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Lateralization of binaural envelope cues measured with a mobile cochlear-implant research processor[a)]

Stephen R. Dennison,[1,b)] Tanvi Thakkar,[2] Alan Kan,[3] and Ruth Y. Litovsky[1]
[1]*University of Wisconsin–Madison, Madison, Wisconsin 53711, USA*
[2]*University of Wisconsin–La Crosse, La Crosse, Wisconsin 54601, USA*
[3]*Macquarie University, Macquarie Park, New South Wales, Australia*

ABSTRACT:
Bilateral cochlear implant (BICI) listeners do not have full access to the binaural cues that normal hearing (NH) listeners use for spatial hearing tasks such as localization. When using their unsynchronized everyday processors, BICI listeners demonstrate sensitivity to interaural level differences (ILDs) in the envelopes of sounds, but interaural time differences (ITDs) are less reliably available. It is unclear how BICI listeners use combinations of ILDs and envelope ITDs, and how much each cue contributes to perceived sound location. The CCi-MOBILE is a bilaterally synchronized research processor with the untested potential to provide spatial cues to BICI listeners. In the present study, the CCi-MOBILE was used to measure the ability of BICI listeners to perceive lateralized sound sources when single pairs of electrodes were presented amplitude-modulated stimuli with combinations of ILDs and envelope ITDs. Young NH listeners were also tested using amplitude-modulated high-frequency tones. A cue weighting analysis with six BICI and ten NH listeners revealed that ILDs contributed more than envelope ITDs to lateralization for both groups. Moreover, envelope ITDs contributed to lateralization for NH listeners but had negligible contribution for BICI listeners. These results suggest that the CCi-MOBILE is suitable for binaural testing and developing bilateral processing strategies. https://doi.org/10.1121/10.0019879

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I. INTRODUCTION

Cochlear implants (CIs) offer the most effective clinical intervention for individuals with moderate-to-profound sensorineural hearing loss. For many patients, bilateral CIs (BICIs) provide several benefits over a unilateral CI (Van Hoesel, 2004; Litovsky *et al.*, 2004; Peters *et al.*, 2010), including improvements in sound localization and speech understanding in noisy environments (Dunn *et al.*, 2010; van Hoesel and Tyler, 2003; Litovsky *et al.*, 2006; Litovsky *et al.*, 2009; Loizou *et al.*, 2009). Despite these documented advances, performance of BICI users is generally worse than that of NH listeners completing the same tasks (Dunn *et al.*, 2010; Kerber and Seeber, 2013; Loizou *et al.*, 2009). Differences in the spatial hearing abilities of NH and BICI listeners are partly explained by differing access to binaural cues. NH listeners are able to localize sounds on the horizontal plane with a combination of (1) interaural time differences (ITDs) in the fine structure of low frequencies of sounds (<1500 Hz), (2) envelope ITDs in the amplitude modulations of high frequency sounds (>1500 Hz), and (3) interaural level differences (ILDs) caused by the head shadow on high frequency sounds (>1500 Hz) (Blauert, 1997; Macpherson and Middlebrooks, 2002; Middlebrooks and Green, 1991; Wightman and Kistler, 1989). When ILDs and ITDs are both available, as can happen with a wideband stimulus, NH listeners give a larger weight to low frequency ITDs than ILDs, with little contribution from envelope ITDs (Macpherson and Middlebrooks, 2002).

BICI users receive ILDs and ITDs from their everyday processors, though CI processing strategies may disrupt delivery of these cues (Gray *et al.*, 2021). Sensitivity to ILDs is apparent from measurements using both clinical processors and research processors on a variety of tasks (Anderson *et al.*, 2019; Grantham *et al.*, 2008; van Hoesel and Tyler, 2003; Seeber and Fastl, 2008; Thakkar *et al.*, 2020). Sensitivity to ITDs in the timing of low-rate pulse trains (<300 pulses per second [pps]) and slowly modulated envelopes (<300 Hz) of high-rate frequency pulses (>900 pps) has been most reliably shown when carefully measured with research processors that allow precise control of stimulation at each electrode and preservation of binaural cues with fidelity (van Hoesel *et al.*, 2009; Laback *et al.*, 2015; Noel and Eddington, 2013; Poon *et al.*, 2009). CI signal processing typically discards all temporal information

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[b)]Electronic mail: srdennison@wisc.edu

except the amplitude modulations in a given frequency band, only providing the envelope ITDs and ILDs of sounds to listeners (Loizou, 2006; Wilson and Dorman, 2008; Wouters *et al.*, 2015). Furthermore, binaural cue sensitivity is not usually measured with clinical processors because BICI listeners are fit with two uncoordinated processors that cannot be synchronized reliably, and sensitivity to binaural cues may be affected by the signal processing strategy (Eklöf and Tideholm, 2018; Gray *et al.*, 2021; Kan *et al.*, 2018). Instead, researchers typically measure sensitivity with synchronized research devices that bypass the clinical processing strategies (Kan and Litovsky, 2015; Laback *et al.*, 2015). However, it is still unclear how to relate the findings on ITD sensitivity derived with research processors to those obtained with clinical processors. There is still little evidence of how BICI listeners perceptually combine envelope ITDs and ILDs when using either clinical processors or research devices (Aronoff *et al.*, 2010; Seeber and Fastl, 2008).

Considering the importance of ITDs for sound localization in NH listeners, much research is focused on developing and validating processing strategies with the hope of encoding or enhancing ITD cues for BICI listeners (Churchill *et al.*, 2014; van Hoesel and Tyler, 2003; Hu *et al.*, 2018; Monaghan and Seeber, 2016; Srinivasan *et al.*, 2018; Thakkar *et al.*, 2018). Most of these strategies would be difficult to implement with clinically available hardware and software because they require precise control of interaural sampling, processing, and stimulation. The inability of clinically available processors to provide coordinated control was part of the motivation for the development of bilaterally linked research processors. The CCi-MOBILE is a portable research device compatible with Cochlear Ltd. (Sydney, Australia) internal cochlear implants (Ghosh *et al.*, 2022; Hansen *et al.*, 2019). The CCi-MOBILE is bilaterally synchronized, meaning that one clock is used to simultaneously drive sampling and stimulation across two microphones and two processor output coils. All analysis, processing, and encoding is performed on an external computing platform. The CCi-MOBILE is capable of real-time processing and can be programmed with software such as MATLAB (Mathworks, Natick, MA). It has the potential to account for the hardware limitations of having unlinked devices by controlling two implants with a single processor. For further discussion on the importance of synchronized processors see Dennison *et al.* (2022).

The CCi-MOBILE has been used for binaural experiments in the sound field (Kan and Meng, 2021), but has not yet been used for a more controlled experiment with simpler binaural stimuli. To allow for manipulation of binaural cues, sounds can be presented directly to listeners via streaming of an audio file. With this direct presentation, bypassing the microphones, listeners will likely perceive these sounds as originating inside their head rather than externalizing the sounds (Best *et al.*, 2020). The perceived change in location from left to right is called "lateralization" to distinguish from localization, which refers to an externalized sound (Mills, 1960). Before conducting more extensive studies with the research device, we aimed to evaluate the capabilities of the CCi-MOBILE for a basic binaural psychoacoustic task with relatively simple but controlled stimuli. Our intention was to present simplified stimuli that allowed us to understand perceptual mechanisms, rather than fully simulate realistic BICI conditions. The CCi-MOBILE offers a unique opportunity for research that begins to close the gap between direct stimulation studies using synchronized processors where all parameters are precisely controlled and free-field studies using unsynchronized clinical processors where conditions are more realistic, but there is the least amount of control over how stimuli are encoded and delivered (Litovsky *et al.*, 2017).

The first question was whether BICI listeners could use binaural cues delivered with the CCi-MOBILE to lateralize sounds. Lateralization was measured using single-electrode pair stimulation of a high-rate pulse train with envelope modulations. Stimuli were encoded with combinations of ILDs and envelope ITDs derived from a spherical model of the human head (Duda and Martens, 1998). These pairings of binaural cues are a simplification of the complexities of ITD-ILD combinations that are typically frequency dependent but were intended to approximate one of the nominally coherent combinations of the two cues. As a control, NH listeners were tested with envelope cues from the same spatial locations. It was hypothesized that BICI users would be able to lateralize sounds using the CCi-MOBILE, with the assumption that their auditory systems' ability to encode envelope cues was intact.

The second question concerned the relative contribution of each binaural cue to lateralization. To understand this, cue shifted combinations were generated based on the approach taken in Macpherson and Middlebrooks (2002). When cue shifted combinations were presented, one cue was held constant while the other cue varied. Cue weights were estimated by comparing the responses to nominally coherent and cue shifted binaural cue combinations. NH cue weights were measured as well to determine a baseline weighting of binaural cues. We hypothesized that BICI listeners would have significant cue weights for both ILDs and envelope ITDs due to their documented sensitivity to both cues when presented in isolation.

II. METHODS

A. Listeners

Nineteen listeners participated in the study. Experimental procedures followed the National Institutes of Health regulations and were approved by the University of Wisconsin-Madison's Health Sciences Institutional Review Board.

Nine BICI listeners who had previously visited the lab were invited to participate in this study. All listeners had previously documented binaural sensitivity when measured using direct electrical stimulation with benchtop research platforms (Thakkar *et al.*, 2020). All listeners had experience with the testing setup and tasks from prior visits. Only six BICI listeners were able to complete the preliminary stages of the current experiment, and lateralization data were not collected for the remaining three; see Table I for information. BICI listeners traveled to the University of Wisconsin-Madison for testing and received payment and travel reimbursement.

Ten NH listeners who passed an audiometric hearing screening at 20 dB HL for the frequencies of 250, 500, 1000, 2000, 4000, and 8000 Hz also participated in the study. NH listeners were not age matched to BICI listeners and ranged between ages of 18 and 37. NH listeners were paid on an hourly basis.

B. Equipment

BICI listeners used the CCi-MOBILE research platform developed at the University of Texas at Dallas (Ghosh *et al.*, 2022). The CCi-MOBILE is a bilaterally synchronized research platform that allows for simultaneous control of two Cochlear Ltd. (Sydney, Australia) internal devices with signals processed using a computer running Microsoft Windows 10 (Redmond, WA). The timing of individual pulses across the ears was confirmed to be synchronized using a Tektronix TDS3014C oscilloscope (Beaverton, OR) and the measurements shown in Fig. 1 [see Dennison *et al.* (2022) for discussion on synchronization]. Mean difference in pulse timing was 3 μs ($\pm$ 4 μs standard deviation) with a maximum pulse timing offset of 8 μs.

NH listeners sat in a single-walled sound-attenuating booth and listened with Sennheiser (Wedemark, Germany) HD600 circumaural headphones. Stimuli were generated and presented using custom-written MATLAB software (Mathworks, Natick, MA) and delivered with an RME Babyface (Haimhausen, Bayern, Germany) soundcard.

C. Stimuli

Stimuli were presented to BICI listeners by stimulating a single pair of electrodes, one electrode in each ear. Stimuli were generated with a sampling rate of 96 kHz as acoustic WAV files consisting of carrier sine waves with an envelope modulation, see Fig. 1(A) for examples of modulated stimuli. The sinusoidal carrier frequency was the arithmetic mean of the channel frequency range for the desired electrode (e.g., for channel #11, which spans 1813 to 2063 Hz, the center frequency is 1938 Hz). This could lead to different carrier frequencies in the left and right ears. The resulting WAV files were streamed through a CCi-MOBILE implementation of the Advanced Combination Encoder strategy, which extracted envelope amplitudes using an overlapped short-time Fourier transform (STFT) with 128 point (8 ms) windows at 16 kHz sampling frequency. The hop size for the STFT is determined by the eventual stimulation rate; for a 1000 pps stimulation rate, the hop size was 16 samples. The envelope was calculated by the weighted magnitude spectrum in each window and compressed within the CI listener's electric dynamic range using the compression function in the Nucleus MATLAB TOOLBOX version 4.20. This function is similar to that implemented in Cochlear Freedom processors. The number of spectral maxima was set to one so that only the target electrode would be activated. The process of deciding which electrode pairs to use is described in the procedure below. Stimuli were calibrated by adjusting the amplitude of the wav files so that the peak of the envelope, with zero ILD, corresponded to the digital maximum value that would lead to presentation of the peak of the envelope at the C-levels for the electrode pair used. Examples of stimulus presented to BICI listeners are shown in Figs. 1(A)–1(C).

Stimuli presented to NH listeners were generated at a sampling rate of 96 kHz. For NH listeners, the stimulus was a 4 kHz sinusoidal carrier, modulated with a 128 Hz envelope. All stimuli were high-pass filtered above 1.5 kHz to remove any low-frequency information resulting from the amplitude modulation. The high-pass filter was designed using the MATLAB function designfilt with the Butterworth method and had a stop band frequency of 1.5 kHz, passband frequency of 2 kHz, stop band attenuation of 65 dB, and passband ripple of 0.5. Pink noise, generated with a new token each time using the MATLAB routine "pinknoise," was added to mask low-frequency distortion products. The masking pink noise was presented at 40 dB SPL. An example monaural stimulus spectrum is shown in Fig. 1(D). The pink noise began 400 ms before the tone and ended 400 ms after the tone. The entire stimulus was presented at 65 dB SPL as measured with a Larson Davis (Depew, NY) AEC100 coupler/artificial ear and digital precision sound level meter (System 824).

The duration of the stimulus that was presented to CI listeners was 400 ms. The duration of the stimulus that was presented to NH listeners was 1.2 s (when accounting for 400 ms of masking noise before, during, and after modulated tone). The envelope pulse shape was a flat pulse with tapered on and off ramps, designed with sharp onsets and pauses between pulses (Klein-Hennig *et al.*, 2011). The tapered ramps were modified raised cosines, according to the piecewise function

TABLE I. Profile, etiology, and binaural sensitivity information for BICI listeners who completed testing.

ID	Age	Etiology	Years bilaterally implanted	Clinical pulse rate (pps)	Completed screening?
IBF	68	Hereditary	12	900	Yes
IBO	54	Otosclerosis	9	1200	Yes
IBY	56	Unknown	8	900	Yes
ICJ	70	Childhood illness	9	900	Yes
IDA	52	Unknown	5	900	Yes
IDH	20	Unknown	14	1200	Yes

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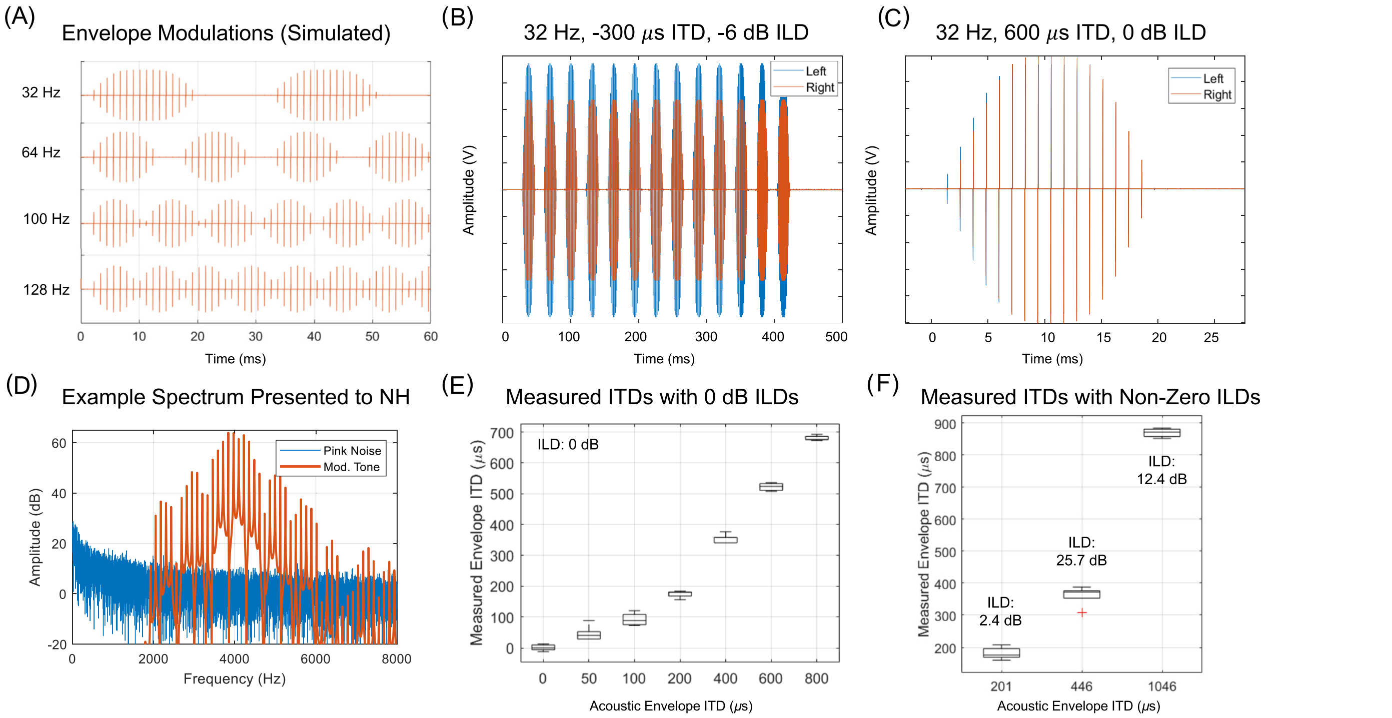

FIG. 1. (Color online) Demonstrations of stimuli and measurements of envelope ITDs. (A) Pulse diagram for various modulation rates via simulation of electrodograms from CCi-MOBILE. (B) Recording from an implant-in-a-box of 32 Hz stimulus with $-300\,\mu$s envelope ITD and -6 dB ILD. (C) Recording from an implant in a box of a single pulse burst with 32 Hz modulation and 600 μs envelope ITD. (D) Example magnitude spectrum of 128 Hz modulated tone with high-pass filter applied above 2 kHz. Masking pink noise is also depicted. (E) Analysis of envelope ITDs calculated via maximum of cross correlation for 32 Hz stimuli. (F) Example ITDs analyzed as in (D) but with various ILDs.

$$H(\beta,f,\tau) = \begin{cases} 1, & |\tau| \le \dfrac{1+\beta_0-2\beta}{2f}, \\ \dfrac{1}{2}\left[1+\cos\left(\dfrac{\pi f}{\beta}\left[|\tau| - \dfrac{1+\beta_0-2\beta}{2f}\right]\right)\right], & \dfrac{1+\beta_0-2\beta}{2f} < |\tau| \le \dfrac{1+\beta+\beta_0}{2f}. \end{cases}$$

Assuming a desired modulation frequency of f_0, then $\beta_0 = 0.4$ is the default roll-off factor, β is the adjusted roll-off factor as calculated below, $f = 2(1+\beta_0)f_0$ is the modulation frequency adjusted to the appropriate pulse width, τ is the time vector varying between $\pm 1/4f_0$ and $H(\tau) = 0$ otherwise. Note that for cases of $\beta = \beta_0$, or when ILD $= 0$ dB, the above equation simplifies to a familiar raised-cosine shape. This function allows for different roll-off factors so that pulse shapes with different maximum amplitudes have similar slopes pulse durations. The adjusted roll-off factor β was recalculated based on the ILD applied. This was done to provide a sharp onset envelope ITD when an ILD was applied. ILDs were applied by reducing the amplitude of the pulse in the ear contralateral to the direction of the ILD and leaving the ipsilateral pulse shape unchanged. Each β was calculated to optimize the following equation:

$$\arg\min_{\beta} \left| \int_a^b H(\tau,f,\beta_0) - cH(\tau,f,\beta)d\tau \right|,$$

where f was the adjusted modulation frequency as above, $= (1+\beta_0)/2f$, $b = (1+\beta_0-2\beta)/2f$, and c is the ILD as converted to a linear ratio on the interval $(0, 1]$. The envelopes calculated with different ILD values are shown in Fig. 1. This pulse shape was then used to modulate a sinusoid with the desired carrier frequency.

Once a modulated pulse was created, its duration was half the period required for the desired modulation frequency. Zeroes were added to the stimulus until the proper duration was achieved. This single pulse period, with on and off portions, was then duplicated until the entire stimulus was 400 ms long. For example, ITDs were applied with a zero-padded shift in the left channel if the ITD was right leading. Examples of modulated pulses, processed by the CCi-MOBILE processing strategy, are available in Figs. 1(A)–1(C). Due to the synchronization of the CCi-MOBILE, ITDs for the stimulus delivered to BICI listeners were in the envelope, and not fine timing, of the electrical stimulation.

There were two kinds of binaural cue combinations applied to these stimuli: “nominally coherent” cue combinations, which were intended to approximate a reasonable combination of binaural cues that a listener would receive in a real-world listening situation, and “cue shifted” cue combinations, where either ILDs or envelope ITDs were varied along a range while the other cue was kept constant.

Nominally coherent combinations of ITDs and ILDs were generated with a rigid spherical head model (Duda and Martens, 1998). The model used an 8 cm diameter head with sources located 1 m from the center of the head. Binaural cue combinations were generated by averaging the ITD cues at a given azimuthal angle over the frequencies 50 to 500 Hz, and by averaging the ILD cues at the same angle over the frequencies from 4000 to 12 000 Hz. For example, at 29°, the ILD was 9.7 dB and the envelope ITD was 346 μs. Locations were determined by calculating ten logarithmically spaced angles from 5° to 70°. These cue pair values, with 0 magnitude cues for 0°, were used for both left and right direction-cue pairs, shown in Table II.

Cue shifted combinations of envelope ITDs and ILDs were created based on the nominally coherent combinations by imposing an additional delay or attenuation on one side of the stimulus, for ITD and ILD, respectively. Cue shifts were: ITD by −600, –300, +300, +600 μs or ILD by −20, –10, +10, +20 dB. Either an ITD or ILD shift was applied to the stimulus at any one time. Not every nominally coherent cue combination was used as the reference for a cue shifted combination. A subset of the azimuthal locations, corresponding to 0°, ±5°, ±9°, ±16°, ±22°, ±29°, ±39°, was used as the base values for this portion of the study, see Table II. This cue combination subset was chosen to avoid ceiling and floor effects that would occur if cue shifts were applied to nominally coherent cue combinations to the far left or far right of the head.

Figure 1(E) shows the ITDs calculated from the stimuli presented to BICI listeners. Envelope ITDs were calculated by recording pulsatile outputs, applying a low pass filter with a cutoff frequency of 100 Hz, and finding the maximum of the cross correlation between left and right channels. ITD values were consistent across trials, but for larger ITD magnitudes, ITD values were often smaller as presented than the ITD applied to the acoustic stimulus. Nonetheless, ITD values were within 100 μs of the applied ITD, which is less than the envelope ITD thresholds for the BICI listeners tested here and around expected the ITD JND for a BICI listener (Laback *et al.*, 2015). Figure 1(F) shows ITDs measured when a non-zero ILD was applied; ITDs are still well-represented even when ILDs are co-presented.

TABLE II. Binaural cue pairs associated with each azimuthal angle. For negative angles, the same values are used, except with the opposite direction.

Angle (deg.)	ITD (μs)	ILD (dB)	Used for reference cues	Used for shifted cues
0	0	0	Yes	Yes
5	64	1.8	Yes	Yes
7	85	2.4	Yes	—
9	113	3.2	Yes	Yes
12	151	4.3	Yes	—
16	201	5.7	Yes	Yes
22	265	7.5	Yes	Yes
29	347	9.7	Yes	Yes
39	446	12.4	Yes	Yes
52	556	15.1	Yes	—
70	655	17.3	Yes	—

D. Procedure

1. BICI only procedure

The following steps were completed for BICI listeners before beginning the experimental protocol. If a listener could not complete all steps of this initial procedure, they did not continue through the rest of the protocol.

Mapping parameters. Information about each listener's fittings, comprising their active electrode channels, number of maxima, threshold levels, comfortable levels, stimulation rates, phase durations, channel gains, and internal devices, was downloaded from their clinical processors using Cochlear Ltd.'s Custom Sound fitting software. This fitting information, which was derived from the "everyday" settings programmed by their clinical audiologist, was used to program the appropriate stimulation parameters into the CCi-MOBILE MATLAB software. Hence, the pulse rate used for the experiment was the same as that of the BICI listener's clinical map. The number of spectral maxima was reduced to one so that stimulation would only be presented on the electrode pair of interest.

Electrode pair selection using ITD matching. Electrode selection was initially considered based on ITD lateralization data that had been collected during previous visits with direct stimulation (see Table III, columns 2 and 3). The electrode selection process was designed to compensate for interaural mismatch in place of stimulation (Noel and Eddington, 2013) by finding the electrode pair with the best ITD sensitivity. It should be noted that there is little to weak evidence that the sensitivity to low rate ITDs depends systematically on the electrode location (Cleary *et al.*, 2022; Laback *et al.*, 2015; Thakkar *et al.*, 2020). Therefore, it was desirable to find the electrode pair with the best ITD sensitivity rather than a tonotopic place that corresponded to 4 kHz in NH listeners. Electrode regions with the lowest estimated ITD just noticeable difference (JND) for low rates of stimulation were selected for testing, as some individual listeners may demonstrate best ITD sensitivity at different locations along the electrode array. To verify that the optimal electrode pair was selected, a range of electrodes around the target range was selected, spanning five electrodes. The previously determined pair served as a reference point for testing. That process, as first described in Litovsky *et al.* (2012), had involved holding an electrode in the left ear constant while testing for the best pitch match with five neighboring electrodes in the right ear. For example, listener IBF was tested with electrode #12 in the left ear and five electrodes in the right ear spanning #10–#14.

The best electrode pair of the five possible electrode pairs identified in the previous section was determined using a basic left-right task. For this task, a stimulus was used with a 32 Hz modulation rate and an envelope ITD of 600 μs

TABLE III. Results of the screening process for each BICI listener. ICD and ICI were not able to complete the electrode selection. IBK was able to complete electrode selection and modulation rate selection but could not perform ITD lateralization. Direct stimulation ITD JNDs were sourced from measurements reported in Thakkar *et al.* (2020). Envelope ITD JNDs were estimated as described in the text.

ID	Direct stimulation electrode pair	Direct stimulation JND at 100 pps (μs)	Envelope electrode pair	Envelope modulation rate (Hz)	Envelope ITD JND (μs)
IBF	L12, R13	38	L12, R12	100	102
IBO	L12, R12	100	L12, R13	64	297
IBY	L4, R7	96	L4, R6	32	290
ICJ	L12, R12	160	L12, R12	64	736
IDA	L12, R13	468	L12, R13	32	642
IDH	L12, R12	165	L12, R14	32	613

to the left or right. Listeners were presented with a single interval stimulus forty times for each electrode pair for 200 total trials. Listeners indicated if the sound was perceived as towards the left or the right by clicking on either the left or right ear of a cartoon representation of a face. The electrode pair with the highest percent correct was selected as the best pair. If multiple electrode pairs had the same percent correct, the pair that was closest based on electrode number in left and right ear was chosen. This electrode pair was used for all tests going forward. If a listener performed at near 100% for multiple conditions, the magnitude of the ITD used was reduced and the protocol was repeated until a best pair could be selected. The final electrodes selected are listed in Table III.

Modulation rate selection. Once the electrode pair was selected, a similar task as for electrode selection was used to select the optimal modulation rate for each listener. A "best" modulation rate for each listener was desired to collect data which would give the best sensitivity to envelope ITDs for that listener, within the envelope modulation range previously identified as having the lowest ITD thresholds (Noel and Eddington, 2013). The modulation rates tested were 32, 64, 100, and 128 Hz. Listeners completed the task with 40 repetitions for each rate. Once again, the condition with the highest percent correct was selected, see scores in Table IV. The resulting modulation rate is listed in Table III.

Remapping modifications. Several listeners noted that the stimulus was very quiet. After data were collected with the first four listeners, an additional mapping procedure was introduced for IBY and ICJ. Remapping for these individuals meant determining new Comfortable (C) and Threshold (T) values that were not in the individuals' clinical MAPs. BICI listeners were remapped by presenting the modulated stimulus to listeners and adjusting the C and T values until listeners reported that the stimulus was comfortably loud and just barely audible, respectively.

TABLE IV. Results of screening process, modulation rate. Numbers are percent correct responses. The highest score, representing the selected modulation rate, is in bold.

ID	32 Hz	64 Hz	100 Hz	128 Hz
IBF	75%	73%	**85**%	85%
IBO	73%	**78**%	65%	60%
IBY	**90**%	83%	83%	73%
ICJ	60%	**78**%	57%	65%
IDA	**73**%	70%	68%	68%
IDH	**68**%	65%	68%	55%

Centering auditory percepts. The final stimulus was presented to the listener at the electrode pair and modulation rate determined in the previous steps. The stimulation level in one of the ears was attenuated as necessary to ensure the auditory percept was perceived at the center of the head with an ILD of 0 dB and envelope ITD of 0 μs. This was done so that listener response locations were not biased towards one side or the other (Fitzgerald *et al.*, 2015; Kan *et al.*, 2015).

2. Lateralization task

Both groups of listeners completed a lateralization task in two phases. Stimuli were presented with combinations of envelope ITDs and ILDs. Listeners initiated stimulus presentation with a button press and responded by marking the perceived location of each auditory object within a bar that spanned the width of a cartoon face on the Graphical User Interface (Anderson *et al.*, 2019; Baumgärtel *et al.*, 2017; Kan *et al.*, 2013; Litovsky *et al.*, 2010). Each location indicated on the face was converted into a value from –0.5 to 0.5, with negative scores indicating a left response, positive scores indicating a right response, and zero indicating an auditory image centered in the middle of the head. Listeners could repeat stimulus presentation as many times as needed before moving to the next trial.

There were two phases to lateralization testing, corresponding to the two research questions we posed in the Introduction. Listeners always listened to the nominally coherent cue combinations first, and once that was complete, they listened to the cue shifted cue combinations. In the first phase, listeners' lateralization abilities were evaluated by responding to stimuli with nominally coherent binaural cue combinations (all angles shown in Table II). Cue combinations were presented in randomized blocks of two or three multiples (42 or 64 trials) until ten repetitions were collected for each angle. In the second phase, listeners' weighting of ILDs and envelope ITDs were evaluated and listeners responded to stimuli with cue shifted binaural cue combinations (shown in Table II). There were 52 trials in a single block for the cue shifted cue combinations. BICI listeners completed 5 repetitions of each unique cue shifted cue combination; each repetition was randomized within a block containing all 104 cue shifted cue combinations. Listener IBY was able to complete 10 repetitions due to extra time. The entire experiment, with frequent breaks, took between five and eight hours for BICI listeners to complete. NH listeners took two hours to complete both phases of the study with 10 repetitions of all conditions. NH listeners also completed an extra block of nominally coherent cue lateralization at the beginning as training to confirm that they understood the task. These data were not included in analysis.

In addition, it was necessary to confirm the ability of BICI listeners to lateralize with envelope ITDs, with ILDs set to 0 dB, using the chosen stimulus parameters. Each BICI listener who finished the screening protocol completed a 0 dB ILD, ITD-only lateralization task prior to lateralization of nominally coherent cue combinations. Listeners reported their left-right perception of stimuli with ITD values of 0, ± 50, ± 100, ± 200, ± 400, ± 600, $\pm 800\,\mu$s with 20 presentations each. NH listeners did not participate in this task.

E. Analysis

1. Lateralization of nominally coherent cue combinations

Lateralization responses to nominally coherent cue combinations were analyzed with two indices of performance. To evaluate the effectiveness of the CCi-MOBILE in delivering binaural cues, we were interested in the spatial acuity of listeners and the lateral extent of their responses. NH listener data were identically analyzed to provide a baseline performance.

First, minimum audible angles (MAAs) were estimated to evaluate the smallest difference in angle that listeners could discriminate (Mills, 1958; Senn *et al.*, 2005). Responses to nominally coherent cue combinations were considered as a function of azimuth angle, allowing for estimation of MAAs in units of angle. MAAs were calculated by deriving d' estimates by dividing the difference in means of response to opposite angles (e.g., $\pm 5^\circ$) by the pooled standard deviation of responses to opposite angles (e.g., –5 and $+5^\circ$), and then taking the line of best fit to estimate where $d' = 1$(Litovsky *et al.*, 2010). Only points within $\pm 22^\circ$ were used to avoid the saturation of the lateralization curves.

Second, lateralization range was estimated, with larger ranges corresponding to a greater ability to use a cue to lateralize (Anderson *et al.*, 2019). Lateralization range was defined as the absolute difference of the lateralization responses to binaural cues corresponding to $\pm 70^\circ$ (or $\pm 800\,\mu$s for ITD-only lateralization) derived from the estimated model fit, as described in Sec. II E 2.

For the two indices, two-sample t-tests were used to evaluate whether there was a difference in lateralization between BICI and NH groups. Levene's test and Shapiro-Wilk test were used to check assumptions of equal variance and normality, respectively. Response data were fit and plotted with the same equation as used to characterize other lateralization curves, as described in Sec. II E 2, but the fitted curves were not used for analysis here.

2. Cue weighting based on cue shifted cue combinations

Cue weights were estimated for each binaural cue to summarizes the impact of one binaural cue when the other was present (Macpherson and Middlebrooks, 2002). The cue weight is in reference to the applied cue shift, and therefore has units of dB/dB or μs/μs for ILD and ITD shifts, respectively.

To calculate the cue weights, several steps were necessary, as summarized in Fig. 2. All data were transformed from the range [–0.5, 0.5] to [–90, 90] by multiplying by 2 and applying the "asind" function in MATLAB.

For each listener, an individual reference function $f(x)$ was fit using the responses to the nominally coherent cue combinations by using the following equation:

$$f(x) = A\mathrm{erf}\left(\frac{x-\mu_x}{\sqrt{2}\sigma}\right) - \mu_y,$$

where A corresponds to the spread of the extent of lateralization, x corresponds to the cue being used as predictor, ILD or ITD, μ_x corresponds to the horizontal shift of the curve, σ is related to the lateralization slope, and μ_y corresponds to the vertical shift of the curve. Methods for fitting are also described in Anderson *et al.* (2019).

An equivalent response cue was calculated for each response to a cue shifted cue combination. This was done by numerically solving for the input cue x that minimized the difference between the reference function $f(x)$ and the cue shifted cue combination response y,

$$\arg\min_{\mathrm{x}} \left|\mathrm{f(x)} - \mathrm{y}\right|.$$

An observed cue bias was calculated by subtracting the equivalent response cue by the cue present in the nominally coherent cue combination:

$$\begin{aligned}&Observed\,ILD\,Bias\\&\quad = Reference\,ILD\,equivalent\,to\,response\,to\,shifted\,cues\\&\qquad - Unshifted\,cue\,amount.\end{aligned}$$

The observed cue bias, as plotted in bottom right of Fig. 2, was then fit with a linear regression as a function of imposed cue shift. The slope of these regressions was taken as the cue weight for each listener for each cue type. To evaluate whether a cue weight was significantly greater than zero, a one-sample t-test was used on each cue group for BICI listeners. Then, to analyze the cue weights, a linear mixed effects model was fit with the lme4 function from the lme4 package in R (version 3.6.1) using the equation $CueWeight \sim Cue*Group + (1|Listener)$. Estimated marginal means were calculated to determine mean cue weights.

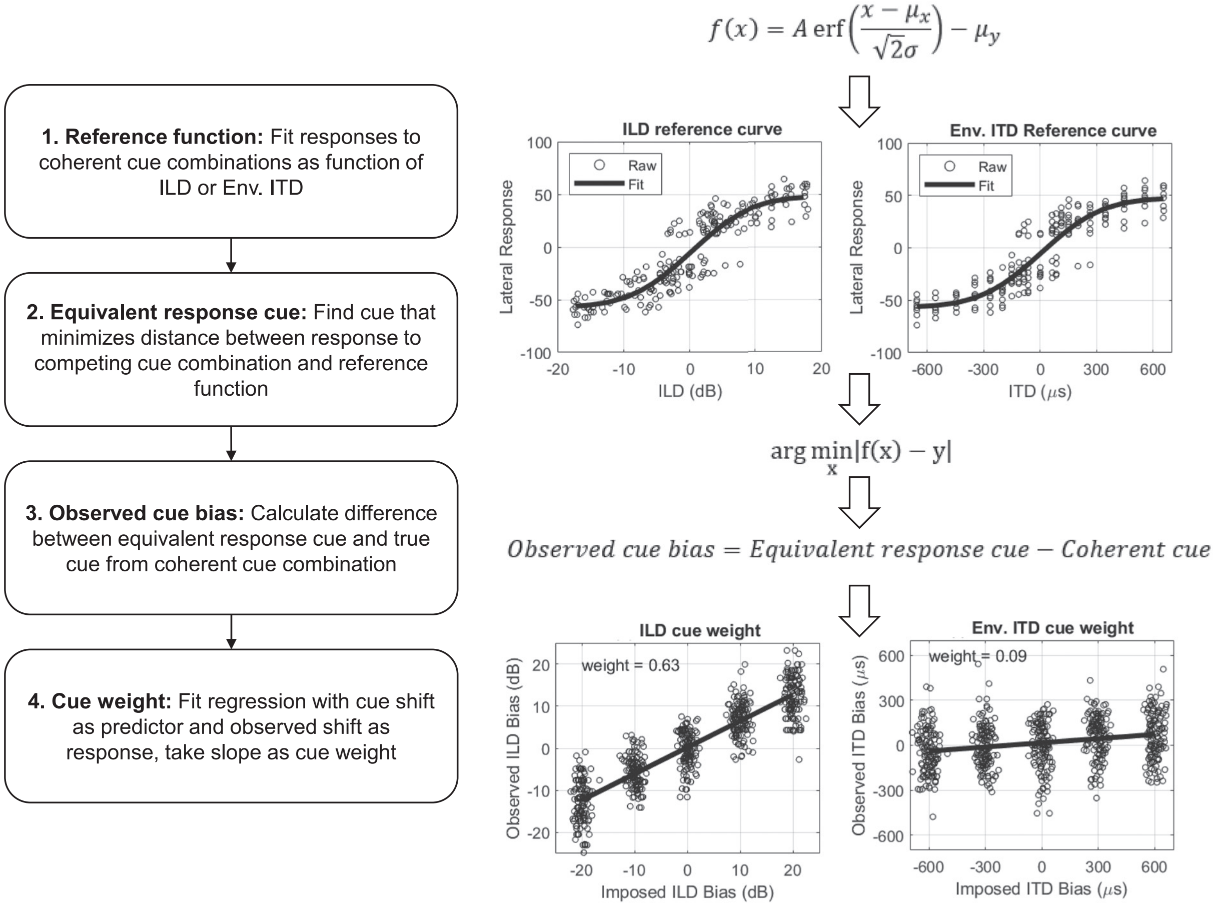

FIG. 2. Diagram explaining how cue weights were calculated, including demonstration of the process for calculating cue weights and example data for BICI listener IBY.

Post hoc multiple comparisons were calculated with the Tukey method for comparing a family of 4 estimates.

Finally, correlation coefficients were calculated to determine a potential relationship between envelope ITD thresholds and envelope ITD cue weights.

III. RESULTS

A. Lateralization of nominally coherent cue combinations

Figures 3 and 4 show individual lateralization responses for BICI and NH listeners. Figure 5 summarizes all lateralization data across listeners, separated by group. The first panel in each sub-figure shows the lateralization of nominally coherent cue combinations. All BICI listeners had full lateralization curves spanning the lateralization space, confirming our hypothesis that BICI listeners could lateralize using the CCi-MOBILE. We had the *a priori* assumption that if the BICI listeners could lateralize sounds using the CCi-MOBILE, their lateralization responses would be similar to NH listeners. The mean MAA for BICI listeners was 4.34° [±1.39° standard deviation (SD)] while the mean MAA for NH listeners was 6.71° (±2.09° SD). MAAs and lateralization range met assumptions of normality and equal variance and were compared across groups using independent sample t-tests. MAAs were not significantly different across groups but there was a trend towards significance ($t(14) = -1.99$, $p = 0.067$). The mean lateralization range for BICI listeners was 135 (±19 SD) while the mean lateralization range for NH listeners was 128 (±21 SD). Lateralization range was not statistically different across groups ($t(14) = 0.68$, $p = 0.51$).

In addition to the six BICI listeners presented here, three more BICI listeners were recruited for the study. Two of the listeners could not complete the pre-test tasks well enough to continue with the rest of the experiment based on the screening protocol. A third listener chose to withdraw from the experiment after listening to the stimulus and describing it as unpleasant. Two of the BICI listeners reported hearing multiple auditory sources when ILDs and envelope ITDs were nominally set to values of 0 dB and 0 μs. The study was designed to be analyzed with only one response location per stimulus presentation. Hence, these listeners could not provide data in the format required for analysis and testing was discontinued for these listeners.

B. Cue weighting based on cue shifted cue combinations

Lateralization data for cue shifted cue combinations for BICI and NH listeners are shown in Figs. 3 and 4.

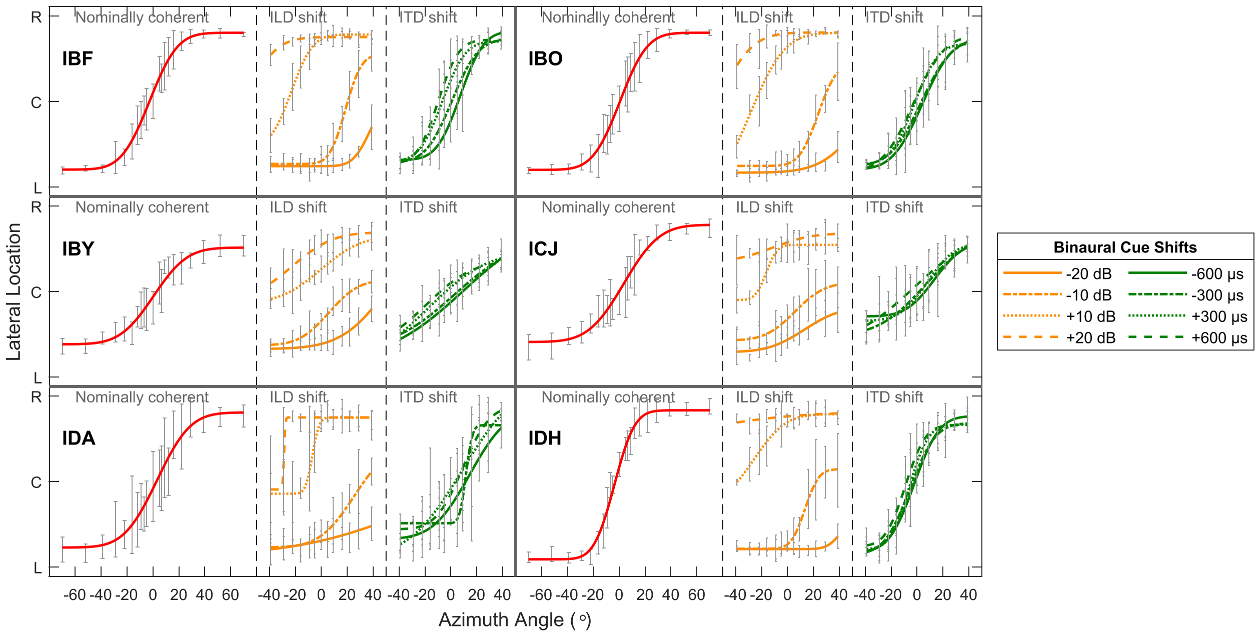

FIG. 3. (Color online) BICI lateralization. Each azimuth angle has an associated binaural cue pair. First panel: Red curves represent a function fit to the average response for each azimuthal angle for coherent angles. Second panel: Yellow curves represent a function fit to the average response for cues where ILDs had been shifted. Third panel: Green curves represent a function fit to the average response for cues where envelope ITDs had been shifted. Black vertical bars represent the standard deviation of responses.

Responses to ILD shifts and envelope ITD shifts are shown in the second and third panels of each sub-plot. In contrast to the lateralization responses to nominally coherent cue combinations, there are clear differences in lateralization responses across groups. Shifts in ILD led to changes in lateralization response for both groups, but responses of BICI listeners seemed to demonstrate a more pronounced shift than those of NH listeners. Shifts in envelope ITD did not appear to lead to changes in lateralization responses for BICI listeners but led to a change in lateralization response for NH listeners. Averages across listener for each group are shown in the right half of Fig. 5, and the individual trends

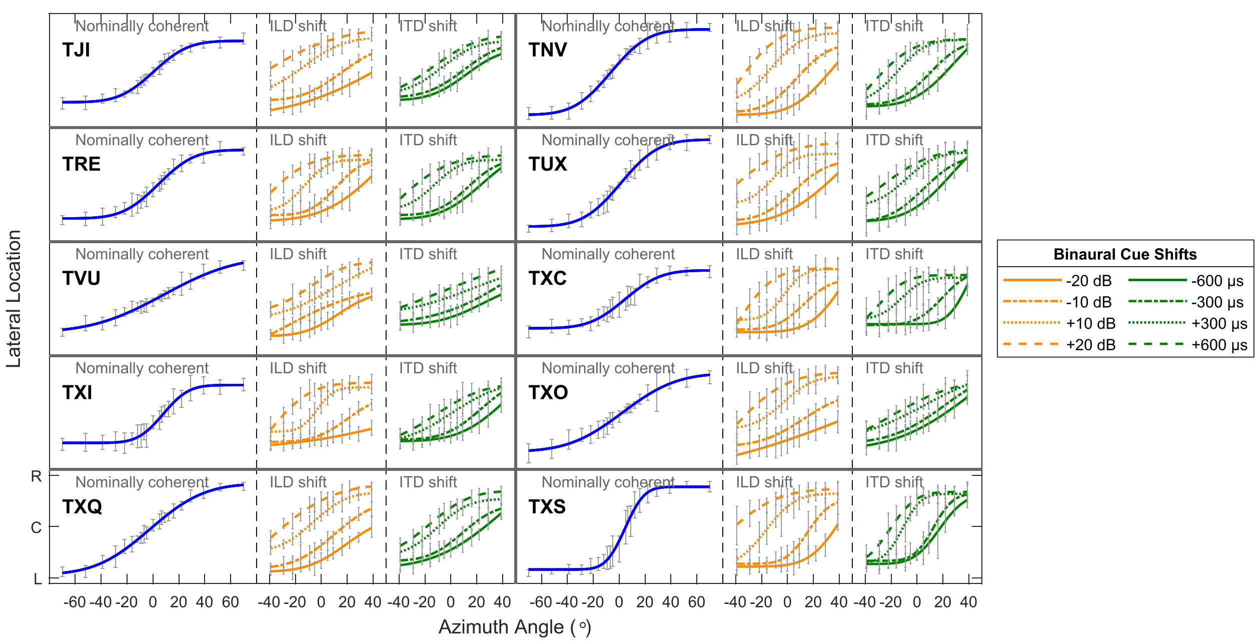

FIG. 4. (Color online) NH lateralization. Each azimuth angle has an associated binaural cue pair. First panel: Red curves represent a function fit to the average response for each azimuthal angle for coherent angles. Second panel: Yellow curves represent a function fit to the average response for cues where ILDs had been shifted. Third panel: Green curves represent a function fit to the average response for cues where envelope ITDs had been shifted. Black vertical bars represent the standard deviation of responses.

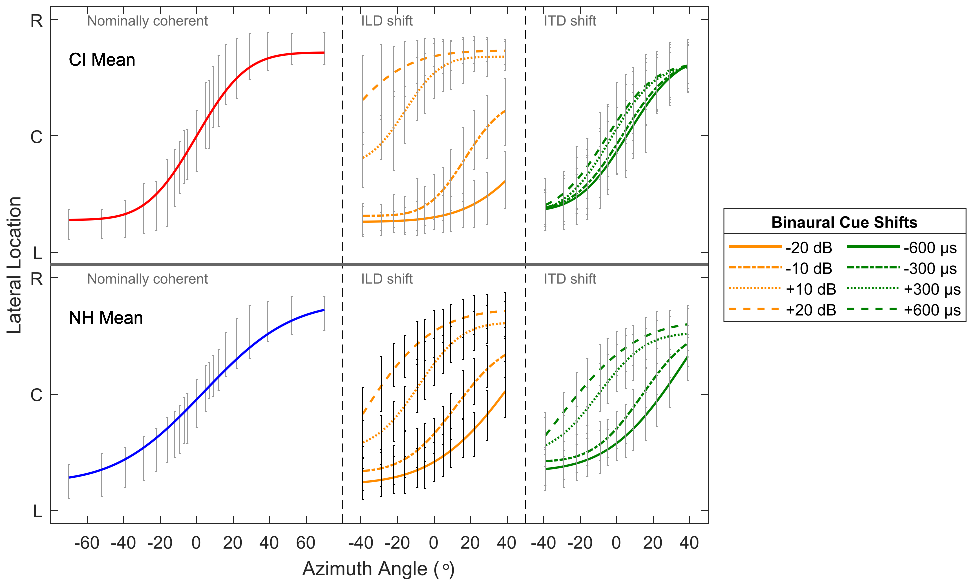

FIG. 5. (Color online) Average lateralization curves for BICI and NH listeners. Error bars represent standard deviation.

continue at a group level: shifts in ILD led to shifts in response location for both groups but shifts in envelope ITDs only led to a change in response for NH listeners.

To quantify these trends, cue weights were estimated and summarized in Fig. 6. Cue weights ranged from 0 to 1, indicating at the extremes that there was no relative contribution or that shifting the cue led a complete shift in lateralization responses, respectively. We hypothesized that BICI listeners would have significant cue weights for both cue types. One-sample t-tests revealed that for BICI listeners, both envelope ITD cue weights $(t(5) = 5.72, p = 0.002)$ and ILD cue weights $(t(5) = 14.51, p < 0.001)$ were significantly different from zero. Estimated marginal means for BICI listener cue weights were 0.58, 95% CI [0.52,0.64] for ILDs and 0.07, 95% CI [0.01,0.13] for envelope ITDs.

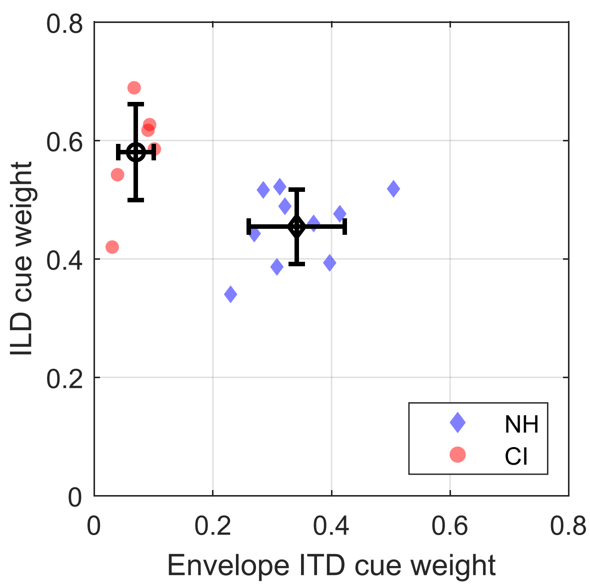

FIG. 6. (Color online) Cue weight summary for NH (blue) and BICI (red) listeners. Error bars represent standard deviation. Black symbols represent group means.

Estimated marginal means for NH listener cue weights were 0.45, 95% CI [0.41,0.5] for ILDs and 0.34, 95% CI [0.29,0.39] for envelope ITDs. Statistical analysis of the cue weights revealed that there was a significant interaction between cue type and group $(F(1, 14) = 95.9, p < 0.001)$. There was a significant effect of cue type $(F(1, 14) = 236.8, p < 0.001)$ and group $(F(1, 14) = 5.63, p = 0.032)$ on cue weight.

Post hoc tests were conducted to examine the interaction between cue type and group. Multiple comparisons with the Tukey method for comparing a family of 4 estimates revealed that ILD cue weights for BICI listeners were significantly larger than envelope ITD cue weights for BICI listeners $(t(14) = 15.9, p < 0.001)$, envelope ITD cue weights for NH listeners $(t(24.3) = 6.5, p < 0.001)$, and ILD cue weights for NH listeners $(t(24.3) = 3.42, p < 0.011)$. ILD cue weights for NH listeners were significantly larger than envelope ITD cue weights for NH listeners, but the effect was not as strong $(t(14) = 4.57, p = 0.002)$. Envelope ITD cue weights for NH listeners were significantly greater than envelope ITD cue weights for BICI listeners $(t(24.3) = 10.47, p < 0.001)$. Therefore, while both groups had a pattern where ILD cue weights were greater than envelope ITD cue weights, BICI listeners had a more extreme difference between cue weights than NH listeners.

BICI lateralization responses for when ILD were set to 0 dB and only envelope ITDs were varied are plotted in Fig. 7. Lateralization range met the assumptions of normality and equal variance, but standard deviation of response did not, so a paired-sample t-test was used for lateralization range and a Wilcoxon signed-rank test was used for standard deviation of responses. Lateralization range was greater for nominally coherent cue combinations as compared to just envelope ITDs $(t(5) = 7.69, p < 0.001)$. Envelope ITD JNDs for BICI listeners were estimated from the lateralization curves with an average of 446 μs (± 251 μs standard deviation). Individual JNDs are included in Table III. The

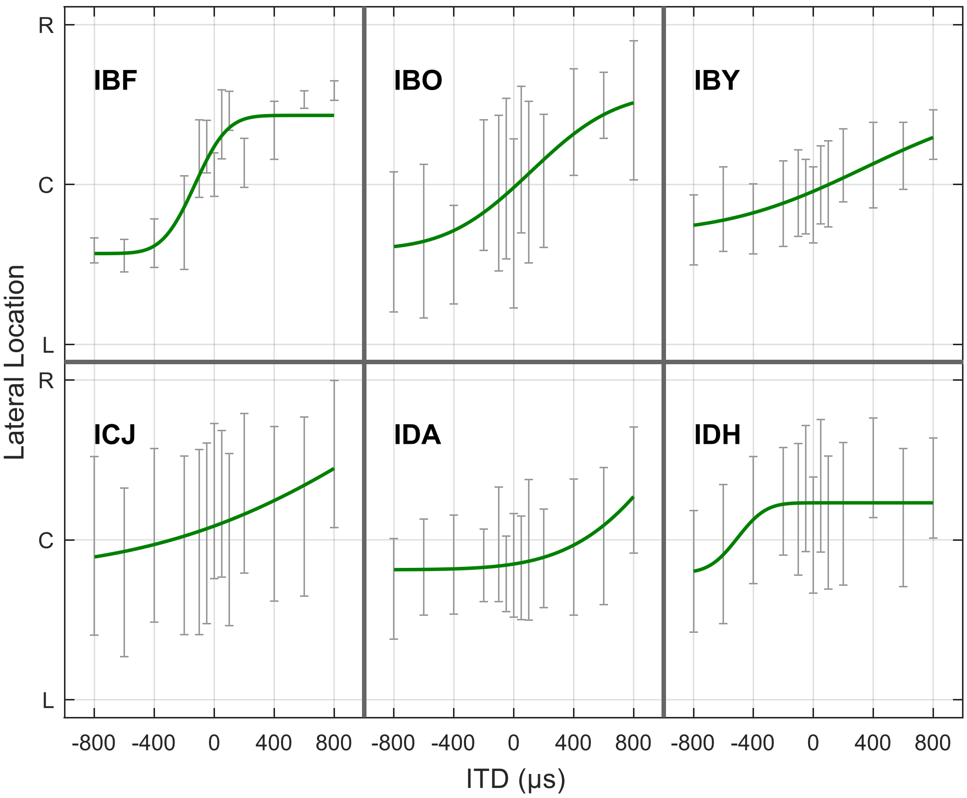

FIG. 7. (Color online) Envelope ITD lateralization for BICI listeners. Green curves represent a function fit to the average response for each ITD. Black vertical bars represent the standard deviation of responses. The bottom right panel shows the group average of mean responses for each listener.

Pearson's correlation coefficient between JNDs and ITD cue weights was –0.69 ($p = 0.13$), indicating that there may be a potential relationship between threshold and cue weight. This would mean that listeners with lower thresholds, indicating higher sensitivity, also had larger envelope ITD cue weights. However, the relationship was not significant.

IV. DISCUSSION

In this set of experiments, we first determined whether BICI listeners could lateralize combinations of binaural cues in the envelopes of stimuli presented through the CCi-MOBILE processor. This was done by measuring the perceived locations of sounds induced by combinations of ILDs and envelope ITDs delivered to single pairs of electrodes that had been shown to yield good ITD sensitivity in previous experiments. Six BICI successfully perceived changes in lateralization for different interaural cue differences. A comparable task was also completed by NH listeners, and responses did not statistically differ as compared to BICI listeners (see first panels of Figs. 3–5). Following these baseline measures of lateralization, the relative contributions of ILDs and envelope ITDs to lateralization were measured by varying one cue while holding the other cue constant and recording perceived lateralization responses (see second and third panels of Figs. 3–5). The estimated cue weights revealed that both NH and BICI listeners demonstrated larger ILD weights than envelope ITD weights, suggesting that ILDs were the dominant cue for lateralization for both groups and for these stimuli (see Fig. 5). However, there were notable differences between the groups. For NH listeners, both ILD and envelope ITD shifts led to significant cue weights for both types of binaural cues. In contrast, BICI listeners demonstrated a larger overall ILD cue weight than NH listeners with negligible cue weights for envelope ITDs.

A. Lateralization of nominally coherent cue combinations

It was an encouraging finding that BICI listeners could lateralize sounds by using nominally coherent combinations of envelope ITDs and ILDs. Lateralization curves have been measured for ITDs and ILDs using both direct stimulation [e.g., van Hoesel and Tyler (2003) and Litovsky *et al.* (2010)] and clinical processors [e.g., Aronoff *et al.* (2010) and Laback *et al.* (2004)]. Estimated MAAs were between 2° and 8°. This finding is consistent with the results for both BICI and NH listeners tested in free-field using white noise bursts of 1 s duration; BICI listeners had 3°–8° MAAs and NH listeners had 1°–4° MAAs (Senn *et al.*, 2005). More recent studies have shown that BICI MAAs are much worse, with median values of 17° (Dwyer *et al.*, 2021). It should also be noted that the smallest angle tested in this current study was 5°; therefore, this can be considered the smallest measurable angle or floor for the estimated MAAs, with many listeners exhibiting a thresholds below this floor.

Considering estimated MAAs and lateralization range response patterns were similar across groups, this suggests that for future studies, delivery of binaural cues with the CCi-MOBILE is feasible. The spatial cues used in this study were not as realistic as cue combinations that a listener would perceive with their personal HRTFs, but they are a reasonable approximation of the cue combinations a listener could experience.

Lateralization range was significantly smaller for BICI listeners with non-zero envelope ITDs and zero ILDs than with both envelope ITDs and ILDs. Anderson *et al.* (2019) showed that when lateralization ranges were measured for just ITD or just ILD, with the other cue held to 0 dB or 0 μs, the range was reported as consistently smaller for BICI listeners than NH listeners. BICI listeners may potentially require even larger magnitudes of ITD, surpassing $\pm$800 μs, in order to achieve full lateralization with just ITDs [Baumgärtel *et al.* (2017); e.g., Thakkar *et al.* (2023)]. There is no guarantee that listeners will hear sounds entirely lateralized with just envelope ITDs, as demonstrated by the compressed range of lateralization when ILDs are 0 dB and envelope ITDs are varied up to $\pm$800 μs [see Fig. 7 and Anderson *et al.* (2019), Baumgärtel *et al.* (2017), Kan *et al.* (2016), and Litovsky *et al.* (2010)].

Most BICI lateralization studies focus on ITDs only, with a specific emphasis on envelope ITD and low-rate ITDs to determine whether or not sensitivity exists (van Hoesel *et al.*, 2009; van Hoesel and Tyler, 2003; Laback *et al.*, 2015; Majdak *et al.*, 2006; Noel and Eddington, 2013). As a result, the combination of both ILDs and ITDs, whether they are present in the pulses or the envelope, has been less studied (Aronoff *et al.*, 2010; van Hoesel, 2008; Klingel and Laback, 2022; Seeber and Fastl, 2008). Conversely, all localization studies with BICI listeners presumably investigate the delivery of both ILDs and envelope ITDs together. There is no guarantee both cues are being delivered by clinical processors because of lack of bilateral synchronization and spectral differences introduced by the shape of the head (Gray *et al.*, 2021; Kan *et al.*, 2018). Therefore, this study begins to fill a space in the literature in which HRTF-derived pairs of binaural cues are introduced yet some aspects of direct psychoacoustic testing are retained, such as precise control of electrode pairs.

One should be cautious when comparing results obtained with multi-electrode stimulation, as provided with clinical processors, against results obtained with single-electrode pair stimulation. While the results here provide a helpful reference for expected results, they should not be directly compared to localization in the sound-field because other considerations are at play in the free-field, such as the dynamics of small human head movements, and the acoustic modifications of the head, torso, and pinna on the incoming sound. These values likely overestimate the sensitivity of a BICI listener to binaural cues, but they do fall within previously established bounds reported in other studies, which is encouraging for validating the use of the CCi-MOBILE (Dwyer *et al.*, 2021; Senn *et al.*, 2005). This suggests that, at least for BICI listeners tested here, angle discrimination may be driven more by ILDs than envelope ITDs, consistent with the weighting results presented here.

B. Cue weighting based on cue shifted cue combinations

It was hypothesized that BICI listeners would have measurable cue weights for both ILDs and envelope ITDs due to their measured sensitivity in isolation. Both NH and BICI listeners perceived changes in lateralization for different ILD cue shifts and ITD cue shifts. However, for BICI listeners, ILDs had a much greater cue weight than envelope ITDs. Although envelope ITD weights for BICI listeners were significantly greater than zero, their contribution appeared negligible when compared to ILDs.

For NH listeners, these results mostly agree with studies that find that both ILDs and envelope ITDs contribute to lateralization (Bernstein and Trahiotis, 2012; Klingel *et al.*, 2021; Macpherson and Middlebrooks, 2002; Wightman and Kistler, 1992). One of the first extensive investigations of natural and unnatural combinations of binaural cues found consistent differences in NH response patterns between the two conditions, suggesting that both cues are processed together (Gaik, 1993). Macpherson and Middlebrooks (2002) found larger ILD weights than envelope ITD weights in a high-passed noise condition, but found that envelope ITD weights increased with modulation more like the stimulus used in the current study. Bernstein and Trahiotis (2012) found that ILDs could be modeled as "weights" on the overall perception of a sound source, and that their influence was independent of envelope ITDs for the most part. It is difficult to directly compare this outcome to our finding that envelope ITDs and ILDs were given similar weightings by NH listeners due to differences in methodology. Klingel *et al.* (2021) used a similar paradigm inspired by Macpherson and Middlebrooks to measure the impact of audiovisual training to induce reweighting of cues and found that prior to training, NH listeners weighted ILDs lower than ITDs. Together these studies have revealed that there is a complex interaction between binaural cue weighting and the stimulus type, with NH listeners capable of combining ILDs and envelope ITDs differently depending on the paradigm.

For BICI listeners, envelope ITD shifts did not significantly influence lateralization in the presence of ILDs. Using virtual acoustic space with broadband stimuli, Seeber and Fastl (2008) similarly found little use of envelope ITDs as compared to ILDs for localization by one exceptional listener. This listener demonstrated an offset in their response locations of up to 50% due to ILDs, but no more than 10% due to envelope ITDs, which ended up less than the error of responses; this result agrees with the results presented here. Aronoff *et al.* (2010) used a virtual acoustic space approach to investigate the relative contributions of ILDs and envelope ITDs. The goal was to investigate the use of each cue alone, and their results showed that localization error was much worse with envelope ITDs only as compared to conditions that used ILDs or ILDs and ITDs together. Aronoff *et al.* (2012) also investigated the use of combinations of interaural cues by NH listeners and BICI users, but did not vary one cue while keeping the other cue constant, making it difficult to directly compare to the weighting results discussed here.

One additional consideration for this portion of the study is that, for BICI listeners, a sufficiently high current level in both ears is likely required to measure ITD sensitivity (Egger *et al.*, 2016). It is possible that applying an ILD where one ear is decreased in intensity might negatively impact ITD sensitivity for BICI listeners, but there is also evidence to suggest that that applying an ILD to center an auditory image does not impact ITD sensitivity (Goupell, 2015; Kan *et al.*, 2015). The low weight for envelope ITD observed in the current study could instead be partly due to the compression of lateralization space experienced away from the midline, which has shown to be a consistent phenomenon in listeners with NH (Yost, 1981). Finally, envelope ITDs may truly contribute to lateralization in a similar fashion as in NH listeners, but to such a small degree that they are negligible in practice. This could be the result of lack of access to ITDs either because of pathology or CI hardware and processing. This line of reasoning is partly why recent research has explored the potential of training listeners to reweight binaural cues for localization (Klingel and Laback, 2022) or replacing instantaneous ITDs with ILDs to improve localization (Brown, 2018).

C. Limitations of study

There are four main limitations to consider for this study. The first is that data were collected for only six BICI listeners. The primary purpose of the study was whether BICI listeners could lateralize using the CCi-MOBILE, and all six listeners displayed this ability. For the secondary purpose of the study, measuring the relative contribution of envelope ITDs and ILDs to lateralization, six listeners may have led to an underpowered study. Envelope ITD cue weights were found to be significantly different from zero, but as the cue weight itself was small, it is difficult to conclude emphatically that this sample represents all BICI listeners. The potentially underpowered study due to the small number of participants also made it difficult to directly compare the results for BICI and NH listeners.

The second limitation was that the stimulus presented to NH and BICI listeners may potentially be different. BICI listeners were presented with stimulation focused on just one pair of electrodes, while NH listeners were presented with envelope cues on a stimulus with a relatively wide spectrum that spanned several auditory filter banks. For NH listeners, the stimulus was centered at 4000 Hz, with a wide bandwidth (see Fig. 1). For BICI listeners, the stimulation site was likely different from the tonotopic location of 4 kHz, with a smaller bandwidth due to single-electrode stimulation. This may mean that only relative changes or shifts in lateralization, due to relative shifts in binaural cues, should be compared across groups. Furthermore, the BICI listeners had different stimulation sites as compared to other BICI listeners, although there was likely a small effect if any for BICI listeners (Cleary *et al.*, 2022; Thakkar *et al.*, 2020). This happened because electrode pairs were selected for each BICI listener to find the best ITD sensitivity, rather than to match tonotopic place of stimulation across listeners. Once an electrode pair was chosen for a BICI listener was selected, that electrode pair was not changed. Therefore, within each listener, the interaural tonotopical variation was controlled for, but variations remained across listeners and groups.

A third limitation of the study is that NH and BICI listeners were not age-matched. Age is known to impact temporal fine structure processing and binaural abilities (Abel *et al.*, 2000; Babkoff *et al.*, 2002; Gallun *et al.*, 2014; Grose and Mamo, 2010). More recent work has demonstrated that age of listener confounds direct comparisons between NH and BICI listeners for lateralization tasks (Anderson *et al.*, 2019). Specifically, smaller lateralization ranges are to be expected for older listeners, regardless of whether listeners are NH or BICI. Therefore, by comparing young NH listeners to older BICI listeners, it should be expected that BICI listeners would have smaller lateralization ranges.

A fourth limitation for this study was the use of different modulation rates for different BICI listeners. Modulation rates were selected on a per-listener basis for BICI listeners instead of standardized across the group because different listeners demonstrated best performance at different rates. Previous studies have found a modulation frequency dependence for ITD sensitivity, with best ITD sensitivity around 128 Hz and rolling off at higher and lower frequencies (Noel and Eddington, 2013). However, combinations of ILD and envelope ITD cues together may not have shown the same envelope frequency dependence. Lateralization range, when measured with ILDs as opposed to ITDs, does not demonstrate the same pattern of peaking around 125 Hz, and instead seems invariant to modulation frequency (Anderson *et al.*, 2019). If only the envelope ITD cue weight varied with modulation frequency, it would be different to generalize these results to stimuli with different modulation frequencies.

While it was of great interest to test the abilities of BICI listeners to lateralize single-electrode stimuli using binaural cues provided by the CCi-MOBILE, the results presented here should not be generalized to more complicated stimuli without further investigation. The variables of interest were "nominally coherent" and "cue shifted" combinations of binaural cues presented to single pairs of electrodes, rather than multi-electrode stimulation. While multi-electrode stimuli may have been more realistic, the relative simplicity of single-electrode stimulation was preferred due to the complicated manipulation of binaural cues. Realistic stimuli would likely contain binaural cues that vary over time and across channels in unpredictable ways and may lead to different results than those discussed here.

D. Implications for future research

In this study, we aimed to investigate the capability of the CCi-MOBILE for controlled binaural studies, a capability well tested and demonstrated using the NIC platform available from Cochlear Ltd. Readers may wonder what benefits the CCi-MOBILE offers over other research platforms. One of the main advantages of the CCi-MOBILE is that it is portable and can process microphone inputs in real-time when connected to a mobile phone (a feature not used in this study). This is in contrast to the NIC, which can only work when connected to a laptop or desktop computer. Further, our software on the CCi-MOBILE is capable of supporting both real-time and offline signal processing using the same code structure and can switch between the two signal processing paths without re-programming. This provides the ability to test new strategies implemented on the CCi-MOBILE and evaluate the delivery of binaural cues to BICI listeners. Prior work has already shown that our software is useful for real-time testing in the sound field (e.g., Kan and Meng, 2021). This experiment allows us to test our implementation with stimuli that have ITDs and ILDs known, *a priori*, and validate that our software can deliver useful binaural cues. Researchers who wish to conduct binaural research with synchronized processors may also consider the similar research device developed for Oticon Medical devices (Backus *et al.*, 2015).

Many signal processing algorithms proposed and tested in the literature have not been implemented or tested with processors capable of real-time processing. In particular, strategies that aim to encode or enhance ITDs are likely impossible without bilaterally linked processors to guarantee synchronized stimulation (Churchill *et al.*, 2014; Dennison *et al.*, 2022; van Hoesel and Tyler, 2003; Srinivasan *et al.*, 2018; Thakkar *et al.*, 2018). The data presented here on lateralization of combinations of cues and just envelope ITDs are promising steps towards validating the use of the CCi-MOBILE for binaural experiments and developing binaural signal processing strategies.

This study investigated whether envelope ITDs can influence lateralization in the presence of ILDs for BICI listeners. If ILDs dominate the lateral position for BICI listeners as they do in this study, then researchers must carefully consider how to effectively provide binaural information to BICI listeners in realistic settings. For example, if the aim is to improve localization, ILDs serve many roles for NH listeners, including removing confusion about the phase of an ITD due to slipped cycles or helping to resolve ITDs that may only be useful at locations where ILDs are unable to provide distinguishing information, due to the non-monotonically increasing ILD cue patterns (Jones *et al.*, 2014; Kelvasa and Dietz, 2015). Any potential solution that successfully provides ITD information to a BICI listener may need to preserve ILDs for best outcomes. As another example, if the aim is to provide speech understanding in noise, then it may be critical to improve the delivery of ITDs to BICI listeners, as ITDs may be more useful for spatial unmasking of speech than ILDs for BICI listeners (Ihlefeld and Litovsky, 2012; Todd *et al.*, 2019). As a result, there may not be a single best combination of binaural cues to restore spatial hearing, and instead different goals may require different solutions. Research platforms like the CCi-MOBILE help us move towards solutions that can provide both ITDs and ILDs for all spatial hearing tasks.

V. CONCLUSIONS

This study measured the lateralization performance of NH and BICI listeners to "nominally coherent" and "cue shifted" combinations of envelope ITDs and ILDs to understand how these cues are weighted to form a lateralized percept. Results showed that ILD cue weights were larger than envelope ITD cue weights for both groups, but envelope ITD cue weights were much greater for NH listeners than BICI listeners. This suggests that even if BICI listeners are sensitive to envelope ITDs, this sensitivity may not persist in the presence of ILDs. Further research is needed to understand how ILDs may impact the delivery of both envelope and low frequency ITDs in bilateral CI sound coding strategies. This work demonstrates that the CCi-MOBILE platform is a suitable platform for studying the delivery of binaural cues with novel signal processing strategies.

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