Interaural envelope correlation change discrimination in bilateral cochlear implantees: Effects of mismatch, centering, and onset of deafness

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Bilateral cochlear implant (CI) listeners can perform binaural tasks, but they are typically worse than normal-hearing (NH) listeners. To understand why this difference occurs and the mechanisms involved in processing dynamic binaural differences, interaural envelope correlation change discrimination sensitivity was measured in real and simulated CI users. In experiment 1, 11 CI (eight late deafened, three early deafened) and eight NH listeners were tested in an envelope correlation change discrimination task. Just noticeable differences (JNDs) were best for a matched place-of-stimulation and increased for an increasing mismatch. In experiment 2, attempts at intracranially centering stimuli did not produce lower JNDs. In experiment 3, the percentage of correct identifications of antiphasic carrier pulse trains modulated by correlated envelopes was measured as a function of mismatch and pulse rate. Sensitivity decreased for increasing mismatch and increasing pulse rate. The experiments led to two conclusions. First, envelope correlation change discrimination necessitates place-of-stimulation matched inputs. However, it is unclear if previous experience with acoustic hearing is necessary for envelope correlation change discrimination. Second, NH listeners presented with CI simulations demonstrated better performance than real CI listeners. If the simulations are realistic representations of electrical stimuli, real CI listeners appear to have difficulty processing interaural information in modulated signals.
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I. INTRODUCTION

There is an increasing number of people who receive bilateral cochlear implants (CIs) and many gain the benefits of better sound localization and speech understanding in noise compared to those who receive a unilateral CI (e.g., Litovsky *et al.*, 2012). Presently, these benefits seem to be produced mostly by head shadow and better-ear listening (Loizou *et al.*, 2009). Ideally, for CI listeners to experience larger binaural benefits, it would necessitate the central neural computation and utilization of small differences in the signals between the ears. Normal-hearing (NH) listeners are incredibly sensitive to long-term interaural time differences (ITDs) (Brughera *et al.*, 2013), long-term interaural level differences (ILDs) (Yost and Dye, 1988), and short-term fluctuations in the ITDs and ILDs that comprise the interaural correlation (Goupell, 2012). However, bilateral CIs are not optimized to take full advantage of the exquisite neural binaural processing abilities that produces larger binaural benefits. For example, clinical CI processors are not bilaterally synchronized and do not encode low-frequency fine-structure. Low-frequency fine-structure ITDs (<1500 Hz) produce the largest binaural benefits in NH listeners (Wightman and Kistler, 1992), making this a major limitation for the devices. One purpose of this work was to investigate the sources of the binaural limitations in CI users through their sensitivity to changes in interaural correlation.

Interaural correlation is the statistical similarity of the signals between the two ears, often measured by the cross-correlation of the signals. Some research shows that interaural correlation change discrimination of 500-Hz narrowband noises are dominated by fluctuating ITDs (van der Heijden and Joris, 2009), which is reminiscent of the dominance of low-frequency static ITDs in sound localization (Wightman and Kistler, 1992). Other research suggests a role for ILD fluctuations in correlation change discrimination of low-frequency narrowband noises (Goupell and Hartmann, 2007; Davidson *et al.*, 2009). For higher-frequency narrowband noises (>1500 Hz), where there is little phase-locking that could provide salient fluctuating ITDs from the acoustic fine-structure, correlation change discrimination is likely mediated entirely by differences in the envelopes or the fluctuating ILDs (Goupell, 2012; Goupell and Litovsky, 2014).[1] Another purpose of this work was to further understand the basic neural processing of correlation changes that are mediated by fluctuating ILDs by measuring correlation change sensitivity in bilateral CI users who typically only receive envelope cues.

Since the fine-structure is not explicitly encoded in most present CI speech processing strategies, the interaural envelope correlation from the explicitly encoded envelopes and the fluctuating ILDs are likely the appropriate metrics related to a CI listener's sensitivity to changes in interaural correlation. Sensitivity to changes in interaural correlation is related to the binaural masking difference (BMLD) phenomenon (i.e., the decrease in thresholds for dichotic tones in noise compared to diotic tones in noise) (e.g., Goupell and

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Litovsky, 2014), which in turn is thought to be related to speech understanding in multi-talker environments, noise, or reverberation (Lavandier and Culling, 2010).

Bilateral CI users are sensitive to changes in interaural envelope correlation because they demonstrate positive BMLDs when stimuli are presented via direct stimulation at a single pitch-matched pair of electrodes (Long *et al.*, 2006; Van Deun *et al.*, 2009; Lu *et al.*, 2010). Goupell and Litovsky (2015) measured BMLDs [in this case, the BMLD equaled the diotic noise with an in-phase target tone (NoSo) threshold minus the diotic noise with an out-of-phase target tone (NoSπ) threshold] and envelope correlation change discrimination just noticeable differences (JNDs) in 11 late onset of deafness bilateral CI listeners using direct stimulation at a single pitch-matched pair of electrodes. The listeners from these studies demonstrated a large variability in sensitivity to interaural envelope correlation and some listeners showed little to no sensitivity (i.e., a BMLD = 0 dB). Goupell and Litovsky (2015) also compared the CI listeners' sensitivity to changes in interaural envelope correlation to those measured in acoustic CI simulations (i.e., a pulsatile vocoder that followed the envelopes of the signal) and found that on average CI listeners were worse than the NH listeners. Furthermore, Goupell and Litovsky (2015) showed that only a small number of listeners had NoSπ thresholds and envelope correlation change JNDs within the range of NH listeners presented the CI simulations. With such a large range in performance, it is difficult to determine the mechanisms that caused the relatively poor performance of the CI listeners.

There are many sources of signal and neural degradation that could account for the relatively poorer performance of the CI listeners compared to the NH listeners presented a CI simulation. Although pitch-matched pairs of electrodes were used in the previously mentioned direct-stimulation experiments, the exact place-of-stimulation may be slightly different. For monopolar electrical stimulation that produces a large spread of current in the cochlea, place-of-stimulation mismatches greater than approximately 3 mm cause a substantial increase in static ITD and ILD JNDs (Long *et al.*, 2003; Poon *et al.*, 2009; Goupell *et al.*, 2013b; Kan *et al.*, 2013). It is unclear what the effect of the mismatch would be for detecting envelope correlation changes because all previous studies investigating mismatch in humans have used static interaural differences, not the dynamic ILDs that occur when there is envelope decorrelation. It may be that dynamic interaural differences are much less resistant to interaural mismatch, which may partially explain the relatively poor performance of the CI listeners.

Another factor that could potentially affect performance is that the stimuli were not centered in the head. It is generally assumed that stimuli that are centered in the head provide the best binaural sensitivity (Yost, 1974; Yost and Dye, 1988; Koehnke *et al.*, 1995). However, this may not be the case because there are no experiments using bilateral CI listeners that have yet directly demonstrated that centering improves binaural sensitivity.

Yet another factor to consider is the previous acoustic experience of the CI users, which is related to the age of onset and duration of deafness, as well as the amount of binaural hearing experience. In contrast to most late onset of deafness CI users, people who have an early onset of deafness who receive CIs as adults (Litovsky *et al.*, 2010) or children (Salloum *et al.*, 2010) for the most part do not show ITD sensitivity even with highly controlled stimulus presentation through direct stimulation. Therefore, achieving sensitivity to interaural envelope correlation changes might necessitate a period of typical binaural acoustic input and neural development.

In this study, three experiments were performed to investigate the mechanisms underlying interaural envelope correlation change sensitivity as well as factors that may be limiting envelope correlation change performance in CI listeners. These experiments were conducted by using direct stimulation at single pairs of electrodes.

II. HYPOTHESES

Figure 1 shows a series of predictions concerning static ITD, static ILD, and envelope correlation change discrimination in CI and NH listeners. Since CI listeners can have different onsets of deafness, two broad categories of listeners will be discussed, early and late onset of deafness. In the case of late onset of deafness, it is assumed that the binaural system has developed properly and that binaural neural computations can be performed by the CI listeners similar to the NH listeners as long as place-of-stimulation matched stimuli are presented. While factors other than onset of deafness may play a role in overall binaural sensitivity (e.g., duration of deafness), it is assumed that these factors will simply shift the sensitivity vs place-of-stimulation matched (Δ) function higher or lower but not change the overall shape of the function relative to the NH listeners. In the case of early onset of deafness, it is assumed that the binaural system has undergone abnormal development and that these listeners will not perform well on binaural tasks because of abnormal encoding of the binaural cues at place-of-stimulation matched inputs. The assumptions concerning development of binaural system and age of onset of deafness are supported by

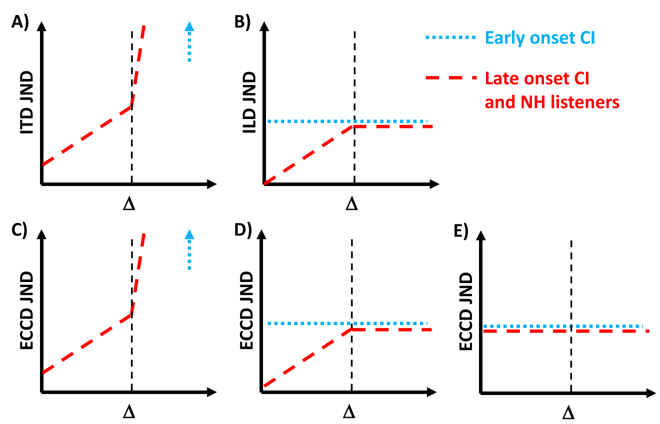

FIG. 1. (Color online) Hypotheses for (A) ITD just noticeable differences (JNDs), (B) ILD JNDs, and (C)–(E) envelope correlation change discrimination JNDs as a function of interaural mismatch (Δ). Performance for the early onset CI listeners are shown by the dotted line. Performance for the late onset CI and NH listeners are shown by the dashed line.

previous research showing ITD sensitivity for late but not early onset CI listeners (Litovsky *et al.*, 2010; Salloum *et al.*, 2010).

Figure 1(A) shows predictions for ITD sensitivity for the three groups of listeners. It is assumed that ITD sensitivity necessitates place-of-stimulation matched inputs (Jeffress, 1948; Colburn, 1973). For the late onset CI listeners, as inputs become mismatched, shown by increasing Δ in Fig. 1(A), ITD JNDs increase. This prediction is supported by previous ITD sensitivity measurements in simulated and real CI listeners (Goupell *et al.*, 2013b; Kan *et al.*, 2013). When inputs becomes mismatched to some critical point where there is an insufficient number of place-of-stimulation matched neurons encoding the stimuli (shown by the vertical dashed line), the NH and late onset CI listeners cannot perform the task. For the early onset CI listeners, they cannot discriminate ITDs for any value of Δ because of the abnormal development of the requisite binaural neural structures (Litovsky *et al.*, 2010; Salloum *et al.*, 2010).

Figure 1(B) shows predictions for static ILD discrimination. It is assumed that ILD discrimination is best for place-of-stimulation matched inputs and JNDs increase with increasing mismatch. However, ILD discrimination can also be performed without place-of-stimulation matched inputs by monitoring the absolute level in a single ear, even in the presence of overall level roving to limit the ability of monaural level cues. Therefore for the NH and late onset CI listeners, the ILD JNDs increase with increasing Δ but plateau where there is an insufficient number of place-of-stimulation matched neurons encoding the stimuli. These predications are supported by previous ILD sensitivity measurements in simulated and real CI listeners (Goupell *et al.*, 2013b; Kan *et al.*, 2013). For the early onset CI listeners, it is assumed that they must rely on the monaural level cues to perform the task and demonstrate no benefit for place-of-stimulation matched inputs. Therefore, early onset CI listeners' ILD JNDs do not change with Δ and their JND has the same value as that for the NH and late onset CI listeners for large values of Δ.

Of concern in this study is whether envelope correlation change discrimination requires place-of-stimulation matched inputs and how performance changes with mismatch. If envelope correlation change discrimination requires place-of-stimulation matched inputs, the envelope correlation change JNDs in Fig. 1(C) should follow the same overall pattern as the ITD JNDs as a function of Δ in Fig. 1(A). If envelope correlation change discrimination is facilitated by place-of-stimulation matched inputs but it is not necessary, the envelope correlation change JNDs in Fig. 1(D) should follow the same pattern as the ILD JNDs in Fig. 1(B). If envelope correlation change discrimination does not require place-of-stimulation matched inputs, then the NH, late onset CI, and early onset CI listeners should all demonstrate envelope correlation change JNDs that are independent of Δ, which is shown in Fig. 1(E). While the latter two predictions are possible, interaurally decorrelated stimuli have no long-term overall level differences, and it is thought that neural computation of interaural decorrelation occurs in the binaural pathways; therefore, the first prediction is the most plausible.

III. EXPERIMENT I: ENVELOPE CORRELATION DISCRIMINATION AS A FUNCTION OF MISMATCH

In experiment 1, interaural envelope correlation change discrimination sensitivity was measured as a function of interaural place-of-stimulation mismatch.

A. Listeners and equipment

CI and NH listeners participated in this experiment. The 11 CI listeners used Nucleus 24-electrode arrays (Nucleus24, Freedom, or N5). They were between the ages of 27 and 80 years old. Eight of the CI listeners were postlingually deafened (late onset of deafness) and three were prelingually deafened (early onset of deafness). Listener codes that are all capital letters denote the late onset CI listeners (e.g., CAB) and codes that have an initial capital letter denote the early onset CI listeners (e.g., Cau). The demographic information and hearing histories of the listeners are presented in Table I. These types of CIs have approximately 0.75-mm center-to-center electrode spacing. The intracochlear electrodes are numbered such that the most apical electrode is 22 and the most basal is 1, and there are two extra-cochlear electrodes. These CIs have a range of 0 to 255 clinical current units (CUs) and the CUs produce logarithmically spaced changes in μA. The CI listeners removed their clinical processors for testing and were presented stimuli via direct stimulation using a pair of bilaterally synchronized L34 processors controlled by the Nucleus Implant Communicator (NIC), which were provided by Cochlear Ltd. (Sydney, Australia). The NIC was controlled by a personal computer running MATLAB (Mathworks, Natick, MA).

Seven of eight NH listeners (ages 20–34 years old) had normal audiometric hearing [thresholds $\leq$ 20 dB hearing level (HL)] at octave frequencies between 250 and 8000 Hz, and the asymmetry of the hearing thresholds were $\leq$ 10 dB in magnitude at each frequency. The one exception was listener SZM who had a mild-hearing loss at 4 kHz (25-dB HL in left ear) and at 8 kHz (30-dB HL in right ear), and had a 20-dB asymmetry at 8 kHz. The NH listeners were presented stimuli that were generated on a personal computer running MATLAB. The stimuli were delivered by a Tucker-Davis Technologies System 3 (RP2.1, PA5, HB7; FL) and a pair of insert earphones (ER2; Etomotyic, Elk Grove Village, IL). These earphones have a flat frequency response out to approximately 16 kHz, which was advantageous for acoustic CI simulations that present stimuli at those high frequencies.

B. Stimuli

Stimuli were delivered as electrical pulse trains for the CI listeners and acoustic pulse trains for the NH listeners. The stimuli started as narrowband Gaussian noises with a 500-Hz center frequency (CF) and 50-Hz bandwidth (BW). They were the same reproducible stimuli as used in previous studies (Goupell, 2012; Goupell and Litovsky, 2014, 2015).

TABLE I. CI listener code, age, age of onset of deafness, duration of CI experience, and the pairs determined to be pitch-matched electrodes (PMEs). Listener codes that contain all capital letters denote late onset CI listeners; codes that contain only initial capitalization denote early onset CI listeners.

Listener	Age (years)	Age Onset of Deafness (years)	CI Experience (years)		PMEs	
			Left	Right	Left	Right
CAB	66	15	17	10	12	14
CAC	80	75	8	6	12	13
CAD	73	62	9	3	12	13
CAE	62	51	6	8	12	14
CAF	59	54	13	8	4	3
CAG	62	32	11	8	12	13
CAH	59	43	5	9	12	12
CAQ	55	44	5	4	8	10
Cau	52	1	11	10	12	6
Cav	27	0	8	4	10	12
Caw	50	0	4	1	9	12

The noises were 500 ms in duration and temporally shaped by a Tukey window with a rise-fall time of 10 ms. Next, the Hilbert envelope was extracted from each channel of the unprocessed analog narrowband noises using the hilbert() function in MATLAB, but no additional low-pass filtering was applied to the envelopes. The electrical and acoustical pulse train stimuli were generated by sampling these envelopes with equal peak-amplitude pulses.

The waveform correlation ρ is used rather than the envelope correlation when discussing the stimuli, procedure, and JNDs as was done in previous studies (Goupell, 2012; Goupell and Litovsky, 2014, 2015). This is because the values of the envelope correlation varies between stimuli for a fixed value of ρ when $\rho \neq 0$. It is also difficult to compare the envelope correlation values between the NH and CI listeners because of the small dynamic range and compression function used on the electrical stimuli (Goupell and Litovsky, 2015).

1. Electrical pulse trains

Individual electrical pulses were biphasic with a 25-μs pulse duration and a 8-μs gap between anodic and cathodic phases of the pulse. The pulses were presented in monopolar configuration, meaning that the ground electrode was extracochlear, and there was a large current spread (Nelson *et al.*, 2008). For the electrical pulse trains, the envelopes were sampled at equal intervals using a 1000 pulse-per-second (pps) pulse train. To do this, the analog amplitudes were compressed, quantized, and placed on a clinical CU scale. The envelopes were compressed using an approximation of the compression function used by Cochlear-type speech processors that has been performed in previous studies (Long *et al.*, 2006; Van Deun *et al.*, 2009; Lu *et al.*, 2010; Goupell and Litovsky, 2015). The electrical amplitudes (A_{El}) of the individual pulses were determined by the equation

$$A_{\mathrm{El}} = \begin{cases} \mathrm{round}\{[1-\exp(-5.09E_{\mathrm{Ac}})]\times(M-T)+T\}, & E_{\mathrm{Ac}} \geq \mathrm{Max}(E_{\mathrm{Ac}}) - 30\,\mathrm{dB} \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where E_{Ac} is the instantaneous normalized analog envelope, M is the maximum comfortable level in CUs, and T is the hearing threshold in CUs. The envelopes were presented on pairs of electrodes that were either matched in pitch, which was assumed to have the same place-of-stimulation, or intentionally place-of-stimulation mismatched. The amount of mismatch is denoted by the symbol Δ. The matched electrode pair (i.e., $\Delta = 0$) was typically in the middle of the electrode array (see Table I).[2] The stimuli were presented at electrode pairs that had $\Delta = 0$, 2, 4, and 8 electrodes, where the electrode in the right ear was shifted in the basal direction.

2. Acoustical pulse trains

The acoustical pulse trains were designed to simulate the electrical pulse trains by using band-limited pulses (Goupell, 2012; Goupell *et al.*, 2013b; Goupell and Litovsky, 2014). The individual pulses were composed of a carrier tone that was modulated by a Gaussian envelope. The carrier CFs depended on the amount of mismatch Δ, which was calculated by converting frequency to cochlear distance assuming a 35-mm cochlear length (Greenwood, 1990). Values of $\Delta = 0$, 1.5, 3, 6, and 9 mm were tested, which translates to mismatches of $\Delta = 0$, 2, 4, 8, or 12 electrodes, respectively. The pulses had a BW = 3 mm. The CFs and BWs of the pulse trains are shown in Table II.

The level of the 4-kHz CF pulse train was 65 dB(A). The higher CF pulse trains were normalized to have the same peak spectral amplitude to best control the spectral overlap for the mismatched conditions (Goupell *et al.*, 2013b). Because of the peak spectral amplitude normalization, the level of the pulse trains decreased with increasing CF. However, since the BW was constant in mm (i.e., the BW in Hz increased with CF, see Table II), the loudness remained similar across CF.

The narrowband noise envelopes were extracted by using the Hilbert envelope, which was temporally sampled at a rate of 500 pps. The rationale for not choosing a 1000-pps pulse rate, the rate presented to the CI listeners, was that (1) a lower rate was required to maintain a modulation depth > 99% for all conditions (of concern was to not decrease the BW of the acoustic stimuli and change the amount of spectral overlap as Δ was varied) and (2) envelope correlation change discrimination performance is unaffected by pulse rate in NH listeners (Goupell, 2012). After the amplitude of the individual pulses in the trains were modulated by the envelopes, the pulses were summed into modulated acoustic pulse trains.

TABLE II. Center frequencies and bandwidths for acoustic stimuli presented to the NH listeners. Values are reported in both mm and Hz for the left and right ears.

	Center frequency (mm)		Center frequency (Hz)		Bandwidth (mm)		Bandwidth (Hz)	
Δ (mm)	Left	Right	Left	Right	Left	Right	Left	Right
0	23.32	23.32	4000	4000	3	3	1731	1731
1.5	23.32	24.82	4000	4955	3	3	1731	2129
3	23.32	26.32	4000	6129	3	3	1731	2619
6	23.32	29.32	4000	9351	3	3	1731	3964
9	23.32	32.32	4000	14229	3	3	1731	6000

Last, the acoustic stimuli were presented in the presence of a low-frequency masking noise to mask any low-frequency distortion products that might be advantageous to perform this task. The noise had two cutoff frequencies: the first cutoff was at 200 Hz where the attenuation was 3 dB/octave and the second was at 1000 Hz where the attenuation was 18 dB/octave (Klein-Hennig *et al.*, 2011). A Tukey window was applied to the noise with a rise/fall time of 10 ms. The noise onset and offset was 250 ms before and after the test stimulus, respectively. The presentation level was 61.1 dB(A), which equates to a 30-dB spectrum level.

C. Procedure

The procedures generally follow those commonly used in experiments with bilateral CI listeners (Litovsky *et al.*, 2012). Procedures for measuring envelope correlation change discrimination JNDs were similar to those used in several recent experiments (Goupell, 2012; Goupell and Litovsky, 2014, 2015).

1. CI loudness mapping

The T, comfortable (C), and M levels for each of the electrodes in both ears were used to determine loudness maps. CI listeners reported the perceived loudness of a pulse train with the CUs varied incrementally, while ensuring comfortable levels at all times.

2. CI pitch matching

A direct left-right pitch comparison was performed in the CI listeners. The electrode in the left ear was fixed. The corresponding number-matched electrode in the other ear, the adjacent electrodes (±1 electrode), and the next adjacent electrodes (±2 electrodes) were chosen for the direct pitch comparison. For listeners who had a poorer ability to discriminate place pitch, the range was doubled so that electrodes ±2 and ±4 from the estimated pitch-matched pair were tested. Listeners were presented 1000-pps, 500-ms constant-amplitude pulse trains at C level in the left ear then in the right ear with a 300-ms inter-stimulus interval. The task of the listener was to indicate whether the stimulus in the right ear was "Much Lower," "Lower," "The Same," "Higher," or "Much Higher" in pitch than the stimulus in the left ear. Listeners were given the option to repeat the stimulus to make their subjective judgment. At least 20 trials were presented for each combination of electrodes. The responses for the electrode pairs were converted to numerical scores where "Much Lower" was −2, "Lower" was −1, "The Same" was 0, "Higher" was +1, and "Much Higher" was +2. The sum of the responses was calculated, which was called μ. The final pitch-matched electrode pair was the pair in which μ was closest to zero. If this method did not yield a definitive pitch-matched electrode pair (i.e., μ was equally close to zero for a number of electrode pairs or there was a non-monotonic change in μ over the range of electrodes), the combination closest in electrode number was chosen. The pitch-matched electrode pair for each CI listener is shown in Table I.

3. CI psychophysical procedure

JND measurements for the CI listeners followed the procedure used in Goupell and Litovsky (2015). The listener initiated each trial by pressing a button. Four intervals were played and each interval contained a different noise token. The inter-interval duration was 250 ms. The non-target stimuli had a correlation of $\rho_{ref} = 1$ or 0, depending on the condition. The first and fourth intervals always contained non-target stimuli. The second and third interval contained a non-target stimulus and a target stimulus; the interval with the target was chosen randomly. The listener was instructed to choose the second or third interval that contained the different stimulus. Correct answer feedback was provided after each trial.

A method of constant stimuli was used where the target correlation and Δ were randomized. The target stimuli had a change in correlation from the reference. Various levels of decorrelation were achieved by orthogonalization of the noises (Culling *et al.*, 2001) and precisely controlling the target correlation on a scale of $\alpha = \sqrt{1-\rho^2}$ with 0.05-α steps (Goupell, 2010), where α represents the dissimilarity between two noises rather than the similarity or correlation ρ. The α levels depended on the sensitivity of the listener. The amount of mismatch was varied from trial-to-trial where $\Delta = 0$, 2, 4, or 8 electrodes. Three-point (or more) psychometric functions with at least 40 trials per point were determined. The JND was calculated as PC = 70.7% using a maximum-likelihood fit (Wichmann and Hill, 2001). In conditions where PC = 70.7% was not achieved, the JND was set to a value of $\Delta\alpha = 1.1$.

JNDs were first measured with perfectly correlated reference stimuli ($\rho_{ref} = 1$). Then JNDs were measured with uncorrelated reference stimuli ($\rho_{ref} = 0$). Only 7 of the 11 CI listeners were tested on the $\rho_{ref} = 0$ conditions because of lack of time or lack of sensitivity to envelope correlation as measured in the $\rho_{ref} = 1$ stimuli. Before testing, a period of training for the easiest condition, $\Delta = 0$ and $\rho_{ref} = 1$, was performed until performance saturated, which typically lasted for about 1–2 h.

4. NH psychophysical procedure

JND measurements for the NH listeners followed the procedure used in Goupell (2012). The four-interval, two-alternative forced choice task that was used for the CI listeners was also used for the NH listeners. However, a two-down, one-up adaptive staircase procedure was used to measure JNDs. The rationale to use the quicker adaptive procedure for the NH listeners was that they in general had better sensitivity to changes in envelope correlation, likely always had monotonic psychometric functions, and performed more conditions than the CI listeners. The initial target value was perfectly uncorrelated ($\rho = 0$) for a correlated reference ($\rho_{ref} = 1$), and perfectly correlated ($\rho = 1$) for an uncorrelated reference ($\rho_{ref} = 0$). The step size was $\alpha = \sqrt{1 - \rho^2} = 0.4$ until the first turnaround, 0.2 until the second, 0.1 until the third, and 0.05 for the rest of the staircase. If listeners could not detect the change in correlation (i.e., had four incorrect answers at the easiest possible testing level), the run was stopped and the JND was recorded as "Not Determinable." As with the CI listeners, an immeasurable JND was given a numerical value of $\Delta\alpha = 1.1$ for that condition when the data were analyzed. Ten reversals were measured for each staircase. The last six reversals were averaged to calculate the JND for a run, which targets a PC = 70.7% (Levitt, 1971). Three simultaneous staircases were performed per condition and the average JND over the three runs was recorded.

JNDs were first measured with perfectly correlated reference stimuli ($\rho_{ref} = 1$). The order of testing was randomized across listeners. Additional control conditions where the CF was increased in both ears (i.e., matched carriers) were included. There were nine conditions tested in this portion of the experiment (mismatched conditions with $\Delta = 0$, 1.5, 3, 6, and 9 mm and matched conditions for CFs associated with $\Delta = 1.5$, 3, 6, and 9 mm).

Then JNDs were measured with uncorrelated reference stimuli ($\rho_{ref} = 0$), which included conditions with mismatches of $\Delta = 0$, 1.5, 3, 6, and 9 mm. The control conditions with the matched carriers as a function of CF were not tested for the $\rho_{ref} = 0$ conditions.

As with the CI listeners, before testing, a period of training with the easiest condition, $\Delta = 0$ and $\rho_{ref} = 1$, was performed until performance saturated, which typically lasted 1–2 h. However, unlike the CI listeners, the NH listeners who could not perform the task for the easiest condition were omitted from the study. Issues related to the differences between the CI and NH testing methodology are discussed in Sec. V B.

After completion of this study, it was determined that the optimal acoustic simulation of monopolar stimulation might have utilized a BW = 1.5 mm (Goupell *et al.*, 2013b; Kan *et al.*, 2013). Therefore, extra conditions were tested that compared the JNDs for $\Delta = 0$ using $\rho_{ref} = 1$ and 0 and BW = 3 and 1.5 mm. Four listeners were the same as in the main NH experiment and four were new listeners (age range of 20–34 years old for the group).

D. Results

JNDs increased with increasing mismatch Δ at the same rate for both the CI and NH listeners, and there was no effect of CF of the matched acoustic pulse trains for the NH listeners. There was substantial inter-individual variability, but CI listeners were on average worse at this task than NH listeners. JNDs for $\rho_{ref} = 0$ conditions were worse than $\rho_{ref} = 1$ conditions. JNDs for $\rho_{ref} = 1$ conditions were measurable for 8 of 11 CI listeners and all the NH listeners; JNDs for $\rho_{ref} = 0$ conditions were measurable for four of seven CI listeners and all the NH listeners.

Figure 2 shows the individual $\rho_{ref} = 1$ JNDs for the experiment, the top row showing JNDs for the CI listeners and the bottom row showing JNDs for the NH listeners. The left column shows the JNDs and the right column shows the normalized JNDs, which was done by subtracting the $\Delta = 0$ JND for each listener. The data were highly variable for both groups. In general, JNDs increased with increasing Δ. Three CI listeners (CAQ, Cau, and Caw) could not perform the task for any condition, including the easiest condition $\Delta = 0$. Two of these CI listeners had an early onset of deafness. Interestingly, early onset CI listener Cav could perform the task and had JNDs near the average JNDs for the CI group. Of the eight remaining listeners, two (CAC and CAH) could not perform the task for $\Delta = 4$ electrodes or 3 mm. In contrast, all of the NH listeners could perform the task for $\Delta = 3$ mm (889 Hz). Many listeners could not perform the task for $\Delta > 4$ electrodes or 3 mm. Three NH listeners (SDL, SDS, and SZZ) could still perform the task with largest amount of mismatch tested, $\Delta = 9$ mm (4270 Hz).

Figure 3 shows the average $\rho_{ref} = 1$ JNDs of the CI and NH listeners for comparison, as well as the control condition (changing CF in both ears, i.e., matched carriers) that was performed by only the NH listeners. Note that the averages for the CI listeners omit the three listeners who could not perform the task for any condition. Data were analyzed using a two-way analysis of variance (ANOVA) with factors Δ and listener type (CI vs NH). JNDs increased with increasing Δ [main effect Δ: $F(4,63) = 11.4$, $p < 0.0001$, $\eta^2_p = 0.42$]. Subsequent Tukey Honestly-Significantly-Difference *post hoc* tests ($p < 0.05$) showed $\Delta = 0$ electrodes was different from $\Delta = 8$ and 12 electrodes, $\Delta = 2$ electrodes was different from $\Delta = 8$ and 12 electrodes, and the other comparisons were not significantly different. Comparing the average JNDs for the CI and NH listeners, the NH listeners had lower JNDs by approximately $\Delta\alpha = 0.2$ [main effect listener type: $F(1,63) = 16.8$, $p = 0.0001$, $\eta^2_p = 0.21$]. The two groups demonstrated the same increase in JND as Δ increased (seen best in the normalized JNDs) [interaction $\Delta \times$ listener type: $F(3,63) = 0.05$, $p = 0.99$, $\eta^2_p = 0.002$].

Comparing the mismatched and matched JNDs for the NH listeners, the data were analyzed with a two-way

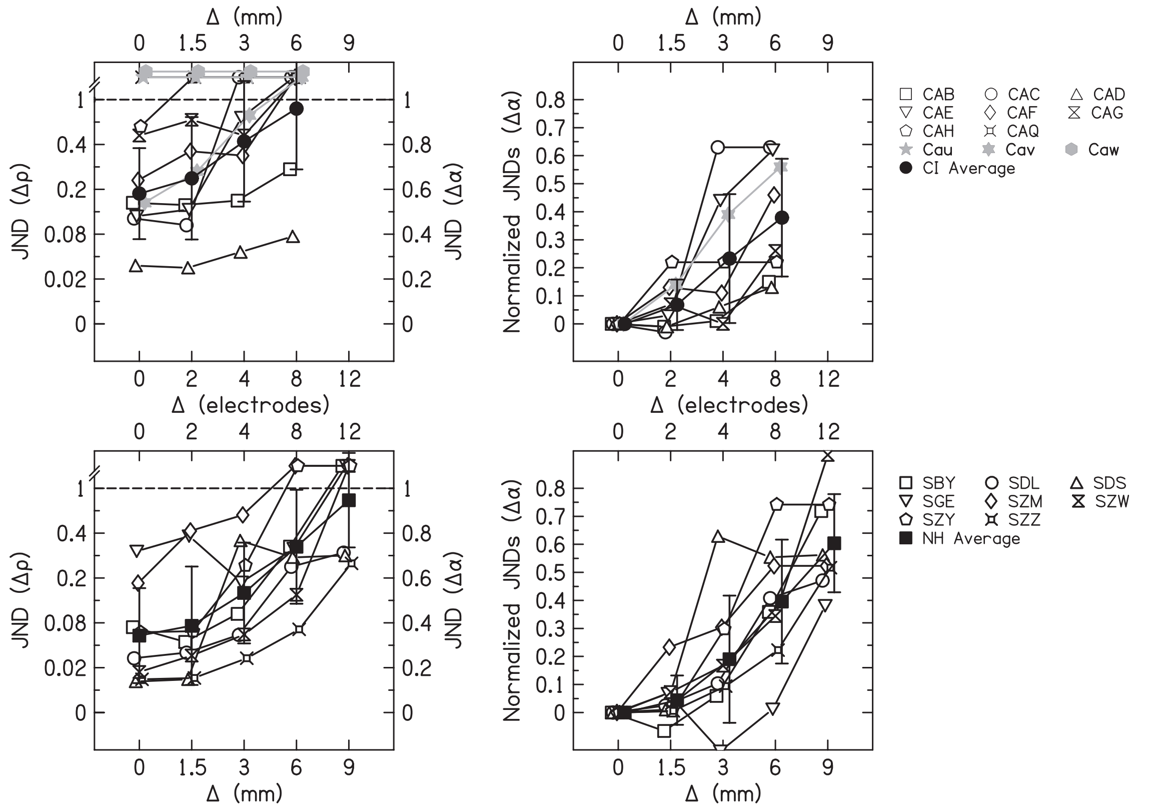

FIG. 2. Individual listener and average $\rho_{ref} = 1$ JNDs as a function of interaural mismatch Δ. The top row shows JNDs for the CI listeners. The bottom row shows JNDs for the NH listeners. The left column shows the JNDs and the right column shows the JNDs after normalization by subtracting the $\Delta = 0$ JND for each listener. Open symbols show the individual JNDs for the late onset CI listeners. The closed symbols show the individual JNDs for the early onset CI listeners. Immeasurable JNDs are set to a value of 1.1. The closed black symbols represent the arithmetic mean for the listeners who had determinable JNDs for $\Delta = 0$. The error bars represent ± 1 standard deviation of the mean.

repeated-measures ANOVA with factors Δ and type (matched vs mismatched). JNDs were lower for the matched conditions compared to the mismatched conditions [main effect type: $F(1,7) = 24.6$, $p = 0.002$, $\eta^2_p = 0.78$]. JNDs increased as Δ increased for the mismatched conditions [main effect Δ: $F(4,28) = 19.7$, $p < 0.0001$, $\eta^2_p = 0.74$], but JNDs did not change as CF is increased for the matched conditions, which produced a significant interaction [$\Delta \times$ type: $F(4,28) = 15.0$, $p < 0.0001$, $\eta^2_p = 0.68$].

Figure 4 shows the $\rho_{ref} = 1$ and 0 JNDs for CI and NH listeners, as well as JNDs where the BW of the acoustic pulse trains was 1.5 or 3 mm for the NH listeners. The average data for the $\rho_{ref} = 1$ conditions for the CI listeners in Fig. 4 differs from the averages in Figs. 2 and 3 because it includes only the seven CI listeners that performed the $\rho_{ref} = 0$ conditions. Of the seven CI listeners that could perform the task for $\rho_{ref} = 1$ at $\Delta = 0$, only four CI listeners could do so for $\rho_{ref} = 0$ at $\Delta = 0$. In contrast, all of the NH listeners could perform the task for $\rho_{ref} = 1$ and 0 for at least one value of Δ. The data were analyzed with a three-way ANOVA with factors Δ, listener type, and reference. As before, JNDs increased with increasing Δ [main effect Δ: $F(4,118) = 15.4$, $p < 0.0001$, $\eta^2_p = 0.34$]. JNDs were higher for the CI listeners compared to the NH listeners [main effect listener type: $F(1,118) = 32.8$, $p < 0.0001$, $\eta^2_p = 0.22$]. JNDs for the $\rho_{ref} = 0$ conditions were higher than JNDs for the $\rho_{ref} = 1$ conditions [main effect reference: $F(1,118) = 11.1$, $p = 0.001$, $\eta^2_p = 0.09$]. None of the interactions were significant ($p > 0.05$ for all).

A two-way repeated-measures ANOVA with factors BW and reference was used to compare the JNDs for the two different BWs for the NH listeners in Fig. 4. There was no change in the JNDs as the BW decreased from 3 to 1.5 mm [main effect BW: $F(1,7) = 5.4$, $p = 0.053$, $\eta^2_p = 0.44$]. The average JNDs increased by $\Delta\alpha = 0.032$ for the $\rho_{ref} = 1$ and $\Delta\alpha = 0.073$ for the $\rho_{ref} = 0$ conditions. The $\rho_{ref} = 0$ conditions were significantly higher than the $\rho_{ref} = 1$ conditions [$F(1,7) = 7.3$, $p = 0.031$, $\eta^2_p = 0.51$]. The interaction BW × reference was not significant [$F(1,7) = 0.42$, $p = 0.54$, $\eta^2_p = 0.06$].

E. Discussion

This experiment showed that interaural place-of-stimulation mismatch was detrimental to envelope correlation change discrimination performance. As the mismatch Δ was artificially imposed from a pitch-matched pair of electrodes in the CI listeners, JNDs increased. Likewise, as the mismatch Δ was artificially imposed on the CF in the NH listeners, JNDs increased in a similar manner to the CI listeners (Figs. 2, 3, and 4). The effect of Δ on the JNDs held for both $\rho_{ref} = 1$ and 0 conditions. Similar to previous studies (e.g., Goupell, 2012; Goupell and Litovsky, 2014, 2015), JNDs for

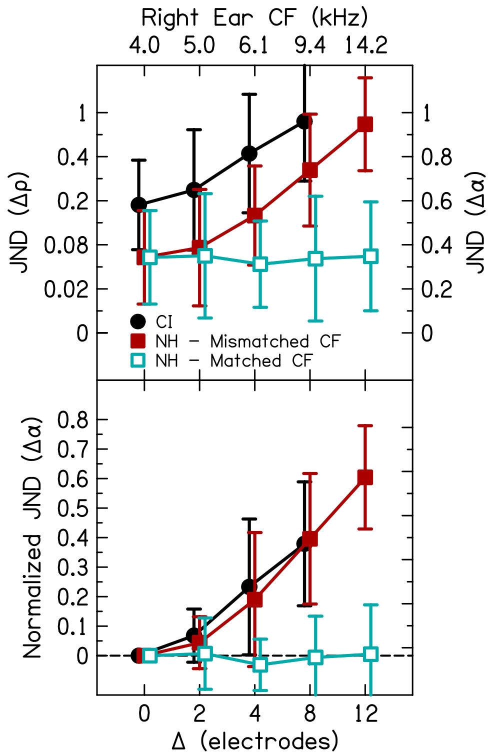

FIG. 3. (Color online) Average JNDs as a function of Δ for the CI listeners (closed circles) and NH listeners (closed squares). The control conditions where the CF was matched across ears for the NH listeners is also shown (open squares). The top panel shows the JNDs and the bottom panel shows the normalized JNDs. The symbols represent the arithmetic mean for the listeners who had determinable JNDs for $\Delta = 0$. The error bars represent ± 1 standard deviation of the mean.

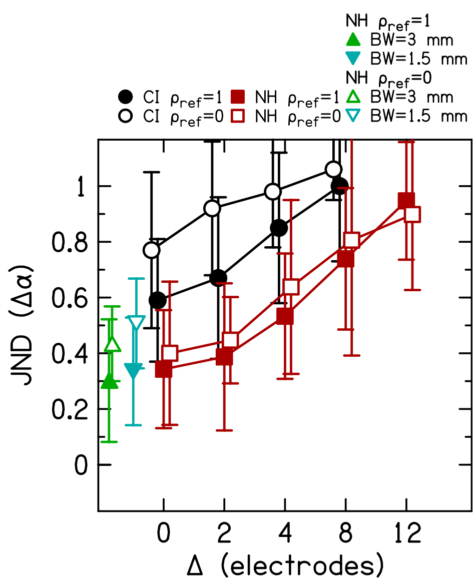

FIG. 4. (Color online) Average JNDs as a function of Δ for the CI listeners (circles) and NH listeners (squares and triangles). The $\rho_{ref} = 1$ JNDs are shown by closed symbols. The $\rho_{ref} = 0$ JNDs are shown by open symbols. Triangles show $\rho_{ref} = 1$ and 0 JNDs for $\Delta = 0$ for pulse trains that had a BW of 3 mm (upward pointing) or 1.5 mm (downward pointing). The symbols represent the arithmetic mean for the listeners who had determinable $\rho_{ref} = 1$ JNDs for $\Delta = 0$. The error bars represent ± 1 standard deviation of the mean.

$\rho_{ref} = 0$ conditions were higher than JNDs for $\rho_{ref} = 1$ conditions (Fig. 4).

Of the hypotheses depicted in Fig. 1, it appears that envelope correlation change discrimination sensitivity best follows the first hypothesis [Fig. 1(C)] where place-of-stimulation matched inputs are necessary to compute interaural envelope correlation. Three CI listeners (one late and two early onset) were not sensitive to changes in interaural envelope correlation. The two early onset CI listeners were predicted to not be sensitive to envelope correlation change [Fig. 1(C)], because they were assumed to have an abnormal development of the binaural circuitry necessary to perform the neural computation. A parsimonious explanation for the lack of sensitivity in the late onset CI listener is that other factors contributed to increasing the JNDs beyond the point in which this listener could perform the task. However, one of the three early onset CI listeners, Cav, was sensitive to interaural envelope correlation changes. This result is contrary to the hypothesis depicted in Fig. 1(C). This result could argue against the need for acoustic experience and normal development of binaural circuitry to detect changes in interaural envelope correlation, as has been demonstrated for detecting static ITDs (Litovsky *et al.*, 2010; Salloum *et al.*, 2010). Given the availability of the dynamic ILDs in the decorrelated stimuli, it is possible that listener Cav utilized these cues despite the assumed abnormal binaural system development. However, if this is the case, one would expect no change in sensitivity as a function of place-of-stimulation mismatch Δ, as predicted for the early onset CI listeners in Fig. 1(D). Another explanation for the performance of the early onset CI listener Cav is that, although he was deafened very early in life, he may have had enough hearing at birth to develop functional binaural circuits. If this were the case, he should be sensitive to static ITDs and this idea was explored in experiment 3. Clearly, a larger number of early onset CI listeners are needed to better interpret the results.

These results concerning mismatch and the interaural envelope correlation change sensitivity can be compared to the sensitivity to static ITDs and ILDs in the NH listeners. Static ITD and ILD discrimination was tested using 1.5- and 3-mm BW pulse trains in NH listeners (Goupell *et al.*, 2013b). They showed that JNDs increased with increasing Δ, a result that is also demonstrated by NH listeners in this study. In that study, $\Delta > 3$ mm was necessary to show a significant increase in JNDs, as was also shown in this study. In that study for $\Delta \geq 6$ mm, ITD JNDs continued to increase for the 3-mm pulse trains and increased sharply for the 1.5-mm pulse trains; 25 of 120 JNDs were immeasurable for $\Delta \geq 6$ mm. This indicates that place-of-stimulation matched inputs are necessary to compute ITDs, consistent with the hypotheses in Fig. 1(A). In contrast, ILDs JNDs plateaued for $\Delta \geq 6$ mm. The plateau in the JNDs is likely because the listeners were using monaural loudness cues to perform the task, consistent with the hypothesis in Fig. 1(B). Therefore, the interaural envelope correlation change discrimination JNDs in this study seem more similar to the ITD JNDs because there were many immeasurable JNDs for the NH listeners at all values of Δ. Specifically, there were immeasurable JNDs for 7 of 112 $\rho_{ref} = 1$ measurements and 14 of 40 $\rho_{ref} = 0$ measurements.

ITD and ILD JNDs were calculated from lateralization data collected from CI listeners in Kan *et al.* (2013). Again, JNDs increased with increasing Δ, a result that is also demonstrated by CI listeners in this study. In that study, normalized ITD JNDs increased more than ILD JNDs and there were many immeasurable ITD JNDs for large values of Δ. Similarly, 21 of 44 $\rho_{ref} = 1$ JNDs and 25 of 36 $\rho_{ref} = 0$ JNDs were immeasurable for the CI listeners in this study. Therefore, not only were CI listeners worse at detecting changes in envelope correlation than NH listeners, they had a much higher prevalence of not being able to perform the task at all.

In this study, control conditions were performed in the NH listeners to verify that the increase in JND as Δ increased was not an effect of CF. This was done by using matched carriers for CFs from 4 to 14.2 kHz. Figure 3 shows that JNDs were constant as a function of CF if the carriers were matched, verifying that the increase in JNDs as Δ increased was produced by a lack of place-of-stimulation matched inputs, rather than place-of-stimulation (i.e., CF). Another important feature of these data is that for real or simulated monopolar stimulation, binaural sensitivity is constant as a function of CF if the BW is constant in mm. Envelope correlation change JNDs increase as CF increases if the BW is held constant in Hz (Goupell and Litovsky, 2014).

The effect of BW of the acoustical pulses was also investigated in the NH listeners because the difference between the CI and NH listeners could have been a result of a poor choice in the acoustic CI simulation. Previous studies have found good correspondence between CI and NH listeners for three different types of binaural tasks if 1.5-mm BW Gaussian pulse trains are used to simulate monopolar stimulation (Goupell *et al.*, 2013b; Kan *et al.*, 2013). There was a small and insignificant increase in JNDs ($\Delta\alpha < 0.1$) as the BW was decreased from 3 to 1.5 mm, similar to that found in Goupell and Litovsky (2014). This difference in the JNDs is small compared to the difference in JNDs between the CI and NH listeners, which was approximately $\Delta\alpha = 0.25$ higher for the CI listeners for the $\rho_{ref} = 1$ conditions. Therefore, it is unlikely that the difference between the CI and NH listener JNDs was simply a result of using a too large BW for the NH listeners. Note that only $\Delta = 0$ was tested for the two BWs. The effect of Δ for the 1.5-mm BW acoustic pulse trains may very well differ from the effect of Δ for the 3-mm BW (i.e., there could be a significant interaction between BW and Δ) because the amount of stimulation overlap would be very different as a function of Δ [see Fig. 2 in Goupell *et al.* (2013b)]. Because of the lack of significant interaction between Δ and group for the data in Figs. 2, 3, and 4, the data in this study argue that a 3-mm BW is an adequate simulation of monopolar stimulation. This result is in contrast to the conclusion of Kan *et al.* (2013), where the 1.5-mm BW simulations for the NH listeners produced data that was a better qualitative match to the data produced by the CI listeners. One way to resolve this discrepancy is that CI listeners are simply less sensitive to changes in interaural envelope correlation compared to NH listeners, and that a good CI simulation accounts for the relative change in sensitivity as a function of Δ rather than the absolute sensitivity. Goupell and Litovsky (2015) also suggested that CI listeners have overall poorer binaural sensitivity compared to NH listeners presented a CI simulation. If this is the case, the next step is to then determine the source of the poorer performance of the CI listeners compared to the NH listeners. Therefore, the next experiment investigates a source of lack of stimulus control that may have affected the CI and NH listeners differently. Namely, the effect of intracranial centering was investigated.

In summary, CI listeners presented with electrical pulse trains and NH listeners presented a CI simulation of acoustic bandlimited pulse trains could detect changes in interaural envelope correlation for interaurally matched place-of-stimulation stimuli. Sensitivity decreased as interaural place-of-stimulation mismatch was increased and mismatches of greater than 3 mm made the task difficult to impossible for many listeners. Most of the data support the interpretation that envelope correlation change sensitivity necessitates place-of-stimulation matched inputs and normal binaural development, as depicted in Fig. 1(C); however, data from one early onset CI listener question that interpretation. In general, CI listeners were worse at detecting changes in interaural envelope correlation compared to NH listeners. The source of this difference is unknown, but it was likely not a result of a poor CI simulation.

IV. EXPERIMENT II: THE EFFECT OF CENTERING ON ENVELOPE CORRELATION CHANGE DISCRIMINATION

Binaural sensitivity is best for acoustic stimuli that are intracranially centered (Yost, 1974; Yost and Dye, 1988; Koehnke *et al.*, 1995). This experiment was performed to investigate if centering can improve JNDs for the CI and NH listeners. CI listeners often have non-centered auditory images for approximately loudness-balanced stimulation across the ears (Goupell *et al.*, 2013a) and interaural mismatch systematically causes sound images to lateralize to the ear with more basal stimulation (Goupell *et al.*, 2013b; Kan *et al.*, 2013). Therefore, it is highly likely that many of the conditions in experiment 1 had non-centered stimuli and this may have impaired performance.

A. Method

For six CI listeners (CAC, CAD, CAE, CAF, CAG, and CAH), lateralization curves were measured as a function of ILD using the methods of Kan *et al.* (2013) to determine if there was a significant intracranial offset from the intracranial midline. Lateralization curves were measured for $\Delta = 0$, 2, 4, and 8 electrodes. The stimuli were 500-ms, 1000-pps constant-amplitude pulse trains presented at *C* level. The rationale to use *C* level was that it was an intermediate level between *T* and *M* that best corresponded to the average energy of the pulses presented to the listeners for the noise-envelope modulated pulse trains. The rationale for using constant-amplitude pulse trains depends on the interpretation of the data from experiment 1. If diotic modulated pulse trains are perceived as interaurally decorrelated for CI listeners, constant amplitude pulse trains would be more likely to produce a punctate auditory image, which in turn would produce more consistent response patterns. ILDs of $0, \pm 5$, ± 10, and ± 20 CUs were tested. The offset was calculated by determining the midline crossing from a cumulative Gaussian least-squares error fit to the data (Goupell *et al.*, 2013a). If there was a non-zero offset, the modulated stimulus was centered by reducing the *M* level by the offset calculated from the lateralization task. Then the $\rho_{ref} = 1$ JND for the envelope correlation change discrimination task was remeasured for that condition using the same methods of experiment 1.

For seven NH listeners (all had participated in experiment 1), explicitly centering each stimulus was not attempted. The reason for this is that previous attempts to center mismatched acoustic pulse trains showed very inconsistent results across listeners for several different types of centering tasks (Goupell *et al.*, 2013b). Therefore, a systematic approach was utilized where ILDs = 0, −3, −6, and −9 dB were imposed for $\Delta = 0$ and 3 mm conditions, which was more similar to the approach of other studies (e.g., Koehnke *et al.*, 1995). Therefore, eight conditions were tested in this experiment (4 ILDs × 2 Δs). The rationale to use negative ILDs is that + 3 mm of mismatch should cause the intracranial image to be moved toward the right ear (Goupell *et al.*, 2013b), which would then be compensated by the negative ILD. A $\Delta = 6$ mm could not be tested because not all NH listeners were able to perform the envelope correlation change discrimination task at $\Delta = 6$ mm. If centering improves envelope correlation change discrimination performance, the $\Delta = 3$ mm condition should have a non-monotonic relationship between the JND and ILD, with a minimum for the stimulus that was intracranially centered. Only $\rho_{ref} = 1$ JNDs were measured using the same methods of experiment 1.

B. Results and discussion

The results of this experiment were inconclusive in that centering for the CI listeners or a systematic attempt at changing the intracranial position for NH listeners did not significantly affect envelope correlation change discrimination JNDs. The offsets and remeasured JNDs for the CI listeners are shown in Table III. For the CI listeners, 20 of 24 conditions had non-zero offsets. Ten of the offsets were small (<5 CUs) and 10 were large (≥5 CUs). The magnitude of the largest offset was 10 CUs. After correcting for those offsets and remeasuring JNDs, the average change in $\Delta\alpha$ was small, only a 0.012 increase in the JND. The largest increase in $\Delta\alpha$ was 0.26 (CAG, $\Delta = 0$, ILD offset = −2 CU). The largest decrease in $\Delta\alpha$ was −0.31 (CAF, $\Delta = 2$, ILD offset = −3 CU). Therefore, large changes in the JNDs could occur when comparing the non-centered and centered conditions, but it was not consistent and produced almost no change on average.

For the NH listeners, the results are shown in Fig. 5. The data were analyzed using a two-way repeated-measures ANOVA with factors Δ and ILD. The assumption of sphericity was violated in the data set, so a Greenhouse-Geisser correction was used for the ANOVA results. Mismatched stimuli had significantly higher JNDs than matched [main effect of Δ: $F(1,6) = 7.7$, $p = 0.032$, $\eta^2_p = 0.56$]. There was no significant effect of ILD [main effect of ILD: $F(2.2,13.3) = 0.39$, $p = 0.70$, $\eta^2_p = 0.06$] and the interaction was not significant [Δ × ILD: $F(2.3,13.6) = 0.25$, $p = 0.81$, $\eta^2_p = 0.04$]. Therefore, even when testing a range of ILDs that may have centered the stimuli, there was no measurable change in JNDs for any condition.

TABLE III. Comparison of non-centered and centered JNDs for the CI listeners. ILD offsets are reported in CUs where a negative value is a bias to the left ear and a positive value is a bias to the right ear. The difference between centered and non-centered JNDs are reported in the right-most column. Immeasurable JNDs are set to a value of 1.1.

	Electrode				JNDs		
Listener	L	R	Δ	ILD Offset (CUs)	Non-centered	Centered	Difference
CAC	12	13	0	−10	0.47	0.56	0.09
	12	15	2	0	0.44	—	—
	12	17	4	2	1.1	1.1	0
	12	21	8	0	1.1	—	—
CAD	12	13	0	−3	0.26	0.27	0.01
	12	15	2	−6	0.25	0.34	0.09
	12	17	4	−7	0.32	0.32	0
	12	21	8	−8	0.39	0.41	0.02
CAE	12	14	0	−1	0.48	0.39	−0.09
	12	16	2	0	0.51	—	—
	12	18	4	−1	0.92	0.64	−0.28
	12	22	8	6	1.1	1.1	0
CAF	4	3	0	3	0.64	0.65	0.01
	4	5	2	3	0.77	0.46	−0.31
	4	7	4	0	0.75	—	—
	4	11	8	−9	1.1	1.1	0
CAG	12	13	0	−2	0.84	1.1	0.26
	12	15	2	1	0.91	0.88	−0.03
	12	17	4	5	0.84	0.99	0.15
	12	21	8	9	1.1	1.1	0
CAH	12	12	0	−7	0.88	1.1	0.22
	12	14	2	−7	1.1	1.1	0
	12	16	4	−4	1.1	1.1	0
	12	20	8	−3	1.1	1.1	0
						Average	0.012

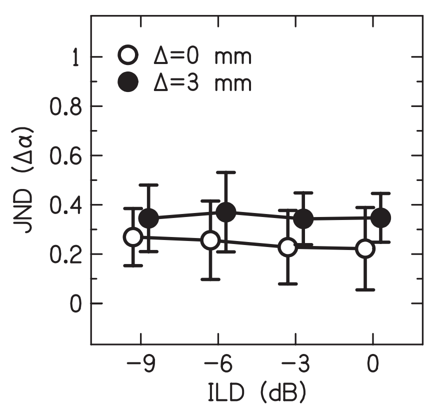

FIG. 5. Average JNDs as a function of ILD for $\Delta = 0$ mm (open circles) and 3 mm (closed circles) for the NH listeners. The symbols represent the arithmetic mean. The error bars represent ±1 standard deviation of the mean.

If centering improves JNDs for matched (in the CI listeners) and mismatched (both NH and CI listeners) stimuli, it was not observed in this experiment. There could be several reasons for the null result in both groups. One reason is that increasing interaural correlation change discrimination JNDs in NH and hearing-impaired listeners requires large ILDs, at least 12 or 24 dB (Koehnke *et al.*, 1995). The ILDs used in this experiment for both the CI and NH listeners may have been too small to see an effect. This result is consistent with the centering results from experiment 3 in Goupell *et al.* (2013b), where there was also no effect of centering on ITD and ILD discrimination for NH listeners.

Admittedly, it was unclear how effective the technique used to center the mismatched stimuli was for the NH listeners. Several techniques were attempted and listeners often had a difficult time with the tasks. The expectation was to observe improved JNDs for the NH listeners at approximately an ILD of −3 dB; this value was determined for the ILD that centered the $\Delta = 3$ mm mismatched pulse trains in Goupell *et al.* (2013b). If this value was appreciably different across individual listeners, this variability could obscure finding a minimum in the JND vs ILD function. In addition, the resolution of the ILDs used in the experiment with the NH listeners may have been too coarse, which would have further obscured finding a significant effect of ILD. Within- and across-listener variability in the envelope correlation change detection task could have been too large to see an effect of centering. An increased number of measurements might address this problem.

It may be that centering mismatched stimuli simply does not improve envelope correlation change JNDs. The lateralization perception of these sounds likely integrates across the full spectrum, including frequencies where there is only stimulation in one ear. However, the data from experiment 1 suggest that the envelope correlation change discrimination task is likely performed using only the information in the frequency region where the stimulation overlaps between the two ears. Perhaps centering should only account for the overlapping region, which would be possible in the NH listeners by bandpass filtering the signals but not the CI listeners.

In summary, the results of the centering experiment were inconclusive as the envelope correlation change JNDs did not change between the non-centered and centered conditions for both the CI and NH listeners. The first steps to follow up on this experiment should systematically investigate a range of ILDs with a fairly small resolution and enough measurements to decrease the variance in the data.

V. EXPERIMENT III: DISCRIMINATION OF ANTIPHASIC CARRIERS IN THE PRESENCE OF CORRELATED ENVELOPE MODULATIONS

The data in experiment 1 demonstrate that the hypothesis that place-of-stimulation matched inputs are necessary to be sensitive to changes in interaural envelope correlation [Fig. 1(C)]. However, one early onset CI listener questions that interpretation of the data. One way to further understand the data in experiment 1 is to change the detection cue in the task. In this experiment, the binaural differences were imposed only in the carrier (effectively an ITD discrimination task) in the presence of correlated or diotic envelope modulations. If the hypotheses in Fig. 1(A) are correct, all of the early onset CI listeners should not be able to perform the task.

A. Method

Nine CI and eight NH listeners participated in this experiment. All aspects of the electrical and acoustical stimuli were the same as in experiment 1 except the following. All envelopes were correlated or diotic, thus having an interaural envelope correlation of $\rho = 1$ before neural encoding. The target stimulus in the four-interval, two-alternative forced choice task did not have a different interaural envelope correlation but was an antiphasic carrier pulse train, meaning that the pulses were not time synchronized across ears but had an interaural phase difference (IPD) of π radians. See Fig. 6 for an example stimulus. PC was measured for each condition. Forty trials per condition were performed. The values of Δ (0, 2, 4, and 8 electrodes for the CI listeners or 0, 1.5, 3, 6, and 9 mm for the NH listeners) and the pulse rate (100, 200, 500, and 1000 pps) were varied.[3] New maps were made for the lower rate stimuli for the CI listeners using the same techniques utilized in experiment 1. There were no attempts to center the stimuli. CI listeners performed 640 trials (4 Δs $\times$ 4 rates $\times$ 40 trials/condition) and NH listeners performed 800 trials (4 Δs $\times$ 5 rates $\times$ 40 trials/condition).

B. Results

The results of this experiment show that for detecting antiphasic pulse train carriers that follow correlated envelope modulations, increasing Δ decreased PC, increasing rate decreased PC, and that the CI listeners were worse than NH listeners. The results from the individual listeners are shown in Fig. 7. Many CI listeners performed near chance (PC = 50%–75%) at 100 pps, which is in contrast to the NH listeners who performed at near perfect out to at least $\Delta = 6$ mm. Late onset CI listener CAD performed most like

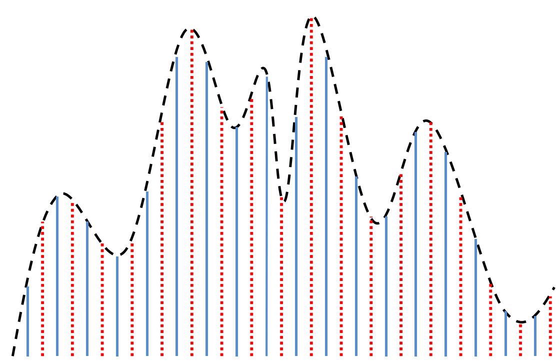

FIG. 6. (Color online) Example of a target stimulus used in experiment 3. The dashed line shows the correlated envelope that is sampled by acoustic or electric pulses. The solid vertical lines show the amplitudes of the pulses for the left ear; the dotted vertical lines show the amplitudes of the pulses for the right ear. Therefore, the target stimulus had an interaurally antiphasic carrier pulse train.

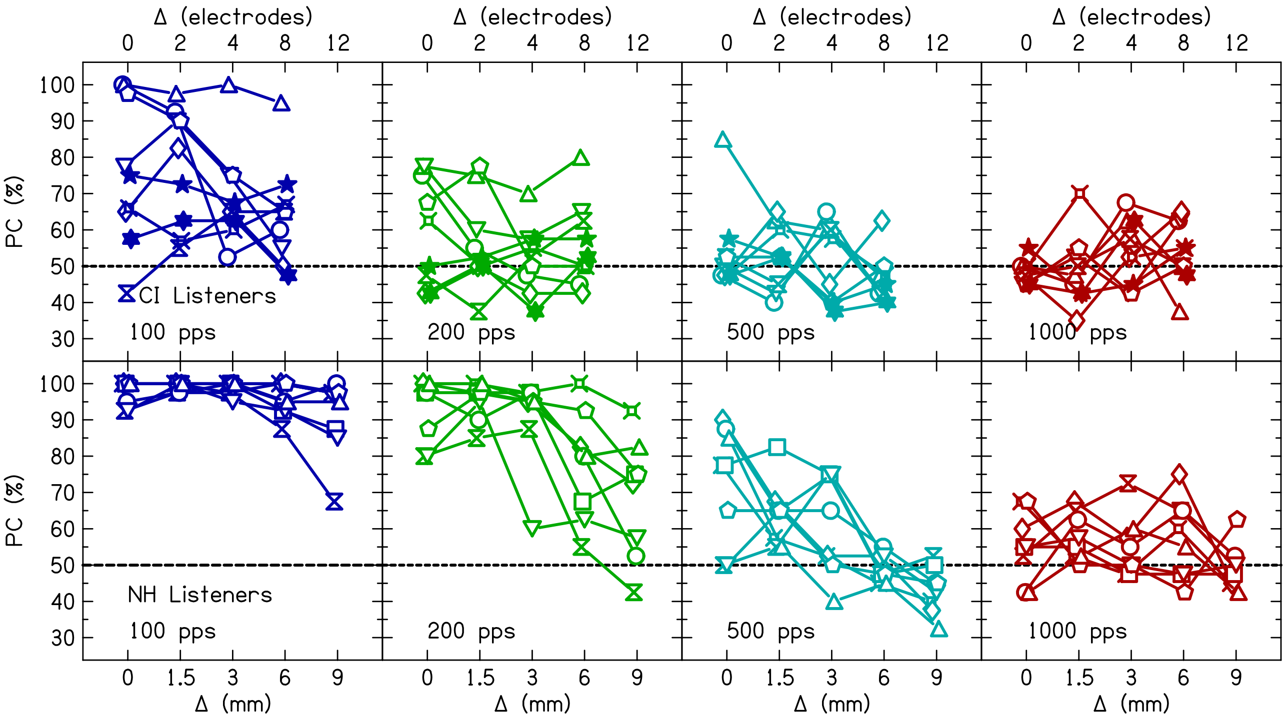

FIG. 7. (Color online) Percentage of correct (PC) identifications of antiphasic target carriers for experiment 3 as a function of Δ. Different rates are shown in different panels. CI listeners are plotted in the top row and NH listeners are plotted in the bottom row. Different symbols follow the conventions of Fig. 2 where the open symbols show late onset CI listeners and the closed symbols show early onset CI listeners. Individual symbols are the same as in Fig. 2. The dashed line shows chance performance.

the NH listeners, particularly at 100 pps. One early onset CI listener Cau showed some sensitivity to the antiphasic target pulse train at 100 pps.

The average results are shown in Fig. 8. Data were analyzed using a three-way ANOVA with factors Δ, group (CI vs NH), and rate. The CI listeners had significantly lower PC values [$F(1,268) = 197.2$, $p < 0.0001$, $\eta^2_p = 0.42$]. Therefore for each group, separate two-way repeated-measures ANOVAs with factors Δ and rate were performed.

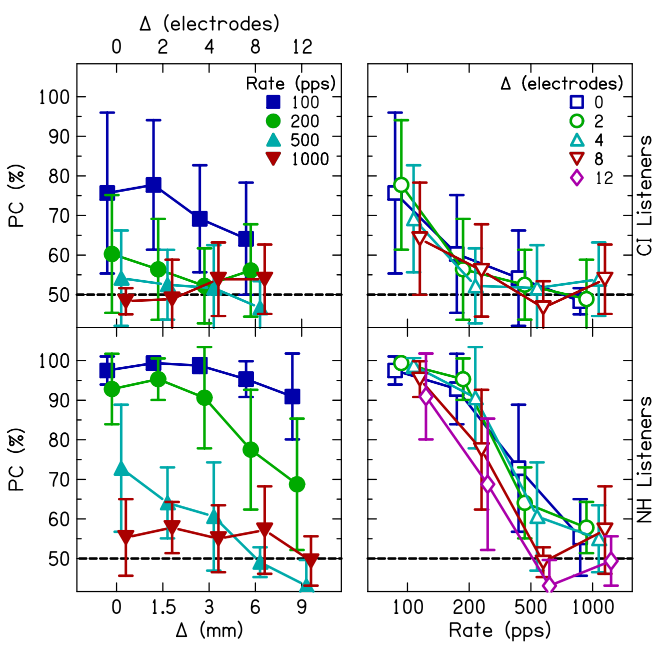

FIG. 8. (Color online) Average PC is shown for experiment 3. CI listeners are plotted in the top row and NH listeners are plotted in the bottom row. The error bars represent ±1 standard deviation of the mean.

For the CI listeners, PC did not significantly change as a function of Δ [$F(4,28) = 20.0$, $p < 0.0001$, $\eta^2_p = 0.74$]. PC decreased as rate increased [Greenhouse-Geisser correction: $F(1.48,11.9) = 17.5$, $p = 0.001$, $\eta^2_p = 0.69$]. Using a Helmert contrast, PC was found to be significantly higher for 100 pps compared to the higher rates ($p < 0.001$). The interaction Δ × rate was not significant [Greenhouse-Geisser correction: $F(3.55,28.4) = 1.73$, $p = 0.18$, $\eta^2_p = 0.18$].

For the NH listeners, PC decreased as Δ increased [$F(4,28) = 20.0$, $p < 0.0001$, $\eta^2_p = 0.74$]. Using a Helmert contrast, PC was significantly higher for Δ = 0 mm compared to the following levels of Δ ($p < 0.01$ for all). PC decreased as rate increased [$F(3,21) = 90.9$, $p < 0.0001$, $\eta^2_p = 0.93$]. Using a Helmert contrast, PC was significantly higher for 100 pps compared to the following rates ($p < 0.0001$), for 200 pps compared to the following rates ($p = 0.0002$), but PC was not different between 500 and 1000 pps ($p = 0.24$). The interaction Δ × rate was significant [Greenhouse-Geisser correction; $F(3.31,23.2) = 3.82$, $p = 0.021$, $\eta^2_p = 0.35$].

C. Discussion

This experiment was novel in that listeners were asked to detect an antiphasic pulse train (IPD = π radians, essentially an IPD or ITD discrimination task) while the pulses sampled correlated envelopes extracted from the modulations of a narrowband noise, rather than detecting changes in the interaural envelope correlation using synchronized carrier pulses (IPD = 0 radians). Similar to experiment 1, Fig. 8 shows that increasing place-of-stimulation mismatch reduced binaural sensitivity, particularly for the NH listeners. The CI listeners would have likely demonstrated the same strong effect, but it was not significant because many of the CI listeners were near chance performance (PC = 50%) for rates above 100 pps. Consistent with the previous literature, Fig. 8 also shows that increasing the pulse rate decreased binaural sensitivity to ITDs in the carrier (e.g., van Hoesel, 2007; Hancock *et al.*, 2012).

Many of the late onset CI listeners tested in this experiment are sensitive to ITDs for constant-amplitude pulse trains presented at 100 pps and at a pitch-matched pair of electrodes (see Litovsky *et al.*, 2012 for the general trend of ITD JND as a function of age of onset of deafness). In addition, other studies have shown fairly good correspondence between ITD JNDs in CI listeners to those measured in NH listeners presented bandlimited acoustic pulses; CI listeners' JNDs were significantly worse than the NH listeners' JNDs however the absolute size of the difference was small (Goupell *et al.*, 2009). Therefore, it is surprising that Fig. 8 shows that the NH listeners were much better at detecting the antiphasic carrier in the modulated pulse trains compared to CI listeners. In Fig. 7 for the 100-pps conditions, the NH listeners were on average near PC = 100% whereas the CI listeners were on average near PC = 70%. Three CI listeners (CAC, CAD, and CAH) had near PC = 100% for the 100-pps, $\Delta = 0$ electrodes condition. However, only CAD maintained this performance for increasing Δ, making this CI listener most similar to the NH listeners. Note, CAD was a star performer who also had the lowest envelope correlation change JNDs in Fig. 2. CAD had a relatively large dynamic range in each ear, nearly 60 CUs at 1000 pps, which was on average 30 CUs larger than the other CI listeners. Perhaps this relatively large dynamic range contributed to this CI listener's excellent performance.

Last, early onset CI listener Cav, who was sensitive to envelope correlation changes in experiment 1 (Fig. 2), was not appreciably above chance performance in experiment 3 (Fig. 7). However, early onset CI listener Cau, who was not sensitive to envelope correlation changes in experiment 1 (Fig. 2), was appreciably above chance performance in experiment 3 with PC = 70% (Fig. 7). This result may be an indication that development of sensitivity to interaural envelope and fine structure differences may be related to two different mechanisms. However, to reach any strong conclusions about binaural development, a larger number of early onset CI listeners needs to be tested.

VI. GENERAL DISCUSSION

A. Understanding the CI-NH binaural performance gap

Bilateral CIs produce improved sound localization and better speech understanding in noise (largely a result of the better ear effect) when compared to a unilateral CI (e.g., Litovsky *et al.*, 2012); however, bilateral CI users demonstrate relatively poor binaural performance compared to NH listeners. This study aimed to understand this gap in performance by trying to present similar electric and acoustic pulse trains to the CI and NH listeners, respectively. In experiment 1, CI and NH listeners detected changes in interaural envelope correlation. CI listeners were significantly worse at detecting changes in interaural envelope correlation compared to NH listeners (Figs. 2, 3, and 4), confirming the binaural benefit gap for this task. In experiment 3, CI and NH listeners detected antiphasic carriers that were modulated by "correlated" envelopes. Again, CI listeners were markedly worse than NH listeners at this task (Figs. 7 and 8). After establishing this CI-NH binaural performance gap in performance, several manipulations were undertaken in an effort to explain this gap.

It was hypothesized that interaural place-of-stimulation mismatch may have contributed to the difference in performance between the groups, even though the CI listeners were presented stimuli at pitch-matched electrode pairs. It is unclear if envelope correlation change discrimination performance for modulated pulse trains would be as tolerant to mismatch as occurs for static interaural difference detection for constant-amplitude pulse trains (Goupell *et al.*, 2013b; Kan *et al.*, 2013). In addition, it is important to understand the effects of mismatch because CIs are likely at different insertion depths. In general, the results of this study (Figs. 2–4, 7, and 8) and previous studies show that relatively large mismatches ($\Delta > 3$ mm) were necessary to significantly degrade binaural performance. Therefore, the binaural performance gap cannot be explained by interaural place-of-stimulation mismatch. Note that large mismatches tend to happen rarely in practice, at least for the listeners that typically participate in psychoacoustical research studies. For example, of the 11 CI users in this study, there was only one listener with a natural interaural mismatch of greater than 3 mm when measured by pitch matching (see the 6-electrode or 4.5-mm mismatch for listener Cau in Table I).

The effect of centering on the binaural benefit gap was explicitly tested in experiment 2. Binaural performance is best for centered stimuli in NH listeners (Yost, 1974; Yost and Dye, 1988). Mismatched stimuli are naturally uncentered and biased to the ear that has the higher CF (Goupell *et al.*, 2013b; Kan *et al.*, 2013). The result of experiment 2 did not produce improved performance for centered stimuli. Since large interaural differences are necessary to degrade performance for complex stimuli (Koehnke *et al.*, 1995), it may be that the relatively small amounts of centering needed for this study did not appreciably improve the performance of the listeners. Therefore, the binaural performance gap cannot be explained by non-centered auditory images.

A parsimonious signal-based explanation for the CI-NH binaural benefit gap is that while modulations are encoded well enough to understand speech at a high level with CIs, the interaural differences may be not encoded well enough to adequately preserve the interaural envelope correlation. While the compression function used to mimic "normal" loudness growth is the same between the ears, it seems highly unlikely that loudness growth functions are similar across the ears of CI users. Modulated stimuli would then evoke a form of neural interaural envelope decorrelation, which would reduce binaural performance (Culling *et al.*, 2001). Therefore, the binaural performance gap may be explained by interaural envelope decorrelation introduced at the level of the neural encoding of the stimuli.

Neural degeneration may also be a factor that contributes to the binaural performance gap. Regions of substantial neural degeneration (i.e., "dead regions") are thought to be related to duration of deafness (Ryugo *et al.*, 2005), which is a factor often associated with poorer CI performance (Blamey *et al.*, 2013). There is no reason why dead regions should be interaurally symmetrical, and a particularly orthogonal set of across-ear dead regions could produce a pitch-matched pair of electrodes that lack binaurally coincident inputs. This factor was not explicitly investigated in this study, but future studies could consider the role of neural degeneration and "holes" in hearing.

Age is often a factor disregarded in CI research. However, the groups of listeners tested in these studies are noticeably mismatched in age (generally much younger NH listeners compared to older CI listeners). There was only one late onset CI listener CAD who performed most like the NH listeners in experiment 3 (Fig. 6). It is well established that temporal processing degrades with age (Gordon-Salant, 2010), which would explain part of the difference between the NH and CI listeners. Therefore, the binaural performance gap might be partially explained by differences in age of the listener groups, and future studies should investigate this further.

Another factor that is often disregarded in psychoacoustical studies is selection of participants. Bilateral CI users are still relatively rare (Peters *et al.*, 2010) and even if they cannot detect a particular cue, they will often be tested in an effort to show that they cannot perform a particular task. Indeed, there were three CI listeners who operated at chance performance for hours to demonstrate no sensitivity to interaural envelope correlation (Fig. 1). While there were a total of 15 different NH listeners who could perform the tasks, there were also six listeners who could not and were disregarded from further testing. Therefore, there was roughly the same proportion of listeners in each group who were not able to perform the binaural tasks. Note that data for listeners at chance performance were explicitly omitted from the averages. Therefore, the binaural performance gap might be partially explained by differences in acceptance of listeners into a study and future studies should investigate this further.

There were also marked differences in the ways that the listeners were tested. The CI listeners were typically tested over multiple consecutive days for up to 6 h per day, which included many breaks. The NH listeners were typically tested over non-consecutive days for up to 2 h per day. While data collection was often halted in the CI listeners if they appeared fatigued, fatigue may be an issue in this comparison. In addition, while both groups were given training, it may be that NH listeners received more opportunity to train and consolidate their learning over multiple days, whereas CI listeners were often tested over a shorter amount of time. Therefore, the binaural performance gap might be partially explained by differences in procedure and training, which should be investigated further.

B. Mechanisms underlying interaural envelope correlation change discrimination

The neural computation of ITDs is thought to occur in the medial superior olive by excitatory-excitatory neurons from place-of-stimulation matched inputs (Goldberg and Brown, 1968). Neural computation of ILDs is thought to occur in the lateral superior olive by excitatory-inhibitory neurons from place-of-stimulation matched inputs (Tsuchitani and Boudreau, 1966). However, it is not clear how interaural decorrelation is represented (Shackleton *et al.*, 2005), particularly interaural envelope decorrelation and in the presence of interaural place-of-stimulation mismatch. To better understand the underlying neural mechanisms, three hypotheses concerning the relationship between interaural envelope correlation change discrimination and interaural place-of-stimulation mismatch were depicted in Fig. 1. The first hypothesis necessitated place-of-stimulation matched inputs [Fig. 1(C)]. The second hypothesis suggested that place-of-stimulation matched inputs would facilitate performance, but would not be necessary if the inputs were not place-of-stimulation matched [Fig. 1(D)]. The third hypothesis suggested that interaural envelope correlation change discrimination did not require place-of-stimulation matched inputs and would be insensitive to interaural place-of-stimulation mismatch [Fig. 1(E)].

The data in Figs. 2–4, 7, and 8 most strongly supported the first hypothesis [Fig. 1(C)] that place-of-stimulation matched inputs are necessary to discriminate changes in interaural envelope correlation. JNDs increased with increasing Δ and many listeners could not perform the envelope correlation change discrimination task for the largest values of Δ. All of the NH listeners and all but one late onset CI listener showed this trend. The one late onset CI listener who could not perform the task might be explained by the relatively poor performance of the CI listeners compared to the NH listeners. Support for the second hypothesis [Fig. 1(D)] was unlikely because there were no long-term average monaural cues that the listeners could utilize to perform the task after a sufficient amount of mismatch. Support for the third hypothesis [Fig. 1(E)] was unlikely because all neural computation of interaural differences are thought to rely on relatively narrowly tuned place-of-stimulation matched inputs.

Age of onset of deafness (implicitly the effect of binaural development) was investigated by including three early onset CI listeners in this study. It was assumed that the early onset CI listeners were not sensitive to ITDs, but were sensitive to ILDs (Litovsky *et al.*, 2010; Salloum *et al.*, 2010). Given this assumption, Fig. 1 showed specific predictions about the effect of mismatch on ITD, ILD, and envelope correlation change sensitivity for the early onset CI listeners. The results of the experiments show that one early onset CI listener could perform the envelope correlation change discrimination task (Fig. 2) and a different early onset CI listener could perform the antiphasic carrier (ITD-based) detection task (Fig. 7). Clearly a larger number of early onset CI listeners is necessary to draw any strong conclusions about binaural development and binaural processing, but the fact that one early onset CI listener could perform each task points to the importance of attempting such experiments in the future. Specifically, future research should involve performing all of the ITD, ILD, and envelope correlation change JND measurements as a function of mismatch as outlined in Fig. 1 for sufficiently large groups of early and late onset CI listeners. Such information would clarify the role of the development of binaural processing in CI listeners and the relationship between ITD, ILD, and envelope correlation change sensitivity.

VII. SUMMARY

There exists a binaural performance gap between bilateral CI and NH listeners, even when attempting to present reasonable acoustic simulations of electrical stimulation. This gap may be a result of stimulus factors (poor control over the modulation encoding), subject factors (age on onset of deafness, neural survival/duration of deafness, age), and methodological factors (participant selection, differences in testing and training). Despite the overall differences between the groups, it was determined that both CI and NH listeners could detect changes in interaural envelope correlation and interaural timing of modulated pulse trains with correlated envelopes. The effect of interaural place-of-stimulation mismatch on envelope correlation change sensitivity was systematically investigated for both groups of listeners. The results showed that envelope correlation change detection necessitates place-of-stimulation matched inputs and that mismatch affects both groups similarly. Namely, mismatches of greater than 3 mm are necessary to significantly degrade performance. This suggests that bilateral CI users who have smaller amounts of mismatch between electrode arrays should have access to binaural cues to perform binaural tasks like sound localization or binaural unmasking of speech in background noise.

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[1]For simplicity, it is assumed that fluctuating ILDs and envelope ITDs provide the same detection cues. It is unclear how similar these two cues are in interaurally decorrelated stimuli and how they are processed by the central nervous system in either normal or electrical hearing.

[2]CAF demonstrated no binaural sensitivity at the middle of the array. Therefore, a basally located pair was chosen to perform the experiment.

[3]For 1000-pps acoustic pulse trains with a nominal BW = 3 mm, the modulation depth of the pulse trains for the $\Delta = 0$ and 1.5-mm conditions was reduced to about 80% and 85%, respectively, rather than >99%. This would reduce the effective BW of the pulse trains. Given that performance was near chance for all of the 1000-pps conditions, this likely produced a minimal effect on the results.

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