be the same (Kan *et al*., 2018) which will likely lead to a discontinuous representation of the sound trajectory.

Additionally, the ability to integrate discrete locations of a moving sound source can be affected by the velocity of movement. Here, we considered the possibility that velocity of a moving sound source could affect motion tracking, which was measured in BiCI users under conditions that would be most optimal for NH adults. As has previously been reported (Perrott and Musicant, 1977), MAMAs in NH adults have been measured using a loudspeaker attached to a moving arm. The MAMA for velocities of 90°/s, 180°/s, and 360°/s were found to be significantly larger with increasing velocity, reaching a threshold of 25° for 360°/s. Here, conditions were selected that were known to produce good performance in NH adults, but these conditions were clearly challenging for BiCI users, as shown by the high errors between groups. Further, within each group, performance was on average similar regardless of the stimulus durations tested, i.e., for the same angle a longer duration would produce a slower velocity (see Table II), but slower velocities did not improve localization accuracy, or auditory motion tracking. In this study, testing conditions selected were limited due to the physical number of loudspeakers the testing apparatus could employ (−90° to +90°, 5° interval), therefore our testing conditions were not comparable to a range that a loudspeaker attached to a moving arm would produce. The velocities and angular ranges employed in this study were most optimal for NH adults but implementing a testing apparatus with less physical constraints may be needed to better assess the auditory motion perception abilities of BiCI users. Future studies assessing auditory motion abilities of BiCI users should consider employing conditions with larger trajectories to possibly aid in their ability to track the angular range of motion.

In the present study we measured, for the first time, the ability of listeners with BiCIs to track the angular range of a moving sound source. We found that, compared to NH adults, BiCI users tended to overestimate how far a moving sound source traversed across azimuth, specifically at longer stimulus durations. One explanation for this finding is that the auditory image may not be perceived as a punctate image, but rather might be "smeared" in space due to factors such as across-ear electrode insertion depth differences leading to poor auditory object formation (Kan *et al*., 2013; Fitzgerald *et al*., 2015) and asymmetric loudness growth (Goupell *et al*., 2013). The smearing or expanded auditory image could lead a subject to report the edge of the expanded percept rather than the center. However, we did not measure auditory fusion or the expansiveness of the auditory percept. Even when a sound source is stationary, BiCI users may perceive stimuli that are not fully fused, which can affect the ability to correctly perceive the location of a sound source. For example, Fitzgerald *et al*. (2015) assessed if loudness balancing would benefit a BiCI user's ability to report a fused auditory image in a binaural fusion task. Subjects reported whether they heard one, two, or three sound sources and to indicate the intracranial image they perceived. The results from this study indicated that the BiCI users perceived the stimuli to be un-fused even after loudness balancing has occurred. These findings have implications for the ability to track a moving sound source, and future studies might address the relationship between fusion and auditory motion.

B. Sound localization in the context of stationary or moving sound conditions

Sound localization was measured in a context of mixed stimulus conditions, where sources were either moving or stationary, and subjects were unaware of the condition. RMS errors in a contextually more complex scenario are nonetheless consistent with previously reported sound localization measures that utilized short stimulus duration (500 ms) and tested only with stationary sound sources. Here, mean RMS error (±SD) of BiCI users was 27.97° (±7.77°), which is comparable with 29.1° (±12.7°) in Grantham *et al*. (2007), 28.23° (±12.42°) in Litovsky *et al*. (2009), and 27.9° (±12.3°) in Jones *et al*. (2014). Similarly, NH adults had mean RMS errors of 9.5° (±2.12°), which is comparable to previous reports of 6.7° (± 1.1°) in Grantham *et al*. (2007), and 8.2° (±1.9°) in Jones *et al*. (2014). The finding that NH adults are better than BiCI users at localizing stationary sound sources has been discussed at length elsewhere (Nopp *et al*., 2004; Litovsky *et al*., 2009; Kerber and Seeber, 2012; Dorman *et al*., 2014).

The difference in performance between adults with NH and with BiCIs on stationary localization tasks has been attributed to two main factors. The first is a limitation in engineering. BiCI users do not receive binaural cues with fidelity because the two processors encode the acoustic signal independently; hence, there is no assurance that binaural cues are presented to the listener with precision (van Hoesel, 2004; Litovsky *et al*., 2012; Kan and Litovsky, 2015). Results from Laback *et al*. (2004) concluded that both BiCI adult subjects in the study were sensitive to ILDs in the broadband stimuli used and had ILD just noticeable differences (JNDs) similar to the NH subjects. In contrast, BiCI subjects in this study had poorer ITD-JNDs compared to the NH subjects.

The second factor is biological in nature. BiCI users have typically undergone auditory deprivation during the time that they experienced hearing loss. Evidence from human temporal bone studies suggests that spiral ganglion cell counts are lower in patients who lost their hearing early in life, who had longer durations of hearing loss, and who had longer periods of total deafness (Otte *et al.*, 1978; Nadol *et al.*, 1989). In addition, studies in non-human mammals have shown that response properties of auditory neurons at all levels of the auditory pathway result in deafness-induced plasticity (for review, see Shepherd and Hardie, 2001; Butler and Lomber, 2013). The impact of biological factors on spatial hearing abilities could be profound. There are changes that are highly likely to induce degraded processing of spatial cues. In the periphery, neurons in the eighth nerve demonstrated diminished myelin sheath and reduced dendritic connections, as well as fewer synaptic vesicles (Ryugo *et al.*, 1998). Further, in the brainstem, at the level of the cochlear nucleus the number and size of neurons declines after deafness, and neuronal activity is reduced. Together these changes are likely to compromise temporal processing (Zhou *et al.*, 1995; Wang and Manis, 2006), thereby leading to degraded sensitivity to timing of information needed to process spatial cues.

As stated above, the extent to which ITD cues are available to BiCI users is not known, but even if some ITDs were available, there is a high likelihood of ITD sensitivity being degraded in BiCI users following deprivation, if the strength of synaptic connectivity and fast membrane responses at the level of the brainstem are compromised (Chung *et al.*, 2015). In addition, if the medial superior olive (MSO), where ITD processing occurs for low-frequency information, undergoes atrophy of dendrites, causing a disturbance in the cellular properties that provides the inhibitory input and helps to shape gradients of ITD sensitive neurons along the MSO (Tirko and Ryugo, 2012). Finally, with regard to the lateral superior olive, which is known for processing high-frequency ILD information, and ITD information in the envelopes of high-frequency sounds, there appears to be some decrease in cell size following deafness (e.g., Moore, 1992).

In summary, sound localization for stationary sounds, when interleaved between presentation of moving sounds, was similar to that obtained in prior stationary-only conditions. In addition, the ability of BiCI users to localize stationary sounds was found to be poorer than NH adults, which is consistent with prior investigations using similar approaches. It remains clear that spatial hearing abilities in adults who use BiCIs have not approached the level of performance seen in NH adults. Regarding perception of auditory motion, we had considered the idea that perhaps sound localization ability of the end-point of a moving sound source could improve compared to a stationary sound. Perhaps the continuity of a moving sound would lead to improved sound localization by providing multiple reference points for anchoring and laying the path that would lead to the end-point of the moving sound. However, results showed that neither group had better end-point localization compared with stationary sound localization. For NH adults, performance may have been closer to ceiling performance, leaving little room for improvement. On the other hand, BiCI users had room for improvement, but the sound coding strategy they used may not have been one in which multiple reference points are used to lay the perceptual foundation for ultimate localization of the end-point of a moving sound. The limitations discussed above that are known to exist for localizing stationary sounds in BiCI users are likely to affect localization ability of a moving sound source as well. The data provided here continue to demonstrate that conventional sound processors are not able to fully provide the benefits of binaural hearing. To overcome these deficits in auditory motion tracking, CI sound processors must be able to encode all the necessary cues needed to convey the changing spatial locations of a moving sound source.

Some interesting caveats arise regarding the approach used here. For example, it has been found that self-motion can improve the minimum angle of a moving sound that can be discriminated in both NH listeners and in listeners with hearing impairment (Brimijoin and Akeroyd, 2014). While the head was not actively restrained in this experiment, head movement was discouraged during the presentation of the sound. It was important to reduce head movement in our experiment because our response method maps the listeners' responses to a physical location in the sound booth. If there were head movements during the presentation of the stimulus, the virtual sound may not be mapped correctly to the physical location. However, the restraint of head movement lacks an aspect of real-world listening whereby people are generally moving their head and/or body relative to sound sources. This issue will certainly need to be explored in future studies on this topic with the BiCI population.

Finally, the NH group tested here were all young adults. Age-related declines in auditory perceptual measures have been well documented. The literature on sound localization and auditory motion is somewhat sparse on the topic of aging, although findings have suggested that sound localization for stationary sounds decreases with age starting with the third decade of life (Abel *et al.*, 2000). One of the most commonly cited is the decline in temporal processing measured with gap detection thresholds (Humes *et al.*, 2012; Ozmeral *et al.*, 2016). Aging effects have also been reported for binaural sensitivity measures, but more so for sensitivity to ITD than to ILD (e.g., Babkoff *et al.*, 2002), thus, to the extent that listeners relied on ILDs to solve the task, older listeners may have had a disadvantage compared with younger listeners. Some insight can also be gleaned from studies showing aging effects on electrophysiological measures related to processing of spatial cues (Briley and Summerfield, 2014; Ozmeral *et al.*, 2016; for a comprehensive review, see Eddins *et al.*, 2018). On a more global functional scale, aging has been associated with a decline in a number of factors that might have contributed to the tasks in the present study. These include cognitive decline, reduced self-motion perception, compromised vestibular ability, and reduced ability to function in a "cocktail party" environment where multiple sound sources are processed and segregated (Gallun *et al.*, 2014; for recent reviews see Campos *et al.*, 2018; Pichora-Fuller *et al.*, 2017). To the extent that the measures used here require cognitive and/or perceptual abilities that are compromised with age would imply that older adults who are age-matched to the BiCI group would have shown a worse performance than the young NH adults. These issues are important and complex, and would thus be excellent topics for future studies in this area.

V. CONCLUSIONS

(1) Observed variability and overall RMS errors when measuring stationary sound localization ability of BiCI users and NH adults were comparable with previous studies.

(2) BiCI users and NH adults did not improve in their sound localization ability of the start- or end-points of a moving sound compared to a stationary sound.
(3) BiCI users had poorer sensitivity when discriminating the movement of a sound source as well as the direction of a moving sound source, compared to NH adults.
(4) BiCI users had significantly further motion tracking responses when compared to NH adults, specifically at longer stimulus durations (1000 and 2000 ms).
(5) As sound processing strategies advance in CIs, enhancing the capability to encode dynamic cues with high resolution may lead to improved auditory motion tracking abilities for BiCI users.

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APPENDIX A

Individual RMS errors for locating stationary sound sources, and the start and end points of moving sound sources are shown for each BiCI user (Table III). The means, SDs, and medians were calculated for each stimulus duration (500, 1000, and 2000 ms) and angular range condition (stationary, 10°, 20°, 40°).

TABLE III. Individual RMS errors for locating stationary sounds, and moving sounds (start and end points) for BiCI listeners.

		Start-point			End-point		
Subj. ID	Stationary	10°	20°	40°	10°	20°	40°
RMS errors (°) for the 500 ms stimulus duration							
B1	22.41	22.86	21.57	23.38	23.41	23.53	22.67
B2	25.31	18.84	20.72	23.7	23.55	23.57	26.33
B3	28.29	37.16	36.94	39.06	32.9	32.72	39.82
B4	22.68	26.43	29.41	37.71	25.47	27.60	31.00
B5	29.43	28.44	31.01	31.89	29.22	31.24	32.2
B6	32.62	32.27	34.58	40.56	28.53	31.93	36.44
B7	47.92	56.46	56.52	57.98	49.45	47.76	54.18
B8	22.94	21.26	19.27	21.56	20.37	19.89	20.08
B9	23.76	24.31	24.99	34.18	24.18	24.19	28.36
B10	24.4	26.05	25.34	29.72	28.4	28.11	31.69
Mean	27.97	29.40	30.03	33.97	28.54	29.05	32.27
SD	7.77	10.89	11.01	10.82	8.18	7.80	9.70
Median	24.85	26.24	27.37	33.03	26.93	27.85	31.34
RMS errors (°) for the 1000 ms stimulus duration							
B1	21.94	22.42	20.72	21.81	22.65	22.14	22.53
B2	29.35	18.44	20.29	24.32	29.58	29.18	29.15
B3	30.81	40.24	40.44	43.61	31.12	34.24	38.08
B4	26.61	28.16	29.59	34.23	26.34	28.45	29.16
B5	37.75	29.98	30.29	32.32	37.54	39.39	39.77
B6	31.34	36.74	35.32	37.36	35.47	34.03	40.55
B7	51.13	54.72	57.99	59.13	53.13	51.59	53.25
B8	20.6	20.5	21.09	21.29	20.65	22.75	22.16
B9	25.92	26.33	27.81	33.63	24.67	25.67	26.62
B10	26.87	25.59	26.64	29.77	27.49	28.62	32
Mean	30.23	30.01	31.01	33.74	30.86	31.60	33.32
SD	8.82	11.48	11.48	11.48	9.45	8.82	9.63
Median	28.11	27.24	28.70	28.7	28.53	28.9	30.58
RMS errors (°) for the 2000 ms stimulus duration							
B1	20.45	22.35	22.32	22.35	22.69	22.8	21.8
B2	29.05	19.84	20.38	26.89	31.93	29.4	34.84
B3	52.76	42.63	40.72	46.42	55.24	50.49	50
B4	25.1	27.14	29.47	35.01	26.28	27.47	27.41
B5	34.12	32.82	32.77	33.67	40.5	39.13	44.89
B6	31.52	33.1	35.15	35.93	36.28	35.97	42.06
B7	59.55	50.05	55.91	55	67.17	66.35	63.38
B8	19.79	22.08	20.74	22.67	20.77	22.68	23.21
B9	30.73	28.29	28.94	31.28	28.17	29.49	27.05
B10	29.37	26.63	28.01	30.74	25.5	28.37	30.82
Mean	33.24	30.49	31.44	33.99	35.45	35.21	36.54
SD	13.02	9.56	10.76	10.18	15.09	13.75	13.35
Median	30.05	27.71	29.20	32.47	30.05	29.44	32.83

APPENDIX B

Individual RMS errors for locating stationary sound sources, and the start and end points of moving sound sources are shown for each NH adult (Table IV). The means, SDs, and

TABLE IV. Individual RMS errors for locating stationary sounds, and moving sounds (start and end points) for NH listeners.

		Start-point			End-point		
Subj. ID	Stationary	10°	20°	40°	10°	20°	40°
RMS errors (°) for the 500 ms stimulus duration							
N1	7.98	12.46	13.14	17.83	10.06	11.42	10.93
N2	12.33	11.08	11.92	16.73	13.81	13.88	11.75
N3	10.94	13.85	13.7	17.09	12.69	13.66	13.3
N4	11.24	13.84	15.66	15.86	12.52	14.86	13.97
N5	9.2	13.09	15.69	20.39	12.4	13.49	13.44
N6	7.03	9.69	10.13	10.69	9.09	11.35	9.54
N7	11.32	12.95	13.22	15.32	12.76	13.78	11.25
N8	6.71	9.31	8.82	13.07	11.14	12.61	9.63
N9	11.13	13.78	18.35	19.78	11.95	18.74	23.31
N10	7.2	10.99	11.94	11.65	9.22	11.66	9.63
Mean	9.50	12.10	13.25	15.84	11.56	13.54	12.67
SD	2.12	1.71	2.80	3.24	1.61	2.17	4.09
Median	10.07	12.7	13.18	16.29	12.17	13.57	11.5
RMS errors (°) for the 1000 ms stimulus duration							
N1	8.17	9.84	12.18	14.24	9.54	13.58	10.49
N2	10.42	8.79	10.13	11.67	10.24	11.81	9.46
N3	9.46	12.32	11.53	14.65	11.43	10.03	10.81

TABLE IV. (*Continued*)

		Start-point			End-point		
Subj. ID	Stationary	10°	20°	40°	10°	20°	40°
N4	11.66	12.97	14.37	13.26	12.69	15.25	13.52
N5	10.43	11.94	12.61	18.27	11.33	11.78	11.1
N6	8.31	10.13	10.18	9.77	9.06	10.24	8.75
N7	10.41	12.94	12.32	13.24	12.88	11.62	9.91
N8	7.03	9.15	9.41	10.16	10.38	11.92	8.53
N9	11.74	14.25	16.5	17.46	13.1	16.34	22.11
N10	7.07	10.63	10.35	10.19	9.28	10.43	8.06
Mean	9.47	11.29	11.95	13.29	10.99	12.3	11.27
SD	1.74	1.84	2.18	2.96	1.52	2.12	4.11
Median	9.93	11.28	11.85	13.25	10.85	11.79	10.2
RMS errors (°) for the 2000 ms stimulus duration							
N1	7.94	9.81	10.88	12.14	10.61	13.67	10.72
N2	7.91	9.22	8.99	10.36	10.44	10.64	9.6
N3	9.39	12.01	12.35	13.03	11.36	10.88	9.94
N4	10.54	12.78	13.93	11.81	12.59	14.72	13.24
N5	10.93	11.85	13.52	14.4	11.81	13.8	10.38
N6	8.2	9.89	10.01	8.3	10.27	11.81	9.6
N7	10.04	13	12.6	11.71	12.81	12.82	9.26
N8	7.49	9.88	9.3	9.63	9.35	11.08	9.13
N9	11.46	13.28	16.98	16.84	13.97	15.6	20.73
N10	8.24	10.67	10.9	8.52	9.09	10.42	8.09
Mean	9.21	11.23	11.94	11.67	11.23	12.54	11.06
SD	1.44	1.51	2.45	2.65	1.57	1.84	3.65
Median	8.81	11.26	11.62	11.76	10.98	12.31	9.77

medians were calculated for each stimulus duration (500, 1000, and 2000 ms) and angular range condition (stationary, 10°, 20°, 40°).

Abel, S. M., Giguère, C., Consoli, A., and Papsin, B. C. (**2000**). "The effect of aging on horizontal sound localization," J. Acoust. Soc. Am. **108**(2), 743–752.

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**, EL87–EL92.

Babkoff, H., Muchnik, C., Ben-David, N., Furst, M., Even-Zohar, S., and Hildesheimer, M. (**2002**). "Mapping lateralization of click trains in younger and older populations," Hear. Res. **165**(1–2), 117–127.

Bates, D., Maechler, M., Bolker, B., and Walker, S. (**2014**). "lme4: Linear mixed-effects models using Eigen and S4," R package version 1.0-6, https://cran.r-project.org/web/packages/lme4/index.html (Last viewed August 28, 2018).

Blauert, J. (**1997**). *Spatial Hearing: The Psychophysics of Human Sound Localization*, 2nd ed. (MIT Press, Cambridge, MA), Vol. 36–200.

Briley, P. M., and Summerfield, A. Q. (**2014**). "Age-related deterioration of the representation of space in human auditory cortex," Neurobiol. Aging **35**(5), 633–644.

Brimijoin, W. O., and Akeroyd, M. A. (**2014**). "The moving minimum audible angle is smaller during self-motion than during source motion," Front. Neurosci. **8**, 273.

Brown, C. (**2014**). "Binaural enhancement for bilateral cochlear implant users," Ear. Hear **35**(5), 580–584.

Brown, C. (**2018**). "Corrective binaural processing for bilateral cochlear implant patients," PLoS One **13**(1), e0187965.

Butler, B. E., and Lomber, S. G. (**2013**). "Functional and structural changes throughout the auditory system following congenital and early-onset deafness: Implications for hearing restoration," Front. Syst. Neurosci. **7**, 1–17.

Campos, J., Ramkhalawansingh, R., and Pichora-Fuller, M. K. (**2018**). "Hearing, self-motion perception, mobility, and aging," Hear. Res. **369**, 42–55.

Carlile, S., and Best, V. (**2002**). "Discrimination of sound source velocity in human listeners," J. Acoust. Soc. Am. **111**, 1026–1035.

Carlile, S., and Leung, J. (**2016**). "The perception of auditory motion," Trends Hear. **20**, 2331216516644254.

Chung, W. S., Allen, N. J., and Eroglu, C. (**2015**). "Astrocytes control synapse formation, function, and elimination," Cold Spring Harbor Perspect. Biol. **7**, a020370.

Churchill, T. H., Kan, A., Goupell, M. J., and Litovsky, R. Y. (**2014**). "Spatial hearing benefits demonstrated with presentation of acoustic temporal fine structure cues in bilateral cochlear implant listeners," J. Acoust Soc. Am. **136**(3), 1246–1256.

Dorman, M. F., Loiselle, L., Stohl, J., Yost, W. A., Spahr, A., Brown, C., and Cook, S. (**2014**). "Interaural level differences and sound source localization for bilateral cochlear implant patients," Ear Hear. **35**, 633–640.

Eddins, A. C., Ozmeral, E. J., and Eddins, D. A. (**2018**). "How aging impacts the encoding of the binaural cues and the perception of auditory space," Hear. Res. **369**, 79–89.

Epain, N., Guillon, P., Kan, A., Kosobrodov, R., Sun, D., Jin, C., and van Schaik, A. (**2010**). "Objective evaluation of a three-dimensional sound field reproduction system," in *Proceedings of the 20th International Congress on Acoustics (ICA)*, Sydney, Australia (August 23–27, 2010).

Fitzgerald, M. B., Kan, A., and Goupell, M. J. (**2015**). "Bilateral loudness balancing and distorted spatial maps in recipients of bilateral cochlear implants," Ear Hear. **36**, e225–e236.

Gallun, F. J., McMillan, G. P., Molis, M. R., Kampel, S. D., Dann, S. M., and Konrad-Martin, D. L. (**2014**). "Relating age and hearing loss to monaural, bilateral, and binaural temporal sensitivity," Front. Neurosci. **8**, 172.

Grantham, D. W. (**1986**). "Detection and discrimination of simulated motion of auditory targets in the horizontal plane," J. Acoust. Soc. Am. **79**, 1939–1949.

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**, 33–44.

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**, 524–541.

Goupell, M. J., Kan, A., and Litovsky, R. Y. (**2013**). "Mapping procedures can produce non-centered auditory images in bilateral cochlear-implant users," J. Acoust. Soc. Am. **133**(2), EL101–EL107.

Harris, J. D., and Sergeant, R. L. (**1971**). "Monaural/binaural minimum audible angles for a moving sound source," J. Speech Hear. Res. **14**(3), 618–629.

Hawley, M. L., Litovsky, R. Y., and Colburn, H. S. (**1999**). "Speech intelligibility and localization in a multi-source environment," J. Acoust. Soc. Am. **105**, 3436–3448.

Humes, L. E., Dubno, J. R., Gordon-Salant, S., Lister, J. J., Cacace, A. T., Cruickshanks, K. J., and Wingfield, A. (**2012**). "Central presbycusis: A review and evaluation of the evidence," J. Am. Acad. Audiol. **23**(8), 635–666.

Jones, H., Kan, A., and Litovsky, R. Y. (**2014**). "Comparing sound localization deficits in bilateral cochlear-implant users and vocoder simulations with normal-hearing listeners," Trends Hear. **0**, 1–16.

Kan, A., and Litovsky, R. Y. (**2015**). "Binaural hearing with electrical stimulation," Hear. Res. **322**, 127–137.

Kan, A., Peng, Z., Moua, K., and Litovsky, R. (**2018**). "A systematic assessment of a cochlear implant processor's ability to encode interaural time differences," in *Proceedings of the Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA-ASC)*, Honolulu, Hawaii (November 12–15, 2018).

Kan, A., Stoelb, C., Litovsky, R. Y., and Goupell, M. J. (**2013**). "Effect of mismatched place-of-stimulation on binaural fusion and lateralization in bilateral cochlear-implant users," J. Acoust. Soc. Am. **134**(4), 2923–2936.

Kerber, S., and Seeber, B. U. (**2012**). "Sound localization in noise by normal-hearing listeners and cochlear implant users," Ear Hear. **33**, 445–457.

Laback, B., and Majdak, P. (**2008**). "Binaural jitter improves interaural-time difference sensitivity of cochlear implantees at high pulse rates," Proc. Natl. Acad. Sci. U.S.A. **105**, 814–817.

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**, 488–500.

Litovsky, R. Y., Goupell, M. J., Godar, S., Grieco-Calub, T., Jones, G. L., Garadat, S. N., and Misurelli, S. (**2012**). "Studies on bilateral cochlear implants at the University of Wisconsin's Binaural Hearing and Speech Laboratory," J. Am. Acad. Audiol. **23**(6), 476–494.

Litovsky, R. Y., Parkinson, A., and Arcaroli, J. (**2009**). "Spatial hearing and speech intelligibility in bilateral cochlear implant users," Ear Hear. **30**, 419–431.

Lorenzi, C., Gatehouse, S., and Lever, C. (**1999**). "Sound localization in noise in normal-hearing listeners," J. Acoust. Soc. Am. **105**, 1810–1820.

Macmillan, N. A., and Creelman, C. D. (**2005**). *Detection Theory: A User's Guide*, 2nd ed. (Lawrence Erlbaum Associates, Inc., Mahway, NJ).

Macpherson, E. A., and Middlebrooks, J. C. (**2002**). "Listener weighting of cues for lateral angle: The duplex theory of sound localization revisited," J. Acoust. Soc. Am. **111**, 2219–2236

Makous, J. C., and Middlebrooks, J. C. (**1990**). "Two-dimensional sound localization by human listeners," J. Acoust. Soc. Am. **87**, 2188–2200.

Middlebrooks, J. C., and Green, D. M. (**1991**). "Sound localization by human listeners," Ann. Rev. Psychol. **42**, 135–159.

Moore, D. R. (**1992**). "Trophic influences of excitatory and inhibitory synapses on neurons in the auditory brainstem," Neuroreport **3**(3), 269–272.

Nadol, J. B., Young, Y., and Glynn, R. J. (**1989**). "Survival of spiral ganglion cells in profound sensorineural hearing loss: Implications for cochlear implantation," Ann. Otol. Rhinol. Laryngol. **98**, 411–416.

Nopp, P., Schleich, P., and D'Haese, P. (**2004**). "Sound localization in bilateral users of MED-EL COMBI 40/40+ cochlear implants," Ear Hear. **25**, 205–214.

Otte, J., Schuknecht, H. F., and Kerr, A. G. (**1978**). "Ganglion cell populations in normal and pathological human cochleae. Implications for cochlear implantation," Laryngoscope **88**(8), 1231–1246.

Ozmeral, E. J., Eddins, D. A., and Eddins, A. C. (**2016**). "Reduced temporal processing in older normal-hearing listeners evident from electrophysiological response to shifts in interaural time difference," J. Neurophysiol. **116**(6), 2720–2729.

Perrott, D. R., and Marlborough, K. (**1989**). "Minimum audible movement angle: Marking the end points of the path traveled by a moving sound source," J. Acoust. Soc. Am. **85**, 1773–1775.

Perrott, D. R., and Musicant, A. D. (**1977**). "Minimum auditory movement angle: Binaural localization of moving sound sources," J. Acoust. Soc. Am. **62**, 1463–1466.

Pichora-Fuller, M. K., Alain, C., and Schneider, B. A. (**2017**). "Older adults at the cocktail party," in *The Auditory System at the Cocktail Party*, edited by J. C. Middlebrooks, J. Z. Simon, A. N. Popper, and R. R. Fay (Springer International Publishing, New York), pp. 227–259.

Pulkki, V. (**1997**). "Virtual sound source positioning using vector base amplitude panning," J. Audio Eng. Soc. **45**, 456–466.

R Core Team (**2015**). "R: A language and environment for statistical computing," R Foundation for Statistical Computing, Vienna, Austria, available at http://www.R-project.org.

Ryugo, D. K., Rosenbaum, B. T., Kim, P. J., Niparko, J. K., and Saada, A. A. (**1998**). "Single unit recordings in the auditory nerve of congenitally deaf white cats: Morphological correlates in the cochlea and cochlear nucleus," J. Comp. Neurol. **397**, 532–548.

Schoen, F., Mueller, J., Helms, J., and Nopp, P. (**2005**). "Sound localization and sensitivity to interaural cues in bilateral users of the MED-EL COMBI 40/40+cochlear implant system," Otol. Neurotol. **26**, 429–437.

Shepherd, R. K., and Hardie, N. A. (**2001**). "Deafness-induced changes in the auditory pathway: Implications for cochlear implants," Audiol. Neurootol. **6**(6), 305–318.

Thakkar, T., Kan, A., Jones, H. G., and Litovsky, R. Y. (**2018**). "Mixed stimulation rates to improve sensitivity of interaural timing differences in bilateral cochlear implant listeners," J. Acoust. Soc. Am. **143**(3), 1428–1440.

Tirko, N. N., and Ryugo, D. K. (**2012**). "Synaptic plasticity in the medial superior olive of hearing, deaf, and cochlear-implanted cats," J. Comp. Neurol. **520**, 2202–2217.

van Hoesel, R. J. M. (**2004**). "Exploring the benefits of bilateral cochlear implants," Audiol. Neurootol. **9**, 234–236.

van Hoesel, R. J. M., and Tyler, R. S. (**2003**). "Speech perception, localization, and lateralization with bilateral cochlear implants," J. Acoust. Soc. Am. **113**, 1617–1630.

Wang, Y., and Manis, P. B. (**2006**). "Temporal coding by cochlear nucleus bushy cells in DBA/2J mice with early onset hearing loss," J. Assoc. Res. Otolaryngol. **7**, 412–424.

Wightman, F. L., and Kistler, D. J. (**1989**). "Headphone simulation of free-field listening. II: Psychophysical validation," J. Acoust. Soc. Am. **85**, 868–878.

Wightman, F. L., and Kistler, D. J. (**1997**). "Monaural sound localization revisited," J. Acoust. Soc. Am. **101**, 1050–1063.

Yost, W. A., Zhong, X., and Najam, A. (**2015**). "Judging sound rotation when listeners rotate and sound rotate: Sound source localization is a multisensory process," J. Acoust. Soc. Am. **38**, 3298–3308.

Zhou, R., Abbas, P. J., and Assouline, J. G. (**1995**). "Electrically evoked auditory brainstem response in peripherally myelin-deficient mice," Hear. Res. **88**, 98–106.