Binaural hearing in children using Gaussian enveloped and transposed tones

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Children who use bilateral cochlear implants (BiCIs) show significantly poorer sound localization skills than their normal hearing (NH) peers. This difference has been attributed, in part, to the fact that cochlear implants (CIs) do not faithfully transmit interaural time differences (ITDs) and interaural level differences (ILDs), which are known to be important cues for sound localization. Interestingly, little is known about binaural sensitivity in NH children, in particular, with stimuli that constrain acoustic cues in a manner representative of CI processing. In order to better understand and evaluate binaural hearing in children with BiCIs, the authors first undertook a study on binaural sensitivity in NH children ages 8–10, and in adults. Experiments evaluated sound discrimination and lateralization using ITD and ILD cues, for stimuli with robust envelope cues, but poor representation of temporal fine structure. Stimuli were spondaic words, Gaussian-enveloped tone pulse trains (100 pulse-per-second), and transposed tones. Results showed that discrimination thresholds in children were adult-like (15–389 μs for ITDs and 0.5–6.0 dB for ILDs). However, lateralization based on the same binaural cues showed higher variability than seen in adults. Results are discussed in the context of factors that may be responsible for poor representation of binaural cues in bilaterally implanted children. © *2016 Acoustical Society of America*.

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I. INTRODUCTION

Spatial hearing is essential for the ability of children to navigate their everyday environments, including location of important sound sources (e.g., parents and teachers), and perceptually separating speech from competing sources. Although children spend much of their time having to attend to important sound sources based on their location in the environment, little is known about their sensitivity to spatial hearing cues that are likely to be involved in performing these tasks.

Spatial hearing abilities rest largely on the extent to which the binaural auditory system is able to integrate acoustic inputs that arrive at the two ears from sounds in the auditory environment (Bronkhorst and Plomp, 1988; Middlebrooks and Green, 1991). Normal hearing (NH) listeners localize sounds in the horizontal plane by relying on variations in interaural differences in time and level (ITDs and ILDs, respectively) as a function of sound source location. ITDs are present in the low frequency region, as well as in the low-frequency envelope of high frequency carriers. The auditory system has mechanisms that enable binaural processing for both types of ITD stimuli. Sensitivity to ITDs in the envelope of stimuli has been demonstrated in psychophysical studies (e.g., Bernstein, 2001) and in physiological responses of neurons in the auditory brainstem (Bernstein, 2001; Joris and Yin, 1995; Joris, 1996, 2003; McFadden and Pasanen, 1978). Finally, there are spatial cues that do not depend on interaural differences, such as monaural spectral and loudness cues; although for sound localization in the horizontal plane, the utility of these cues is relatively weak.

To date, spatial hearing abilities in children have been studied primarily in free-field environments, where all spatial cues are naturally combined, and therefore not independently controlled. Studies on the ability of children to locate sound sources in the free field (Grieco-Calub and Litovsky, 2010; Litovsky and Godar, 2010) and on the ability of children to discriminate changes in a sound source location (estimating the minimum audible angle, MAA; Litovsky, 1997, 2011; Litovsky *et al.*, 2006) have been informative regarding emergence of spatial hearing accuracy and acuity, respectively. By 4–5 yrs of age, root-mean-square (RMS) errors for sound localization can be as low as 8°, similar to that of adults (Grieco-Calub and Litovsky, 2010; Litovsky and Godar, 2010; Litovsky, 2011; Van Deun *et al.*, 2009). MAA thresholds for single source (non-reverberant) stimuli undergo substantial maturation in infancy and early childhood, with thresholds estimated to be $\sim 12°$ at 6-months of age, $4°–6°$ at 18-months of age, and $1°–2°$ (adult-like) by 5 yrs of age (Litovsky, 1997). Thus, assuming that the auditory signal reaches the developing auditory system with fidelity, spatial hearing abilities undergo substantial maturation, and come to approximate those of adults, during early childhood.

A different developmental trajectory appears to be emerging from studies with children who receive cochlear implants (CIs) in both ears, i.e., bilateral cochlear implants

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(BiCIs). MAA thresholds are better (smaller) when children listen with both CIs (bilateral condition) compared to when they listen with a single CI (unilateral condition) (Grieco-Calub and Litovsky, 2010; Litovsky *et al.*, 2006). RMS localization errors are also generally better in the bilateral condition compared with the unilateral condition (Grieco-Calub and Litovsky, 2010). However, even when using BiCIs, these children show significantly poorer performance compared to their NH age-matched peers; this gap in performance is observed even after several years of experience with BiCIs (Zheng *et al.*, 2015).

The gap in spatial hearing abilities between NH children and children with BiCIs may be attributed to numerous factors. First, in the BiCI population there may be poor neural survival due to a lack of early acoustic hearing, leading to degraded processing of auditory cues that are important for binaural hearing (Leake *et al.*, 1999). Second, surgical issues can lead to different depths in the insertion of electrode arrays in the cochleae in the two ears, thus yielding mismatched place of stimulation across the ears for same-frequency information which has been shown to affect sensitivity to ITDs (Kan *et al.*, 2015; Kan *et al.*, 2013; Poon *et al.*, 2009). Third, CI processors act as independent systems that do not recognize frequency-specific interaural differences. Fourth, in CI processing the detailed temporal structure of the original sound is replaced with constant-rate pulsatile stimulation (van Hoesel, 2004; Wilson and Dorman, 2008), but the rate is generally too high to provide reliable ITD cues from the temporal fine structure, but is only available in the signal envelopes. For a further review of these issues, see Kan and Litovsky (2015). It is not clear which of these factors contributes most significantly to the gap in performance described above. As a first step, the present study was concerned with the extent to which a lack of temporal fine structure ITDs is the limiting factor in performance.

This study focused on the fact that, while short-term ITDs in the fine structure are not available in CI processors, BiCI users might have access to ITDs in the ongoing envelopes of signals (Wilson and Dorman, 2008). Psychophysical data suggest that adult BiCI users are sensitive to such envelope ITD cues (van Hoesel *et al.*, 2009; van Hoesel, 2007). Therefore, the important question is whether NH children demonstrate the ability to extract ITDs in the envelope. If not, then there may be additional constraints imposed on the ability of pediatric users of BiCIs to perform spatial hearing tasks using the limited cues available to them. To date, research on binaural sensitivity in the BiCI pediatric population has been sparse. There is evidence to suggest that, when stimuli are synchronized via research hardware, children with BiCIs show reliable sensitivity to ILDs, but are much less sensitive to large ITDs (Salloum *et al.*, 2010). In contrast, NH children listening to acoustic sounds are able to detect the presence of either ILD or ITD cues (Salloum *et al.*, 2010). However, in the aforementioned study, when testing NH children, CI processing was not simulated. Thus it remains unclear whether NH children were relying on fine structure ITD cues, which are not available to CI users.

Here we asked whether NH children are capable of using envelope ITDs as transmitted by CI-like processing. CI simulations have been used to ascertain aspects of speech perception and psychophysics that are affected by some basic elements of CI processing (Dorman *et al.*, 1997; Goupell *et al.*, 2008). The present study used simulations that were designed to provide insight into the manner by which a specific aspect of CI processing (i.e., envelope ITDs) might provide access to binaural cues. Two stimuli were selected: transposed tones and Gaussian envelope tone (GET) pulse trains. Both stimuli provide only envelope ITD cues, as temporal fine structure cues are restricted to high-frequency regions, rendering them imperceptible (as they are in CI processing across the entire frequency spectrum). Transposed tones have been used extensively in binaural studies with NH adult listeners (Bernstein and Trahiotis, 2002, 2003; Bernstein, 2001), but never with children. Typically, transposed tones have been the focus of studies aimed at exploring auditory mechanisms involved in ITD sensitivity that occurs with high-frequency modulated signals (Bernstein and Trahiotis, 2002). Here, for the transposed tone, a 125 Hz modulation rate was chosen in order to compare to previous literature, which demonstrated that this modulation rate provided the best ITD sensitivity (Bernstein and Trahiotis, 2002). A GET pulse train (Goupell *et al.*, 2013; Kan *et al.*, 2013) is similar to a transposed tone, but can be used to approximate the spread of current that occurs with monopolar stimulation in CIs (Boëx *et al.*, 2003) by varying the bandwidth of the GET. Finally, the spondaic words were also used because they have been used in the past for studies on sound localization in the free field with children due to their ecological validity and ease of obtaining responses from the subjects (e.g., Grieco-Calub and Litovsky, 2010).

In Experiment I, a left–right discrimination task was used to estimate just-noticeable-differences (JNDs) for ITDs and ILDs in children, and results are compared with published data in NH adults (Bernstein and Trahiotis, 2002; Goupell *et al.*, 2013). In Experiment II, a lateralization task was used to investigate the ability of NH children to perceive an intracranial position of stimuli that had either an ITD or ILD imposed on them. The lateralization task is designed to measure the ability of listeners to map binaural cues to perceptual space, providing more information than acuity-based measurements of cue discrimination. The lateralization task is important for ascertaining spatial mapping, rather than sensitivity to changing cues; this task also provides different information than the free-field localization task, because ITDs and ILDs can be manipulated independently. Together the lateralization and discrimination experiments provide information that benchmarks sensitivity to envelope ITDs in NH children using stimuli that simulate an important aspect of the cues received by BiCI users under ideal listening conditions.

II. EXPERIMENT I: DISCRIMINATION OF BINAURAL CUES

A. Methods

1. Subjects and equipment

Results are presented from 11 NH children (8 yrs, 7 months to 10 yrs, 8 months; mean 9.5 yrs). Data were collected over three 2-h sessions (spread over an average of 10.6 weeks). All subjects had hearing thresholds at or below 20 dB hearing level in both ears, measured at octave interval frequencies between 250 and 8000 Hz. None of the subjects had a known illness or ear infections on the day of testing. In addition to the 11 NH children, for Experiment I, six NH adults were tested on ILD discrimination using the transposed stimuli, as there are no previously published data with these stimuli in adults.

The experiments were performed in a single-walled sound booth (Acoustic Systems, TX). Stimuli were generated in MATLAB (Mathworks, Natick, MA). A Tucker-Davis Technologies System 3 (RP2.1, PA5, and HB7; Alachua, FL) was used to deliver the stimuli to the ear-insert headphones (ER-2, Etymotic, Elk Grove Village, IL). All sounds presented were calibrated to 60 dBA. ER-2 headphones were used because they could be deeply inserted into the ear canal, therefore bypassing the resonances of the ear canal and outer ear. This is much like what occurs for behind-the-ear microphones of CIs, thus providing a better simulation of CI processing. Additionally, ER-2 headphones have good isolation of external sounds and have a relatively flat frequency response up to 10 kHz.

Subjects were paid $7.50/h for their participation. All experimental procedures followed the regulations set by the National Institutes of Health and were approved by the University of Wisconsin's Human Subjects Institutional Review Board. Each parent of a child participant signed a consent form. In addition, each child signed an assent form prior to commencing the experiment.

2. Stimuli

Stimuli consisted of two types of acoustic pulse trains, which had two different envelope shapes, shown in Fig. 1. The first was a GET pulse train with a 4 kHz center frequency that was presented at a rate of 100 pulses per second [see Fig. 1(a)] with a 1.5 mm (∼861 Hz) bandwidth (Goupell *et al.*, 2013). The second was a transposed tone with a 4 kHz carrier tone modulated at a rate of 125 Hz; this essentially shifts the positive temporal envelope of a 125 Hz tone up to the 4 kHz region [Fig. 1(b)], where the ITDs present in the fine structure should be unusable, leaving only envelope cues (Bernstein and Trahiotis, 2002). Both stimuli had 300 ms duration, and were presented at a typical conversation level of 60 dBA. For the ILD condition stimulus levels were randomly varied between 50 and 70 dBA (roved by ±10 dB) from trial to trial.

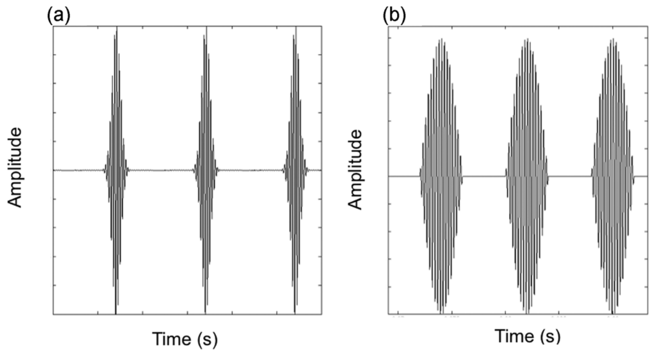

FIG. 1. Waveforms for the two stimuli selected to simulate CI processing: (a) a Gaussian-enveloped tone pulse train, demonstrating the bell-shaped curve which causes greater spread of excitation in the cochlea and (b) a transposed tone which shows the low-frequency envelope (125 Hz) imposed on a high frequency carrier (4 kHz).

ILDs or ITDs were imposed on the stimuli and each cue was tested in separate blocks of trials. In this paper, positive ILDs indicate a higher level (louder) in the right ear and negative ILDs indicate a higher level in the left ear. ILDs were applied by shifting the louder channel up by half of the ILD amount, and shifting the quieter channel down by the other half of the ILD. Similarly, positive ITDs indicate the right ear was leading and negative ITDs indicate the left ear was leading. Like ILDs, ITDs were applied by shifting the lead channel earlier by half of the ITD amount and shifting the lag channel later by the other half of the ITD.

3. Procedure

In this experiment, listeners' ability to determine whether the sound shifted intracranially, from left to right, or from right to left, was measured. Feedback regarding correct/incorrect responses was provided on each trial. Testing was conducted using an adaptive tracking algorithm, and within each run, either ITDs or ILDs were adjusted adaptively using a two-down, one-up procedure. During testing, initial values were 800 μs for ITDs and 15 dB for ILDs. ITDs changed by a factor of 3 for the first two turnarounds, 2 for the next two, and then $\sqrt{2}$ for the rest of the run. For the ILD condition, ILDs were changed by 2 dB for the first 2 turnarounds, 1 for the next two, and 0.5 for the remainder of the test. The last six turnarounds were averaged and that value was used to estimate the 70.7% JND thresholds (Levitt, 1971). This procedure is consistent with previous literature on experiments conducted on NH listeners (Goupell *et al.*, 2013). Subjects were first tested with the GET stimuli followed by the transposed stimuli. Testing was done in blocks of trials in which only one cue was varied at a time (i.e., when varying ILD, ITD was set to zero, and vice versa). Order of blocks was randomized within subject.

B. Results

Results from Experiment I are shown in Figs. 2 and 3, for the ILD and ITD data, respectively. In Figs. 2(a) and 3(a), individual JND thresholds are shown for ILDs and ITDs, respectively. In Figs. 2(b) and 3(b) the group average and standard error are shown for ILDs and ITDs, respectively. Note that JND values shown here have been doubled to reflect methodological differences and simplify comparison with existing literature, where JND thresholds are typically measured with a center reference (Bernstein and Trahiotis, 2002). All subjects demonstrated measureable JNDs for both ILDs and ITDs, but performance varied amongst the children. Regarding the ILD data, the four best-performing children [left-most in Fig. 2(a)] showed little or no difference between the transposed and GET stimuli, whereas the remaining children showed low JNDs for the transposed tone and higher JNDs for the GET stimulus. A

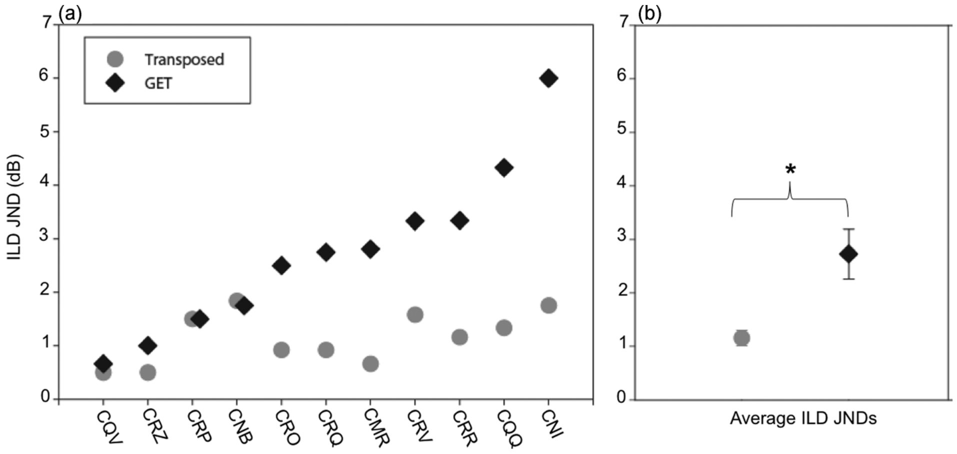

FIG. 2. ILD JND data are shown for the GET (diamond) and transposed stimuli (circle). Panel (a): individual ILD JND values. Panel (b): average (+/− standard error). Significant differences are indicated with an asterisk (*).

repeated-measures analysis of variance (ANOVA) confirmed that, on average, ILD JNDs were significantly lower for the transposed tone than the GET stimuli [$F(1, 10) = 14.813$, $p = 0.003$]. Regarding ITD data, all children but one showed very low JNDs with the GET stimulus, and there was some variation in the transposed tone JNDs. Contrary to the ILD data, a repeated-measures ANOVA on ITDs revealed no significant differences between JNDs for the transposed tone and GET stimuli.

In Fig. 4, individual ITD JNDs are plotted with their corresponding ILD JNDs, for the GET and transposed stimuli. A Pearson correlation test confirmed a significant correlation between JNDs in the ILD and ITD tasks for the GET stimuli ($R^2 = 0.921$, $p < 0.01$); however, no significant correlation was found for the transposed tone ($R^2 = 0.174$, $p = 0.608$).

Figure 5 compares results from the present study with previously published results from adult listeners using the same stimuli (Bernstein and Trahiotis, 2002; Goupell *et al.*, 2013). Figure 5(a) shows data for ITD JNDs and Fig. 5(b) shows the ILD JNDs. One-way ANOVAs were conducted to compare the effect of group (child and adult) for each of the stimuli (transposed or GET). Results revealed no significant differences between adults and children for the ILD or ITD JNDs with either stimulus ($p > 0.05$), suggesting that, as a group, children with an average age of 9.5 yrs have a mature ability to extract ILD and ITD cues from the stimuli used here. However, individual data from Figs. 2 and 3 do suggest that some of the children's JND thresholds are on the high end of the distribution. Although there were no statistically significant differences between children and adults, it should be noted that there were some methodological differences between the studies, which may affect interpretation of these results. In prior studies in adults, low levels of noise have been typically used to mask low-frequency distortion products that occur in the cochlea with the use of transposed stimuli. Low-frequency distortion products may potentially provide an unintended low-frequency ITD cue (Goupell *et al.*, 2013; Heller and Richards, 2010; Bernstein and Trahiotis, 2002). Low-frequency masking noise was not included in these experiments because pilot testing indicated that the introduction of low-frequency masking noise rendered the task difficult and confusing for young children. Thus, we may be over-estimating performance in children, especially for ITD estimates, where low-frequency ITD cues are dominant. Another methodological difference between our study and previous work is that Bernstein and Trahiotis (2002) used a four-interval, two-cue, two-alternative forced choice task, where the first and fourth intervals were diotic and the listener was required to detect an ITD in the second or third interval. In contrast, our task was a two-interval, two alternative forced choice task, where the listener indicated the direction of the second sound relative to the first. This methodological difference may have an effect on measured thresholds because a four-interval task may require a greater memory load compared to a two-interval task. As such, our

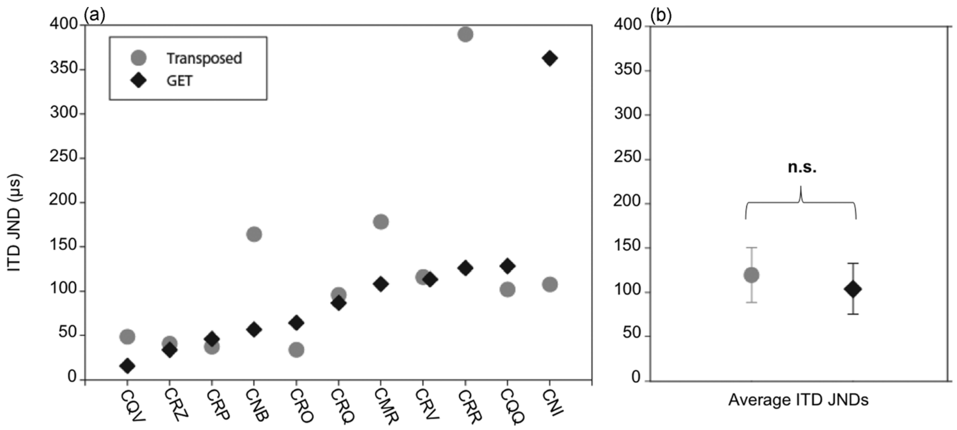

FIG. 3. ITD JND values are shown for the GET and transposed stimuli, in the same arrangement as shown in Fig. 2.

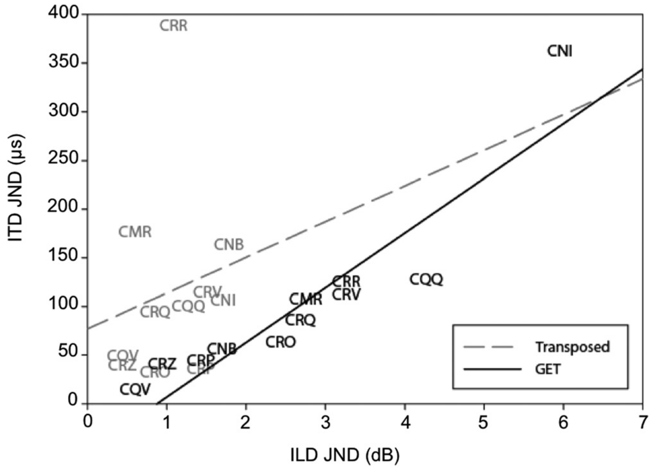

FIG. 4. ITD JND values are plotted as a function of ILD JNDs for individual subjects.

results may again be over-estimating performance in children.

III. EXPERIMENT II: LATERALIZATION

A. Methods

1. Subjects and equipment

The same 11 subjects that participated in Experiment I also participated in Experiment II. The same equipment as Experiment I was used.

2. Stimuli

In addition to the two stimuli tested in Experiment I, spondaic words were also used here, in order to draw comparisons to previous free-field data. ILDs (0, ±1.5, ±3, ±6, ±9, and ±15 dB) or ITDs (0, ±50, ±100, ±200, ±400, and ±800 μs) were imposed on the stimuli and each cue was tested in separate blocks of trials.

3. Procedure

For this experiment, subjects sat facing a computer monitor that displayed a cartoon image of a head with a red shaded area spanning between the right and left ears, to provide subjects with a visual scale that would enable them to indicate the perceived intracranial location of sound sources. Each trial was initiated by the subject selecting a "start" icon on the monitor. After stimulus presentation, subjects indicated the perceived intracranial position of the sound source by using the computer mouse to move a visual pointer to a selected position inside the red shaded area of the head. This method was selected for data collection after extensive pilot testing showed that both adult and child listeners were able to follow the instructions and to reliably use the pointer method to indicate perceived intracranial positions. Similar approaches were taken in recent studies (Litovsky *et al.*, 2010; Kan *et al.*, 2013). Responses were coded using an arbitrary scale from −10 (at the left ear) to +10 (at the right ear), with 0 being at the center of the head. This scale was linearly transformed for analysis (described below). Subjects were allowed to repeat sound presentation on each trial as many times as they wished, although the majority of subjects selected their response after a single presentation.

Before testing began, each subject underwent a familiarization procedure for approximately 30 min, so that they were comfortable using the testing interface and reporting the perceived intracranial position of stimuli on the computer. Once familiarization was completed, subjects were tested with ten repetitions for each level of each binaural cue, for the three stimulus types. Cue levels were randomized within blocks of cue type and stimulus type. In addition, although every participant began with spondees, both cue and the remaining two stimulus types were randomized among listeners.

B. Analysis

Psychometric functions relating perceived intra-cranial position to ILD or ITD values were modeled using the R

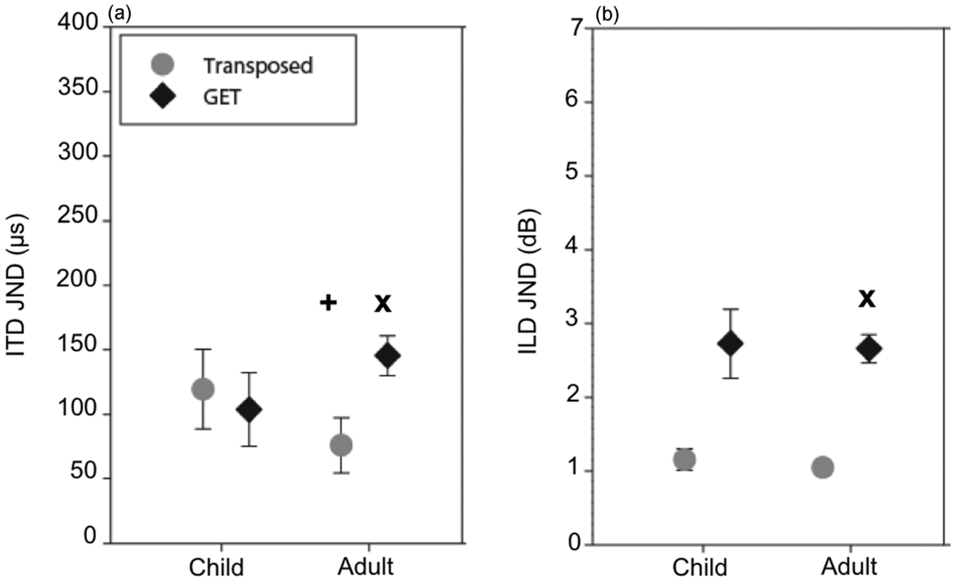

FIG. 5. Average (+/− standard error) ILD JNDs (a) and ITD JNDs (b) are shown for the transposed tones and GET stimuli, for children and adults. In addition, comparisons are made with data that were previously published in adult listeners (× depicts data replotted with permission from Goupell *et al.*, 2013; + depicts data replotted with permission from Bernstein and Trahiotis, 2002).

software (R Development Core team, 2014) with a non-linear least squares (NLS) curve fitting procedure using the Levenberg-Marquardt algorithm available in the "minpack.lm" package. A standard four-parameter logistic function was used, scaled to the input and output levels for each cue type. The form of the function was as follows:

$$\text{Position} = \frac{\text{Range}}{1 + e^{(-\text{Slope}\times\text{ILD}+\text{Shift})}} + \text{Floor} - 10.$$

"*Position*" refers to the intracranial location response of the participant. "Range" refers to the space between the upper and lower ends of the range of lateralization responses, which was roughly 20 (-10 to $+10$). "*Floor*" refers to the lower end of this range (which was typically -10). "*Shift*" refers to the overall bias in responses, which might occur if listeners shifted all responses uniformly to the left or right; in general, no listener demonstrated such behavior. "*ILD*" refers to the ILD applied to the stimuli (or ITD, as appropriate). ILDs were varied within the range of -15 to $+15$ dB and ITDs were between -800 and $+800\,\mu$s. The formula used the standard logistic function, including the natural e exponential as a growth curve from min to max. The value of the slope is an index of the listeners' perceptual mapping of the cues to the response range, and refers to the natural log change in output value (lateralization response between -10 and 10) resulting from a change in input level by one unit (either one microsecond ITD or one decibel ILD). The -10 on the right-hand side of the equation translates the predicted values between 0 and 20 back to the results scale between -10 and $+10$. All four terms of the model were free to vary across individuals; this flexible modeling approach proved to provide much better fits than an approach with fixed terms for the minimum or maximum asymptotes.

C. Results

Data from Experiment II are plotted in Fig. 6, showing individual subjects' average intracranial locations as a function of ILD [Fig. 6(a)] and ITD [Fig. 6(b)]. Within each column (subject), results are compared for the three stimulus conditions (GET pulse train, Transposed tones, and Spondees). Children's performance in the lateralization task was highly variable, akin to performance in the discrimination task described above. Some children had patterns of responses that were more categorical in nature and lateralized sounds mainly to the right or left (i.e., subject CNB), while others used the entire range, showing smaller changes for each ITD/ILD (i.e., subject CQV).

A repeated measures one-way ANOVA was conducted to compare the effects of stimuli (spondees, transposed tones, and GET) on subject's slope, revealing no significant differences between stimulus type for ILD cues. In addition, when running a linear model instead of an ANOVA for ILD cues, no comparisons reached significance, even when a random effect of listener was used (i.e., to produce a mixed-effects model). A repeated-measures one-way ANOVA for ITD cues revealed no significant main effects. However, a linear model suggested marginally smaller slope values obtained from the GET and transposed tone stimuli compared to the spondees. GET stimuli were subsequently chosen as the default stimuli for the linear mixed model because they yielded psychometric functions that were intermediate to the other two conditions and could therefore be used to test significant differences in either direction. A linear mixed-effects model was created, using a random effect of listener in addition to the stimulus-type predictor. P-values were estimated using the z-distribution as a substitute for the t-distribution; using that approach, the spondee slope values were found to be significantly smaller in magnitude compared to the default (GET) stimulus type ($p < 0.05$), but slopes for transposed tones were not found to be significantly different from those for GET stimuli. These general trends can be seen in Fig. 7 for both ILDs [Fig. 7(a)] and ITDs [Fig. 7(b)], where average slopes are compared. Comparison of the three stimuli for ILD revealed no significant differences and although the ITD spondees were significantly different from the GET and transposed stimuli, this only occurred with a linear effects model. This suggests a weak effect of stimulus type on slope.

Data collected from ten adults using GET stimuli (replotted, with permission, from the condition without low-frequency masking noise in Goupell *et al.*, 2013) are also included in Fig. 7 for comparison (far right panels). Data for ILD [Fig. 7(a)] and ITD [Fig. 7(b)] stimuli were analyzed using the same NLS curve-fitting model that was used for the children's data. Between-subjects one-way ANOVAs revealed no significant differences between the slopes of the data from children and adults for ILDs [$F(1, 18) = 0.622$, $p = 0.440$] or ITDs [$F(1, 18) = 0.496$, $p = 0.490$]. One note regarding the range of ILD cues: the adults were only tested on ILDs as large as 9 dB, however, when testing children the ILD range was extended to 15 dB, as some of the children required a larger value in order to perceptually lateralize the stimuli to the most extreme locations (near the ears). The data were thus also analyzed to compare children and adult lateralization functions with the restricted ILD range (up to 9 dB only for both groups). A between-subjects one-way ANOVA revealed no statistically significant differences [$F(1, 18) = 0.826$, $p = 0.375$] between children and adults. In summary, children were tested using three stimuli, and results from the GET stimuli were compared with those from adults published earlier. Overall, findings suggest that by age 8–10 yrs, the ability of NH children to lateralize sounds using ILDs or ITDs is not different than observations reported in adults.

IV. GENERAL DISCUSSION

These experiments were motivated by the fact that children with BiCIs show significantly worse sound localization skills than their NH peers, but there is no clear understanding of what contributes to this deficit. In two experiments, we investigated binaural sensitivity in NH children in order to begin understanding the factors that contribute to limitations observed in the pediatric BiCI population. We used acoustic stimuli that were (1) same as those used in free field studies

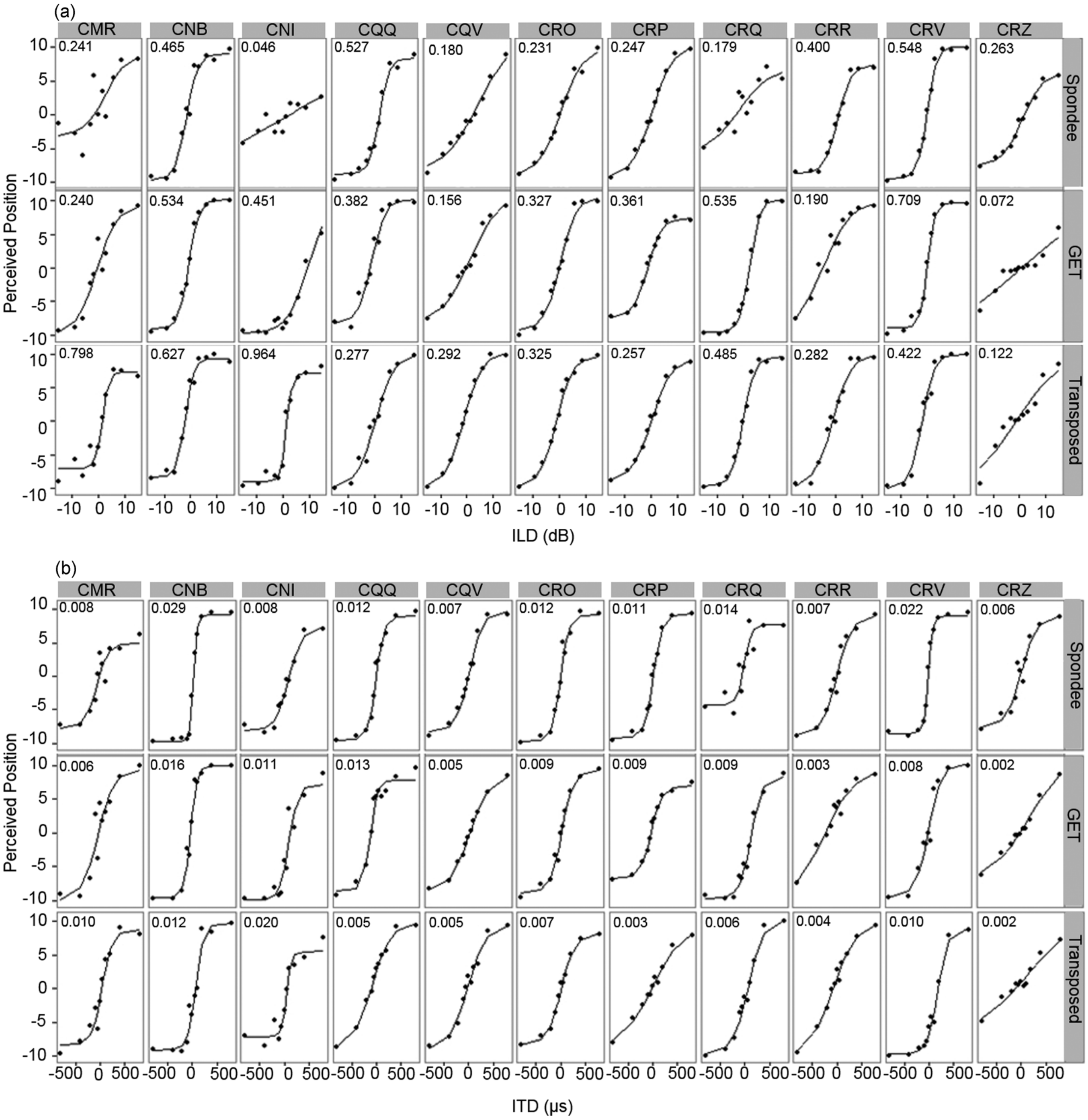

FIG. 6. Individual data from the lateralization task are shown. In each panel, data from a single listener showing the average perceived intracranial position as a function of ILD (a) or ITD (b). In (a) and (b), panels are arranged in rows according to the three stimuli that were tested (GET, spondee, transposed), with subjects in each column. Slope values are inserted in the top left corner of each panel.

with BiCI users (spondees); or (2) required listeners to rely on the ITD information present in the envelope (transposed and GET) which is similar to the manner in which CI processing disregards fine structure information. This study is also the first to systematically test discrimination and lateralization abilities of ITDs and ILDs in NH children; it thus contributes to our knowledge about the sensitivity of the binaural system in children in this age range.

In Experiment I, common methods for assessing binaural sensitivity were used to measure JNDs. For both the GET and transposed stimuli, children demonstrated JNDs that may be comparable to those obtained in NH adult subjects, suggesting that in a discrimination paradigm, NH children demonstrate sensitivity to ITD and ILD cues by age 8–10. Notably, this occurs even when using stimuli that require use of envelope ITDs, when the fine structure ITD cues are presented in a frequency range known to be too high to be reliable. This approach simulates aspects of CI processing and current findings will thus be a useful benchmark for research with children who have CIs. Interestingly, there was an effect of stimulus type on performance with the ILD cues for 7 of 11 children. Note that the four children with lowest thresholds did not show a difference in performance based on stimulus type; however, the differences seen in the other seven children suggest that it may have been easier to extract ILD cues from the transposed stimuli than from the GET

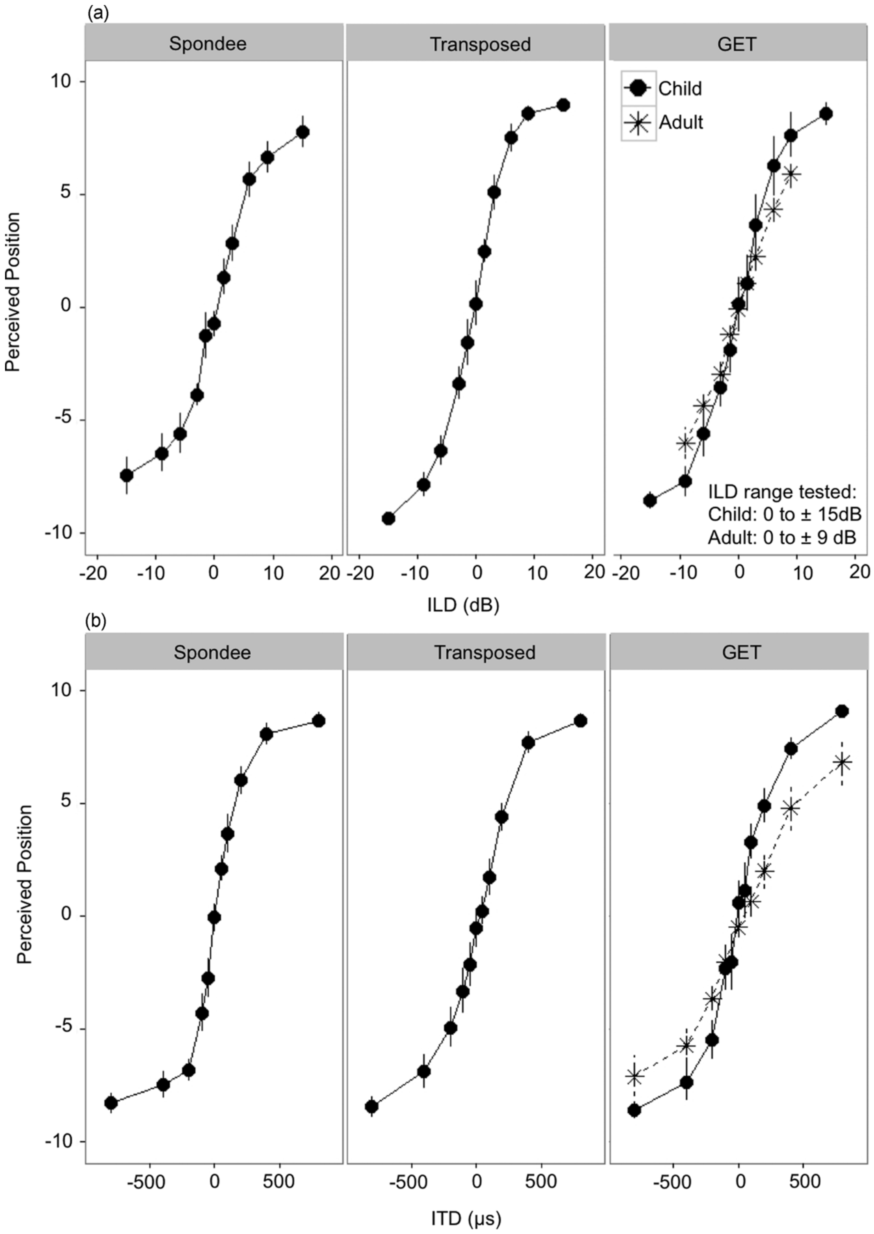

FIG. 7. Average lateralization data are summarized for the ILD (a) and ITD (b) tasks. Included in the right-most panel are data from NH adults and replotted with permission from Goupell *et al*. (2013).

stimuli. The reason for this difference is not obvious. Prior work in adults shows better performance with transposed vs sinusoid amplitude modulated tones (e.g., Bernstein and Trahiotis, 2002); however, that difference was only reported for ITD cues, as opposed to the difference seen here which is with ILD cues. We speculate that the wider bandwidth of the transposed tone compared to the GET may be providing a wider-band signal for an interaural level comparison. However, because so little is known about ILD sensitivity with any of these stimuli, further research is required. In particular, because CIs transmit ILDs better than ITDs (van Hoesel, 2004; Aronoff *et al.*, 2010; Litovsky *et al.*, 2012) children with CIs may show better ILD than ITD sensitivity, in which case future research should explore the importance of envelope shape for ILD sensitivity. Another possibility is that the difference between GET and transposed for ILD stimuli was due to an order effect because GET was always tested before the transposed tone stimuli. However, this is unlikely because the effect was found only in the ILD but not the ITD condition. If this was an order effect, performance should have been poorer for both ITDs and ILDs with the GET stimuli.

Experiment II further investigated usability of binaural cues for perceptual mapping of auditory space to a range of intracranial positions. Data showed that children ages 8–10 can map ITD and ILD cues to perceived intracranial position in a manner consistent with adult performance, regardless of the stimulus type. To our knowledge, there is prior literature on the ability of children to locate sounds from a select known set of stimulus locations, but there is no previous literature on the ability of children to perceptually map lateralized images on a continuous scale. The lateralization task is unique because it does not restrict responses to a predetermined set of options; rather subjects use a continuous scale to report perceived locations in the head. Experiment II also differs from prior work because the task was specifically designed to test the ability of children to utilize a single binaural cue at a time (ITD or ILD). This differs from free-field stimulus presentation, whereby spatial cues can potentially include not only ITDs and ILDs, but also monaural head shadow and spectral cues.

Although the statistical tests revealed no differences between groups, there was notable variability in performance for the children on both tasks used here. As has been noted in prior literature, psychophysical tasks may require the use of non-sensory abilities and selective attention, which are undergoing continued maturation throughout childhood beyond 8–10 yrs (Litovsky, 1997; Lutfi *et al.*, 2003; Davidson *et al.*, 2006; Jones *et al.*, 2015). These non-auditory factors may be underlying the variability in performance seen in both experiments. In particular, the variability is greater for lateralization (Experiment II), which requires a listener to perceptually map auditory cues to intracranial position. This may be more challenging for listeners because unlike discrimination, there is no perceptual reference to make a judgment as it is a one-interval task. In addition, this task required that children be able to translate continuously varying cues into a response system to which they are not accustomed. Several hours of testing may not have been sufficient to maximize their performance on the task. Future work involving auditory training for many more hours may reveal that lateralization abilities can improve with training. To date, work on training of auditory cues has focused on improved performance measured with discrimination tasks, similar to that used in Experiment I (Wright and Zhang, 2009). The notion of training may also be applicable to children with BiCIs, who might benefit from feedback-driven experiences with spatial cues. Finally, other unknown factors that may contribute to the variability include top-down processes that depend on more mature executive function and working memory (Davidson *et al.*, 2006).

In sum, the motivation behind this study was to help us better understand why children with BiCIs might perform more poorly on spatial hearing tasks than their NH peers. It is reasonable to presume that in BiCI users, a great limitation in use of ITDs is lack of temporal fine structure cues in the signal, as discussed above, which renders use of ITDs difficult or impossible to perceive. In the present study, NH children performed similarly to adults with NH when tested using stimuli that have the fine structure ITD cue deliberately neutralized. Therefore, the conclusion is that the deficits in BiCI localization for stimuli comparable to those used in this study are likely due to other factors besides the lack of fine structure ITDs. For example, the children may suffer from lack of exposure to fine structure ITDs during development, or degradation of neural substrates that mediate binaural sensitivity. Another factor is binaural frequency mismatch, which has been shown to limit binaural sensitivity in both NH adults and adults who use BiCIs (Goupell *et al.*, 2013; Kan *et al.*, 2013; Kan *et al.*, 2015). These factors and others are discussed in greater detail elsewhere (e.g., Kan and Litovsky, 2015). The impact of these factors on spatial hearing acuity is not well understood even in adults, and further research is needed in order to better understand the cause of the performance gap between NH and BiCI children.

V. SUMMARY AND CONCLUSIONS

Two experiments were conducted in children with NH, measuring binaural discrimination and lateralization. The following conclusions were made:

(1) On discrimination tasks, children might show ITD and ILD sensitivity comparable to adults, even with stimuli that rendered temporal fine structure ITDs unusable.
(2) Performance on tasks of binaural sensitivity is variable at this age. However, performance on tasks with ILDs was correlated with performance on tasks requiring use of ITDs, suggesting that ILD and ITD sensitivity may be linked in terms of binaural sensitivity for NH children.
(3) Future research on children with BiCIs could reveal factors other than binaural sensitivity, such as neural degradation or interaural frequency mismatch that may be responsible for poor binaural performance with BiCIs.
(4) This work serves as a starting point toward improving our understanding of the auditory cues that children might need to utilize to localize sounds, which should promote better listening in complex environments such as classrooms and playgrounds.

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