JASA ARTICLE

# Asymmetric temporal envelope sensitivity: Within- and across-ear envelope comparisons in listeners with bilateral cochlear implants

Sean R. Anderson,[1,a)] Alan Kan,[2] and Ruth Y. Litovsky[1]
[1]Waisman Center, University of Wisconsin-Madison, Madison, Wisconsin 53705, USA
[2]School of Engineering, Macquarie University, Sydney, New South Wales 2109, Australia

**ABSTRACT:**
For listeners with bilateral cochlear implants (BiCIs), patient-specific differences in the interface between cochlear implant (CI) electrodes and the auditory nerve can lead to degraded temporal envelope information, compromising the ability to distinguish between targets of interest and background noise. It is unclear how comparisons of degraded temporal envelope information across spectral channels (i.e., electrodes) affect the ability to detect differences in the temporal envelope, specifically amplitude modulation (AM) rate. In this study, two pulse trains were presented simultaneously via pairs of electrodes in different places of stimulation, within and/or across ears, with identical or differing AM rates. Results from 11 adults with BiCIs indicated that sensitivity to differences in AM rate was greatest when stimuli were paired between different places of stimulation in the same ear. Sensitivity from pairs of electrodes was predicted by the poorer electrode in the pair or the difference in fidelity between both electrodes in the pair. These findings suggest that electrodes yielding poorer temporal fidelity act as a bottleneck to comparisons of temporal information across frequency and ears, limiting access to the cues used to segregate sounds, which has important implications for device programming and optimizing patient outcomes with CIs.
 https://doi.org/10.1121/10.0016365

(Received 17 February 2022; revised 14 November 2022; accepted 16 November 2022; published online 7 December 2022)
[Editor: Joshua G. Bernstein] Pages: 3294–3312

## I. INTRODUCTION

Patients with bilateral cochlear implants (BiCIs) demonstrate poorer sensitivity to many sound source segregation cues compared to listeners with normal hearing (NH) (e.g., Anderson *et al.*, 2019a; Kong *et al.*, 2009; Thakkar *et al.*, 2020). Many sound source segregation cues rely on a comparison of temporal information conveyed via different places of stimulation on the auditory nerve (Grose *et al.*, 2005). This raises some questions: does sensitivity to source segregation cues compared between different frequencies or ears correspond more closely to the portions of the auditory nerve with greater or lesser temporal fidelity? Is performance instead related more closely to the difference in sensitivity between the ears? A recent report investigating sensitivity to binaural stimuli suggests that the ear with poorer temporal sensitivity predicts sensitivity to binaural cues (Ihlefeld *et al.*, 2015), i.e., binaural sensitivity is limited by the worse ear's sensitivity to monaural temporal information. The present study attempted to expand on these findings in listeners with BiCIs by exploring this relationship more generally, for different places of stimulation within the same ear or across ears. By using stimuli and cues (e.g., fluctuations in the temporal envelope) that can be conveyed via most present-day cochlear implant (CI) processing algorithms, we aimed to characterize the relative sensitivity to temporal envelope differences across frequency (i.e., place of stimulation) in both ears.

### A. Temporal envelope information in auditory scene analysis

Auditory signals contain two different types of temporal information. Faster fluctuations in pressure over time make up the temporal fine structure. Changes in the instantaneous amplitude over time determine the temporal envelope. In other words, if one thinks of the basilar membrane as a frequency analyzer whose narrowband components are made up of a carrier that is modulated by another signal, the temporal fine structure is the carrier, and the temporal envelope is the modulator [for review, see Moore (2008)]. Most CI processing algorithms discard temporal fine structure and replace it with constant-rate, pulsatile stimulation, where amplitude modulation (AM) is applied according to the temporal envelope (e.g., Loizou, 2006). Thus, temporal envelope information is well-preserved by CI processing and could be especially important to perception.

One approach to evaluate sensitivity to temporal envelope cues has been to measure sensitivity to differences in the temporal envelope between frequencies or ears and then make predictions about the utility of these cues for perception. In one example, stimuli were presented simultaneously,

[a)]Electronic mail: sean.hearing@gmail.com

 

and listeners were asked to indicate whether those sounds had the same or different noise-based (i.e., stochastic) temporal envelope fluctuations. Listeners with NH showed sensitivity to coherence of temporal envelopes in monaural (Richards, 1987) and binaural (e.g., Bernstein and Trahiotis, 1992) hearing tasks. Listeners with BiCIs showed poorer sensitivity to coherence of temporal envelopes in binaural tasks compared to NH (Goupell, 2015; Goupell and Litovsky, 2015) but have not been tested monaurally. Another example is interaural timing differences (ITDs) conveyed in the temporal envelope. Listeners with BiCIs demonstrate sensitivity to envelope-based ITDs, but to a lesser extent than ITDs conveyed by a single pulse and poorer than listeners with NH (Anderson *et al.*, 2019a; van Hoesel and Tyler, 2003).

In the present study with BiCI listeners and in a previously published experiment with younger NH listeners (Anderson *et al.*, 2019b), we asked listeners to compare temporal patterns in the same or different spectral channels within and across ears. We employed sinusoidal envelopes to examine listeners' ability to judge differences between predictably and parametrically manipulated modulation frequency. Different ears or frequency regions were stimulated simultaneously, and listeners responded to one stimulus presentation, identifying whether the AM rates were the same or different. This paradigm allowed us to determine the sensitivity to differences in the temporal envelope when compared within or across ears, at the same or different frequency regions. Listeners with NH using sinusoidally amplitude-modulated (SAM) tones where the center frequency was varied to change place of stimulation showed similar sensitivity to differences in AM rate whether stimuli were compared against same or different frequencies across or within ears. When poorer temporal representations were simulated in listeners with NH by reducing the depth of AM, the greatest decrement occurred when stimuli were presented at different frequencies within the same ear. Ihlefeld *et al.* (2015) examined how monaural and binaural sensitivity are related, but they used low-rate, constant-amplitude electrical pulse trains. The present study used high-rate, amplitude-modulated pulse trains, more similar to CI-processed stimuli. Listeners with BiCIs have varying access to the temporal envelope information provided by CI processors (see Sec. I B) and have compromised binaural processing, which may alter how the temporal envelope from different electrodes is compared. In particular, it may be that the worse ear (Anderson *et al.*, 2019b; Ihlefeld *et al.*, 2015) or the degree of asymmetry between ears (Yoon *et al.*, 2011) predicts binaural outcomes. Given that listeners with BiCIs can have major differences between the ears related to differing durations of deafness, surgical outcomes (e.g., interaural place of stimulation mismatch, scalar translocation of electrodes), or the etiology of their hearing loss, it is possible that the sensitivity within ears is better than across ears.

### B. Factors limiting access to the temporal envelope

Behavioral experiments show listener-dependent, idiosyncratic relationships between place of stimulation with CIs and monaural temporal sensitivity (Chatterjee and Oberzut, 2011; Chatterjee and Peng, 2008; Galvin *et al.*, 2015; Ihlefeld *et al.*, 2015; Kong *et al.*, 2009; Kong and Carlyon, 2010), as well as binaural temporal sensitivity (Laback *et al.*, 2015; Thakkar *et al.*, 2020). These findings contrast with those from listeners with NH, who show better performance when stimulated closer to the cochlear apex at the same sound level relative to more basal locations for high frequency transients that stimulate similar areas of the cochlea to CIs (e.g., Bernstein and Trahiotis, 2014; Monaghan *et al.*, 2015). It is well known that loudness and audibility vary with frequency. Thus, one difference between CI and NH studies is the loudness balancing that precedes CI stimulation. Alternatively, the interface between CI electrodes and auditory nerve fibers varies in effectiveness with place of stimulation (Garadat *et al.*, 2013; Goupell *et al.*, 2022; Schvartz-Leyzac *et al.*, 2020; Zhou and Pfingst, 2012), and experiments in listeners with CIs show that binaural sensitivity is related to monaural sensitivity to temporal information (e.g., Ihlefeld *et al.*, 2015), suggesting that these factors are related.

There is also a similar "rate limitation" for monaural (Baumann and Nobbe, 2004; Chatterjee and Oberzut, 2011; Chatterjee and Peng, 2008; Goldsworthy *et al.*, 2022; Ihlefeld *et al.*, 2015; Kong *et al.*, 2009; Kong and Carlyon, 2010; Kreft *et al.*, 2010; Lindenbeck *et al.*, 2020) and binaural stimulation (Anderson *et al.*, 2019a; Ihlefeld *et al.*, 2015; Kan and Litovsky, 2015; Laback *et al.*, 2015; van Hoesel *et al.*, 2009), where pulse or AM rates near or above 300 Hz result in poor sensitivity in listeners with CIs. To better understand the relationship between monaural rate sensitivity and binaural sensitivity, Ihlefeld *et al.* (2015) examined monaural pulse rate discrimination (i.e., temporal pitch discrimination) and ITD discrimination in the same listeners with BiCIs. They tested three different places of stimulation in each ear and evaluated the relationship between monaural pulse rate and ITD discrimination at each place of stimulation. Crucially, their study showed that the ear with poorer pulse rate discrimination sensitivity was predictive of poorer ITD discrimination. This suggests that when there is a place of stimulation yielding poor sensitivity to temporal information in one ear, it places a limitation on the ability to compare temporal information across the two ears.

A further important consideration is whether monaural temporal sensitivity to the type of stimulation conveyed via today's CI processors (i.e., envelope-modulated pulse trains) reflects a limitation on binaural sensitivity. Because that issue had not been investigated in listeners with NH, we recently tested the same relationship while manipulating the monaural resolution at one cochlear place of stimulation. In that study, the fidelity of temporal cues was reduced by applying AM in a smaller dynamic range (Anderson *et al.*, 2019b). Instead of manipulating ITDs, the AM rate was varied in each ear. The results indicated that, indeed, the ear conveying poorer temporal information limited sensitivity to binaural cues.

The present study expands on the results of Ihlefeld *et al.* (2015) by testing the same task and configurations as those used in Anderson *et al.* (2019b) in listeners with BiCIs. We focused on AM rate, which is conveyed by current CI processing algorithms and is therefore much more likely to be useful in everyday listening. This is in contrast to pulse rate manipulated in Ihlefeld *et al.* (2015), which is not varied by most CI processing algorithms in a way that reflects the stimulus. Because pulses in a constant-amplitude train only reflect present or absent stimulation, they do not need to conform to individuals' perceptions of loudness as current is varied up and down, unlike representations of the temporal envelope. Loudness growth varies by electrode (Bierer and Nye, 2014), and there is indirect evidence suggesting binaural cues conveyed in the envelope might be obscured by these differences (Anderson *et al.*, 2019a; Goupell, 2015; Goupell and Litovsky, 2015). Thus, there may be additional factors at play that limit access to envelope rate compared to pulse rate cues.

### C. Study aims and hypotheses

In the present study, we investigated sensitivity to differences in the rate of AM for pairs of stimuli presented to two different electrodes in listeners with BiCIs. The first goal was to determine the relative efficacy of temporal envelope comparisons of different within- and across-ear configurations. It was hypothesized that listeners with BiCIs would be most sensitive to differences in AM rate for pairs of stimuli presented to the same approximate place of stimulation in each ear because of the additional contribution of binaural cues (e.g., binaural beats; McFadden and Pasanen, 1975). The second goal was to determine whether the electrode in a pair yielding less temporal sensitivity was predictive of sensitivity to differences across places of stimulation (i.e., acted as a bottleneck). It was hypothesized that the electrode yielding least temporal sensitivity (experiment 1) would be predictive of the sensitivity for pairs of electrodes (experiment 2). Alternatively, it may be that increased differences in sensitivity between electrodes (i.e., asymmetry itself) results in poorer sensitivity of pairs of electrodes. This could be due to physiological encoding problems like adaptation to stimulus statistics that are no longer conveyed correctly or auditory grouping problems where sounds that are "different" are simply not grouped together.

## II. EXPERIMENT 1: SEQUENTIAL ENVELOPE DISCRIMINATION

### A. Motivation

Experiment 1 was a calibration experiment that indexed the fidelity of AM rate coding by the auditory periphery using psychophysics for all four places of stimulation (apical or basal in the left or right ear) used in experiment 2. We assumed that a reasonable proxy ascertaining AM rate encoding fidelity would be AM rate discrimination thresholds. Thus, in experiment 1, thresholds were measured by having listeners discriminate between three stimuli played in a sequence and indicate the stimulus that sounded different (i.e., with a higher AM rate). We predicted that there would be no consistent pattern in sensitivity at each place of stimulation (apex or base) across listeners in experiment 1 and that listeners would be most sensitive to changes in AM rate when compared against a reference AM rate of 90 Hz. In other words, sensitivity should decrease when AM rate is compared to standard AM rates below 90 Hz (tested in the present experiment), consistent with previous AM rate discrimination experiments in listeners with CIs (Chatterjee and Oberzut, 2011; Chatterjee and Peng, 2008; Lindenbeck *et al.*, 2020). Previous research has shown that AM rate discrimination also worsens for AM rates above 100 Hz (Chatterjee and Oberzut, 2011; Chatterjee and Peng, 2008; Kreft *et al.*, 2010; Lindenbeck *et al.*, 2020). Because testing time was already close to 24 h, it was not feasible to test AM rates above and below 90 Hz in both experiments. We chose to focus on low AM rates because they are important for speech understanding and span a wide range of perceptual phenomena (see Sec. IV).

### B. Methods

#### 1. Listeners

Eleven listeners with bilateral CIs (age 51–90+ years; mean 63 years) participated in this experiment. Demographics and CI processor information are listed in Table I. All listeners had at least 1 year of listening experience with bilateral CIs. All listeners provided informed consent, and procedures were approved by the Health Sciences Institutional Review Board of the University of Wisconsin-Madison. Best practices for direct stimulation experiments were followed according to Litovsky *et al.* (2017).

#### 2. Stimuli and procedures

Stimuli were SAM pulse trains. Pulse trains consisted of monopolar, biphasic pulses presented at a rate of 3000 pulses per second (pps) and a comfortable level. The pulse duration was 25 $\mu$s with an 8-$\mu$s interphase gap consistent with listeners' clinical programming, except for listener ICP, who used a pulse duration of 50 $\mu$s consistent with their clinical programming. Studies on AM detection and pitch ranking in listeners with CIs have shown that four to five pulses per AM cycle are sufficient for psychophysical sensitivity and neural representation of AM (Busby *et al.*, 1993; McKay *et al.*, 1994; Wilson, 1997).

Temporal fluctuations are conveyed via populations of auditory nerve fibers, and the health and number of auditory nerve fibers are suspected to vary with place of stimulation or electrodes. Models of CI stimulation on auditory nerve fibers suggest that high rates of stimulation ($\gtrsim$3000 pps) result in more stochastic firing of model auditory nerve fibers (e.g., Rubinstein *et al.*, 1999). Moreover, temporal refinement occurs in early stages of the auditory pathway for temporal fine structure (Joris *et al.*, 1994) and envelope cues (Rhode and Greenberg, 1994). One mechanism associated with temporal refinement is monaural coincidence detection via

TABLE I. Listener demographics. All listeners used a 22-electrode array, where lower values indicate closer proximity to the base of the cochlea. Listener ICP had several basal electrodes deactivated in their clinical strategy due to discomfort, so they were tested at more apical electrodes.

| Listener ID | Electrodes (apex/base) | AM depth (%) | Etiology | Age at onset of deafness (years) | Age at implantation (left/right; years) | Age at testing (years) | Internal processor (left/right) |
|---|---|---|---|---|---|---|---|
| IAJ | 16/4 | 50 | Progressive | 5 | 51/58 | 71 | CI24M/CI24R |
| IBF | 16/4 | 50 | Hereditary | 38 | 56/54 | 65 | CI24RE/CI24RE |
| IBK | 16/4 | 50 | Hereditary; noise exposure | 53 | 63/69 | 80 | CI24R/CI24RE |
| IBO | 16/4 | 50 | Otosclerosis; sudden | 20 | 45/42 | 52 | CI24RE/CI24RE |
| IBZ | 16/4 | 50 | Unknown; sudden | 38 | 40/38 | 51 | CI24RE/CI24RE |
| ICD | 16/4 | 50 | Enlarged vestibular acqueduct | 3 | 50/44 | 59 | CI24R/CI24RE |
| ICI | 16/4 | 50 | Unknown | 31 | 50/51 | 58 | CI24RE/CI24RE |
| ICM | 16/4 | 100 | Unknown | 23 | 57/58 | 64 | CI512/CI24RE |
| ICP | 20/8 | 100 | Unknown; progressive | 3 | 46/49 | 54 | CI24RE/CI24RE |
| ICS | 16/4 | 100 | Unknown | 68 | 82/74 | 90+ | CI24R/CI512 |
| IDA | 16/4 | 100 | Progressive | 8 | 47/46 | 51 | CI24RE/CI24RE |

convergence of many stochastic inputs, which is thought to occur in the cochlear nucleus (Rothman *et al.*, 1993). Thus, if auditory nerve inputs to cochlear nucleus cells are fewer or more stochastic, temporal refinement may be compromised. In other words, compared to low-rate stimulation that is known to be highly phase-locked and may not require over-representation of inputs, high-rate stimulation might interfere with the ability to encode temporal cues and help illuminate the electrode sites with fewer or less reliable inputs.

Stimuli were generated in MATLAB (Natick, MA) and presented via RF Generator XS research processor (Cochlear, Ltd., Sydney, Australia). Stimuli had 10-ms cosine onset and offset ramps. Testing was completed in a quiet, private room free from distractions.

Loudness balancing was completed to ensure that stimuli resulted in equal loudness on each electrode following procedures described in a previous methodological paper from our laboratory (Litovsky *et al.*, 2012). Briefly, the threshold (T), comfortable (C), and maximum comfortable (M) levels were determined using a 600-ms duration, constant-amplitude pulse train. Then SAM pulse trains were presented at an AM rate between 100 and 160 Hz and an AM depth specific to that listener (in most cases 50%; see Table II for AM depths as well as T and M levels) for all possible pairs of electrodes used in the present study. We defined AM depth relative to the dynamic range of each electrode [in current units (CUs)], with the M level representing the peak and the T level representing the trough of a 100% AM depth signal. AM depth was introduced relative to the M level, so a 50% AM depth signal would have a peak at the M level and a trough at 50% of the dynamic range for the listener. For Cochlear devices, CUs range from 0 to 255 and result in logarithmic increases in current as CUs increase linearly. The M level (in CUs) was adjusted by the experimenter until the listener-reported equal loudness for all possible pairs of electrodes. If listeners reported a change in loudness on later days of testing, M levels were adjusted. No loudness balancing was completed across the AM rates used in this study because most previous experiments showed no change in loudness over AM rate (Chatterjee and Oberzut, 2011; Kreft *et al.*, 2010). It should be noted that one previous experiment showed small differences in loudness between AM rates of 100 and 200 Hz compared to 300 Hz (Vandali *et al.*, 2013), suggesting that differences in loudness across AM rate are usually small or inconsistent across listeners.

Before testing began, listeners were familiarized with perceptual changes associated with increasing AM rate. Listeners were presented with AM rates of 10, 50, 90, 180, and 900 Hz and asked to describe their perception (e.g., compare sounds to something encountered in real life).

Listeners completed a three-interval, two-alternative forced-choice "oddball" discrimination task. On each trial, the first interval presented a standard AM rate (10, 30, or 90 Hz). The second or third interval (with equal probability) also presented the standard AM rate. The other interval consisted of an oddball (higher) AM rate, which was determined via adaptive tracking. Neither stimulus level nor AM rate was roved. AM rate discrimination in listeners with CIs using stimulus parameters similar to those used here showed no effect of level roving on discrimination (Chatterjee and Oberzut, 2011; Kreft *et al.*, 2010). AM rate was not roved because there was already considerable overlap between the oddball rates for each standard AM rate. Each stimulus interval had a duration of 600 ms. An inter-stimulus interval of 300 ms separated each presentation, and listeners were not allowed to repeat stimuli. Three two-down, one-up adaptive staircases (corresponding to standard AM rates of 10, 30, and 90 Hz) were interleaved such that on each trial, the standard rate was randomly chosen from one of the remaining unfinished staircases. A staircase was considered complete after 12 turnarounds. Step sizes for adaptive staircases were determined using a hybrid set of rules from the parameter estimation by sequential testing (PEST) and Levitt (1971), as implemented in Litovsky (1997) to minimize confusion (Macmillan and Creelman, 2005). The maximum step size for each standard AM rate was 16/3, 16, and 48 Hz, and the minimum was 1/3, 1, and 3 Hz, such that the relative change was equal across standard AM rates (10, 30, and 90 Hz, respectively). Each adaptive staircase was initiated at

TABLE II. Current level mappings. All listeners used a 22-electrode array, where lower values indicate closer proximity to the base of the cochlea. AM depth is expressed relative to the dynamic range, or the CUs between T and M levels. Because some listeners required level adjustments to maintain equal loudness, the final mapping levels were reported. Listener IBF's MAPs were lost when data were moved from the testing computer to the server where data are stored onsite.

| Listener ID | AM depth (%) | Electrode (number) | Left ear T level (CU) | Left ear M level (CU) | Right ear T level (CU) | Right ear M level (CU) |
|---|---|---|---|---|---|---|
| IAJ | 50 | 16 | 99 | 175 | 130 | 213 |
| | | 4 | 118 | 184 | 146 | 203 |
| IBF | 50 | 16 | — | — | — | — |
| | | 4 | — | — | — | — |
| IBK | 50 | 16 | 135 | 238 | 119 | 229 |
| | | 4 | 118 | 221 | 123 | 221 |
| IBO | 50 | 16 | 70 | 160 | 65 | 163 |
| | | 4 | 70 | 160 | 60 | 140 |
| IBZ | 50 | 16 | 59 | 147 | 109 | 165 |
| | | 4 | 60 | 141 | 109 | 169 |
| ICD | 50 | 16 | 136 | 190 | 142 | 215 |
| | | 4 | 116 | 188 | 122 | 214 |
| ICI | 50 | 16 | 92 | 137 | 90 | 145 |
| | | 4 | 96 | 136 | 78 | 121 |
| ICM | 100 | 16 | 86 | 155 | 54 | 118 |
| | | 4 | 73 | 117 | 57 | 126 |
| ICP | 100 | 20 | 51 | 157 | 55 | 148 |
| | | 8 | 102 | 180 | 112 | 185 |
| ICS | 100 | 16 | 90 | 146 | 124 | 181 |
| | | 4 | 124 | 177 | 142 | 185 |
| IDA | 100 | 16 | 88 | 169 | 97 | 160 |
| | | 4 | 79 | 125 | 78 | 113 |

five times the standard AM rate, and this was the maximum oddball AM rate allowed during testing. The minimum oddball AM rate tested was 31/30 times the standard AM rate. Testing was blocked by electrode (apical or basal in the left or right ear), and the order of testing was partially counterbalanced across listeners. Visual feedback of the correct answer was given after each trial. One practice block was given using the first electrode to be tested to ensure that listeners understood the task. Testing took approximately 2–3 h for each listener.

#### *3. Analysis*

Thresholds for the oddball AM rate resulting in 71.1% correct discrimination were estimated by fitting a logistic function bounded between 50% and 100% using a weighted maximum likelihood procedure. Curve fitting was completed using version 2.5.6 of the psignifit toolbox in MATLAB (Wichmann and Hill, 2001). Lambda (lapse rate) was included as a free parameter. Data were analyzed by converting discrimination threshold in Hz to $\Delta f_m/f_m$, where the numerator represents the rate presented at threshold (rate that could be discriminated) minus the standard AM rate and the denominator represents the standard AM rate, both in Hz. This was completed to express thresholds in terms of relative change from standard AM rate, allowing comparison across standard AM rates.

Data were analyzed using the aligned-rank transformation (ART) on a mixed-effects analysis of variance (ANOVA) (Wobbrock *et al.*, 2011). This procedure changes the mixed-effects ANOVA into a rank-based, non-parametric test for factorial experiments, similar to a Friedman non-parametric ANOVA except that it allows for multiple factors. The dependent variable was the base-10 logarithm of threshold rate minus reference rate, divided by reference rate, henceforth abbreviated $\log(\Delta f_m/f_m)$. A random intercept associated with listener was included to account for variability in means across individuals. Fixed effects of standard AM rate treated categorically, electrode treated categorically, and their interaction were included in the ART ANOVA in version 0.11.1 of the ARTool package (Kay *et al.*, 2021) and version 3.6.0 of R (R Core Team, 2019). Ear was not considered as a random or fixed effect, so thresholds from each ear within each listener were treated as replicate observations. This was done because there was no *a priori* prediction that the left or right ear should yield better (or worse) performance. Degrees of freedom were estimated using the Kenward–Roger approximation (Kenward and Roger, 1997) to provide consistent estimates between ANOVAs and pairwise comparisons. All pairwise comparisons were completed using *t*-tests based upon estimated marginal means with Tukey adjustments for multiple comparisons within the ARTool package. R code and data are available with the supporting information included with this paper to replicate analyses.[1]

### C. Results and discussion

The goal of experiment 1 was to assess the sensitivity to different AM rates of listeners with BiCIs to stimuli delivered at one of four electrodes used in experiment 2. Data from individuals are shown in Fig. 1 plotted as in Chatterjee and Oberzut (2011) for ease of comparison. It was not possible to estimate a threshold from the data in some conditions because individual listeners achieved consistently above or consistently below 71.1% performance for a broad range of oddball AM rates such that the psychometric function did not cross the 71.1% threshold criterion ("CND" upper and lower lines, respectively, in panels of Fig. 1). Because our analysis was rank-based, these thresholds were treated as minimum or maximum threshold ties, respectively. Listener ICS had several psychometric functions that were non-monotonic, so no threshold was recorded in those cases; therefore, this listener was excluded from analysis. There was considerable variability across listeners, consistent with previous experiments examining SAM rate discrimination in listeners with CIs (Chatterjee and Oberzut, 2011; Chatterjee and Peng, 2008). For most listeners, 10- and 30-Hz reference rate thresholds were similar to one another. For the 90-Hz reference rate, thresholds were the most variable, with some listeners performing better than, and others performing worse than, 10- or 30-Hz reference rate thresholds.

Results of an ART mixed-effects ANOVA indicated that there were significant main effects of place of stimulation [$F(1,105) = 14.462$, $p < 0.001$], but not standard AM

https://doi.org/10.1121/10.0016365

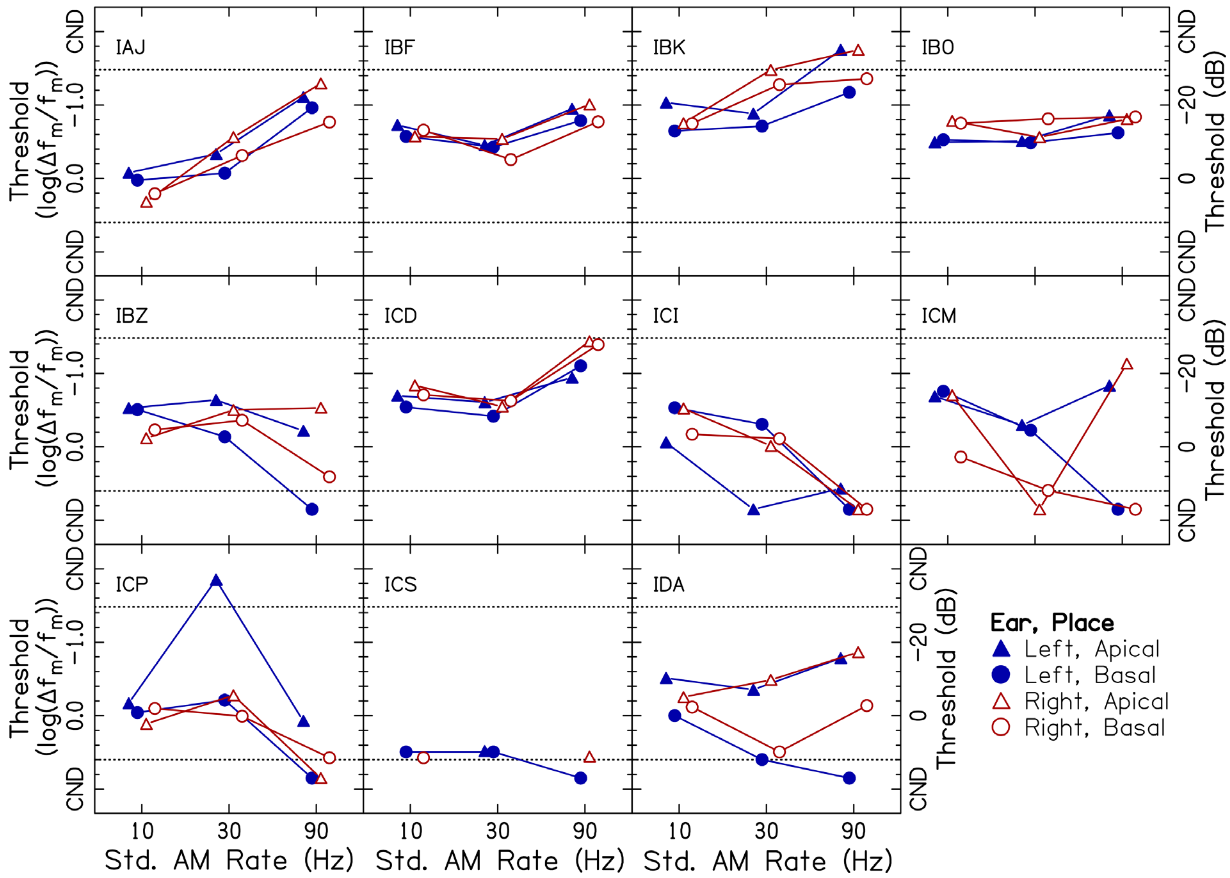


FIG. 1. (Color online) Thresholds for sequential AM rate discrimination. Each panel corresponds to a different listener whose subject code is given in the upper-left corner. The *x* axis corresponds to the standard AM rate. The *y* axis corresponds to the threshold, presented in reverse order such that higher values indicate better performance as in Chatterjee and Oberzut (2011). Triangles and circles represent apical and basal places of stimulation, respectively. Open and closed shapes represent the left and right ear, respectively. "CND" indicates, a threshold could not be determined because performance fell consistently above or consistently below 71.1% correct. The upper and lower dashed lines represent 5 and 31/30 times the standard AM rate, or the maximum and minimum variable AM rates tested, respectively.

rate $[F(2,105) = 82.039,\ p = 0.135]$ or their interaction $[F(2,105) = 2.725,\ p = 0.070]$. Stimulation of apical electrodes resulted in better (lower) AM rate discrimination thresholds compared to basal electrodes.

The AM rate discrimination thresholds obtained in the present study were generally higher than those from previously published studies in listeners with CIs (Chatterjee and Oberzut, 2011; Chatterjee and Peng, 2008; Green *et al.*, 2012; Kreft *et al.*, 2010; Landsberger, 2008). For example, most AM rate discrimination thresholds ranged from –1.0 to 0.5 $\log(\Delta f_m/f_m)$ units in the present study, with some unable to be determined even at 0.5 $\log(\Delta f_m/f_m)$ units, whereas they ranged from –1.5 to 0 $\log(\Delta f_m/f_m)$ units in the most similar and highest powered study by Chatterjee and Oberzut (2011). A value of zero means that $\Delta f_m = f_m$ (e.g., 180 Hz for a standard AM rate of 90 Hz), so positive values indicate that threshold for discrimination was even larger than the standard AM rate. In a study of listeners with NH using SAM tones and the same behavioral task, we also showed that discrimination thresholds were higher than typically observed in that listener population (Anderson *et al.*, 2019b). Thus, it seems likely that something about the task made this experiment more challenging, resulting in poorer performance. Interleaving of standard AM rates within the same trial block may have played a role. This is consistent with findings of Lee (1994) in listeners with NH showing that discrimination thresholds increased when the carrier frequency (and corresponding pitch) was chosen randomly from trial-to-trial. Though the AM depths employed in the present experiment (see Tables I and II) were smaller than the full dynamic range for most listeners, other experiments have shown better (lower) discrimination thresholds when even smaller AM depths (around 20%) were used (Chatterjee and Oberzut, 2011; Chatterjee and Peng, 2008). Moreover, AM rate discrimination saturates for AM depths greater than 20% of the dynamic range for listeners with CIs (Geurts and Wouters, 2001; Lindenbeck *et al.*, 2020). The present study used very high pulse rates (3000 pps), which is one major difference from previous studies. Pulse rate has shown no consistent effects across listeners in previous studies (Green *et al.*, 2012; Lindenbeck *et al.*, 2020), but rates below 3000 pps were used.

Results from the present study showed no significant differences between standard AM rates. This is inconsistent with previous results showing best sensitivity to a 100-Hz standard AM rate (Chatterjee and Oberzut, 2011; Chatterjee and Peng, 2008; Lindenbeck *et al.*, 2020). A closer inspection of Fig. 1 reveals that there were two patterns of results. Five listeners (IAJ, IBF, IBK, IBO, and ICD) showed the best thresholds overall and evidence of better thresholds with 90 Hz. In contrast, six listeners (IBZ, ICI, ICM, ICP, ICS, and IDA) showed worse thresholds and tended to be worst with the 90-Hz standard AM rate. These two groups of listeners with different patterns likely contributed to a non-significant overall effect when data were pooled across listeners. Specifically, the better-performing group demonstrated (1) better thresholds with standard AM rate of 90 Hz, (2) average or better performance than other listeners with CIs in the same task, and (3) thresholds that were measurable or better than the lowest rate that could be measured. The better-performing group also demonstrated performance that was comparable to previous results reported in the literature. In contrast, the poorer performing group demonstrated (1) worse thresholds with standard AM rates of 90 Hz, (2) worse average performance than other listeners with CIs in the same task, or (3) multiple thresholds above the highest rate that could be measured. The most sensitive criterion for delineating groups was threshold at 90-Hz standard AM rate, so performance at 90-Hz standard AM rate was used to group listeners into better or poorer performers throughout this manuscript. Criteria for the better-performing group were measurable or better-than-measurable thresholds at the 90-Hz standard AM rate and mean measurable thresholds better (lower) than or equal to −0.5 at the 90-Hz standard AM rate. Better sensitivity near 100-Hz AM rate relative to lower rates has been demonstrated in most published studies evaluating AM rate discrimination with CIs, except for Green *et al*. (2012).

The present experiment showed that apical stimulation resulted in better (lower) average discrimination thresholds to AM rates than basal stimulation. These results are somewhat consistent with Chatterjee and Peng (2008), who found that a subset of listeners had better (lower) AM rate discrimination thresholds at apical electrodes. Their laboratory did not replicate this result when a similar paradigm was employed with a larger group of listeners (Chatterjee and Oberzut, 2011). Listeners with NH show no consistent effect of carrier frequency (and, correspondingly, place of stimulation) on AM rate discrimination (Anderson *et al*., 2019b; Lee, 1994).

## III. EXPERIMENT 2: SIMULTANEOUS ENVELOPE DISCRIMINATION ACROSS PLACES OF STIMULATION

### A. Motivation

Experiment 2 investigated the sensitivity of differences in AM rates across pairs of electrodes in different configurations (i.e., within or across ears, stimulating the auditory nerve in similar or different frequency regions). The results of experiment 1 were then used to predict sensitivity of electrode pairs.

### B. Methods

#### *1. Listeners*

All listeners that participated in experiment 1 also participated in experiment 2. However, not all listeners were able to complete the task. For more details, see Sec. III C.

#### *2. Stimuli and procedures*

The stimuli and psychophysical procedures employed in the present study were similar to those used in Anderson *et al*. (2019b) except that AM depth was not varied systematically and carriers were electrical pulse trains instead of SAM tones. Testing procedures are explained succinctly here, but for more details, please see Anderson *et al*. (2019b).

Stimuli were presented using the same equipment as experiment 1. The primary difference between experiments 1 and 2 was that in experiment 2, two SAM pulse trains were presented simultaneously via different electrodes in the same interval, either within the same ear or in different ears. Each SAM pulse train was of 600 ms duration and random envelope phase in both electrodes. The timing of electrical pulses was identical at both electrodes. Given that ITD sensitivity declines precipitously for listeners with BiCIs above 300 pps (Kan and Litovsky, 2015; Laback *et al*., 2015), it was unlikely that the simultaneous presentation of individual pulses contributed to temporal binding. All stimuli were presented at a comfortable level.

Experiment 2 consisted of a one-interval, two-alternative forced-choice task where listeners indicated whether the AM rates presented via both electrodes were the same or different. One electrode in an experimental block always presented the standard AM rate (10 or 90 Hz). The other electrode presented either the standard AM rate or a higher, variable AM rate with equal probability of 0.5. Variable AM rates of $\log(\Delta f_m/f_m)$ = –0.71, –0.42, –0.12, 0.17, 0.47, 0.76, and 1.06 were tested an equal number of times in each block to estimate a psychometric function. For most listeners, 30 repetitions per variable AM rate were tested (exceptions noted in supplementary Table I[1]). Listeners were not allowed to repeat stimuli, and visual feedback of the correct answer was provided after each trial. Visual feedback was provided to give listeners maximal opportunities to learn the changes in perception associated with differing AM rate. The possible impact of visual feedback is discussed in more detail in Sec. III D 1.

There were three possible ways to pair electrodes by varying the place of stimulation (apex or base) or ear (left or right). These AM pairing configurations were (1) same place, across ears, (2) different place, across ears, and (3) different place, within ears. Broadly speaking, each configuration represents the different kinds of comparisons the auditory system can complete using the temporal envelope. For a graphical representation of these conditions, see Fig. 2 of Anderson *et al*. (2019b). No attempts were made to match place of stimulation between ears beyond using the same electrode number. Thus, there may have been mismatches in the place of stimulation between ears [for review, see Kan and Litovsky (2015)], but large mismatches occur only in a very small number of individuals (Bernstein *et al*., 2021; Goupell *et al*., 2022). It was assumed that the wide spread of current resulting from monopolar stimulation would lead to excitation of overlapping neural populations in each ear, resulting in within- or across-ear envelope beats from overlapping neural populations. Trials were blocked by AM pairing configurations according to a Latin square design across listeners to partially account for learning effects. For each listener within each AM pairing configuration, there were two different electrode pairs and two possible ways to present the standard and variable AM rates. For example, in the same place, across ears AM pairing configuration, an apical and basal pair were tested. Within the apical and basal pair, the electrode in the left ear could receive the standard or variable AM rate. The order of the two pairs tested (i.e., apical or basal) was randomly chosen. The electrode presenting the variable AM rate (i.e., in the left or right ear) was randomly chosen for the first half of trials, and the other electrode in the pair presented the variable AM rate in the second half of trials. An example testing order is provided in supplementary Table II.[1]

Listeners were familiarized with the task each time that a new AM pairing configuration was introduced. Familiarization took place with the pair of electrodes that was tested first. Listeners were presented with a 10-Hz AM rate in both electrodes. They were then asked to describe the sound to the best of their ability and compare it to some real-life examples. Next, listeners were presented with 10 Hz in the reference (standard AM rate) electrode and 50 or 100 Hz in the variable electrode. A hypothetical response could be "10 Hz in both ears sounds like a ringing telephone, but 10 Hz in the left ear and 100 Hz in the right ear sounds like a ringing telephone and busy signal mixed together." The experimenter documented these descriptions in case the listeners became confused and descriptions were used during later testing. For example, "I see that this might be getting frustrating because the feedback is telling you that your answer is incorrect. Remember the ringing telephone and the busy signal? Try listening for those to tell the sounds apart." Without exception, listeners described 10;50 and 10;100 Hz pairings as similar to one another (sometimes the latter, higher rate being higher in pitch). The process then was repeated, but with 90-Hz AM rate in the reference electrode and 450- or 900-Hz AM rate in the variable electrode. These correspond to $\log(\Delta f_m/f_m)$ values of 0.60 and 0.95. Reports of sounds tended to consider comparisons to real-life sounds (e.g., rotary or digital telephones, doorbells, animals), pitch (low, high, or absent), changes in loudness (e.g., sound being turned on/off, consistent), location (e.g., near/far from the head, static vs moving), and quality (e.g., "tone-like," "clicking"). Finally, listeners completed a practice block of the experiment with the AM rates used in the familiarization procedure. The time spent during familiarization varied considerably across listeners, and this sometimes took up to 4 h to complete. During testing, if there was evidence that the listener became confused (e.g., a change in the shape of their psychometric function), they were given a practice block containing only the two highest variable AM rates, and data were collected *de novo*.

Four blocks of trials were excluded from figures and analyses.[2] In the same place, across ears configuration, listener IBF showed uncharacteristically high bias toward responding "Different" for all intervals containing 90 Hz (standard and variable AM rate trials; $n = 5$ repetitions per variable AM rate). This occurred in the final block of the testing for this configuration with apical electrodes. In the different place, across ears configuration, listener IBF showed an uncharacteristic U-shaped psychometric function for the 10-Hz standard AM rate ($n = 8$ repetitions per variable AM rate). This occurred when listener IBF stayed late to complete an additional block of trials after a full day of testing. In the different place, within ears configuration in the right ear, listener ICM showed an uncharacteristic inverted U-shaped psychometric function and high amounts of bias toward responding "Different" with the 10-Hz standard AM rate ($n = 8$ repetitions per variable AM rate). This occurred during listener ICM's first full block of trials in the experiment. In the different place, within ears configuration in the right ear, listener IDA showed larger than normal amounts of bias and performance close to floor ($n = 8$ repetitions per variable AM rate). This occurred on listener IDA's first full block of trials in the experiment.

One of the challenges in designing this experiment was to limit the usefulness of attending to only the higher AM rate to make decisions on each trial. For example, the listener could have simply attended to the electrode with the variable AM rate and responded "different" if it increased above the standard AM rate, effectively shifting this task to something like that in experiment 1. Several methodological choices were made to minimize the utility of such a listening strategy. First, two psychometric functions corresponding to standard AM rates of 10 and 90 Hz were interleaved. Second, an overlapping range of variable AM rates was tested (the highest variable AM rates re: 10 Hz and lowest variable AM rates re: 90 Hz). Third, a small amount of AM rate roving [$\pm 0.12$ in $\log(\Delta f_m/f_m)$ units] was applied to both electrodes on each trial. AM rate roving was accomplished by multiplying the variable and standard AM rate to be tested by a factor chosen randomly between 3/4 and 4/3 on each trial. Roved rates were sampled from a uniform distribution [described in more detail in Table II of Anderson *et al.* (2019b)]. At the two highest variable AM rates tested with the roved 10-Hz standard AM rate, 50% of trials would have overlapped with the roved 90-Hz standard AM rate. Relying on a single electrode to complete the task would result in a precipitous decrease in sensitivity at the two highest variable AM rates for the 10-Hz standard AM rate and/or less sensitivity overall for the 90-Hz standard AM rate.

### 3. Analysis

Data were analyzed using a mixed-effects ART ANOVA including random effect of listener and fixed effects of variable AM rate [$\log(\Delta f_m/f_m)$] treated categorically, standard AM rate treated categorically, AM pairing configuration treated categorically, and their interactions. The dependent variable was sensitivity in $d'$ units. Sensitivity in $d'$ units was calculated using Eq. (1),

$$d'_i = \Phi^{-1}\left(\frac{\text{Hits}_i}{\text{Hits}_i + \text{Misses}_i}\right) - \Phi^{-1}\left(\frac{\text{False Alarms}}{\text{False Alarms} + \text{Correct Rejections}}\right), \quad (1)$$

where $d'_i$ is sensitivity for the $i$th variable AM rate; $\Phi^{-1}$ is the inverse standard normal cumulative density function; $\text{Hits}_i$ and $\text{Misses}_i$ are the numbers of "different" "same" responses for the $i$th variable AM rate, respectively; False Alarms and Correct Rejections are the number of "same" and "different" responses for all standard AM rate trials, respectively. If the first or second quotient in Eq. (1) was equal to 1 or 0, it was reset to 0.99 or 0.01 to avoid infinite values from the inverse standard normal function. There were an equal number of "signal" and "no signal" trials overall, meaning that a greater number of "no signal" trials (30 repetitions $\times$ 7 variable AM rates $=$ 210 "no signal" presentations per standard AM rate) were used to compute $d'$ at each variable AM rate in $\log(\Delta f_m/f_m)$ units. The same statistical packages were used as described in Sec. II B 3.

In a second set of analyses relating the results of experiments 1 and 2, rank-based, mixed-effects regression included fixed effects of worse threshold in experiment 1 (for one electrode in a pair, defined in more detail in Sec. III C 3) treated continuously, variable AM rate [$\log(\Delta f_m/f_m)$] treated categorically, and standard AM rate treated categorically. These fixed effects were used to predict sensitivity in $d'$ units. To prevent using the same thresholds from experiment 1 multiple times within one model to predict different conditions in experiment 2, separate regressions were completed for each AM pairing configuration. For example, say that the thresholds from experiment 1 ordered from best to worst were R4, R16, L16, and L4. Then the basal electrode in the left ear (L4) would be used to predict the sensitivity of the basal pair of electrodes in the same place, across ears configuration and the left ear in the different place, within ears configuration because it was worse than R4 and L16, respectively. Rank-based, mixed-effects regression was implemented using version 0.5 of the rlme package in R (Bilgic and Susmann, 2013).

For consistency with previous reports (Ihlefeld *et al.*, 2015), an additional analysis was completed using the within-subject correlation procedure described by Bland and Altman (1995) (fixed-effects ANOVA including intercepts for each listener). When these models were fit with sensitivity in $d'$ units using the previously described methods, they systematically underestimated the highest and lowest values of sensitivity, resulting in curvilinear, non-normally distributed model residuals. Thus, sensitivity in $d'$ units was transformed according to the top half of a sigmoidal function[3] as described in Eq. (2),

$$d'^{*}_{ij} = \frac{1}{1 + e^{-\left(d'_{ij} - d'_{\min}\right)}}, \quad (2)$$

where $d'^{*}_{ij}$ is the transformed dependent variable for the $j$th observation from the $i$th listener, $d'_{ij}$ is the $j$th observation of sensitivity for the $i$th listener, and $d'_{\min}$ is the minimum value of sensitivity observed in the experiment across all listeners. Effectively, this equation compressed the highest values of sensitivity, which corrected some systematic overestimation of the dependent variables, but there was still some evidence of underestimation of residuals at the worst (lowest) sensitivities. To see the relationship between the observed sensitivity in $d'$ units and the transformed values, see the data and code accompanying this paper.[1] This transform was chosen because it resulted in the best improvement of model diagnostics. Model diagnostics consisted of plots of residuals across predicted values to check for homogeneity of variance, as well as quantile-quantile plots and Shapiro–Wilk tests to check normality of residuals. Other transforms tested were log, Box–Cox, several sigmoidal functions, and reciprocal of $d'$.

### C. Results

The goal of the present experiment was to assess sensitivity to differences in AM rate across pairs of electrodes in various configurations for listeners with BiCIs. Mean and individual data for listeners with BiCIs are shown in Fig. 2(A), where higher values indicate better performance and vice versa. Figure 2(A) demonstrates that there was substantial variability across listeners, both with respect to overall performance and effects of independent variables. There were three basic trends in performance: (1) similar (low) sensitivity across variable AM rates; (2) increasing sensitivity until the two highest variable AM rates, where sensitivity began to decline; or (3) monotonically increasing sensitivity. Similar patterns were observed in listeners with NH, with a higher proportion of listeners able to complete the task and showing better sensitivity (Anderson *et al.*, 2019b). Individual data from listeners with poorer performance in experiments 1 and 2 are shown by the dashed orange lines (IBZ, ICM, and IDA). This will be explored in more detail in Sec. III C 1. Most listeners reported the task as very difficult, which may have contributed to variability in performance across individuals. Figure 2(B) shows a subset of the data from listeners with NH in a previously published experiment using the same paradigm with 50% AM depth for both places of stimulation (Anderson *et al.*, 2019b). Though there was also considerable variability in listeners with NH completing the same task with SAM tones, listeners with BiCIs showed worse performance (less sensitivity) and more poorly behaved psychometric functions (e.g., more non-monotonicities, greater bias).

In the previously published study of listeners with NH, additional ANOVAs were completed in experiment 2 excluding the two greatest variable AM rates [$\log(\Delta f_m/f_m)$] relative to the 90-Hz standard AM rate because they likely

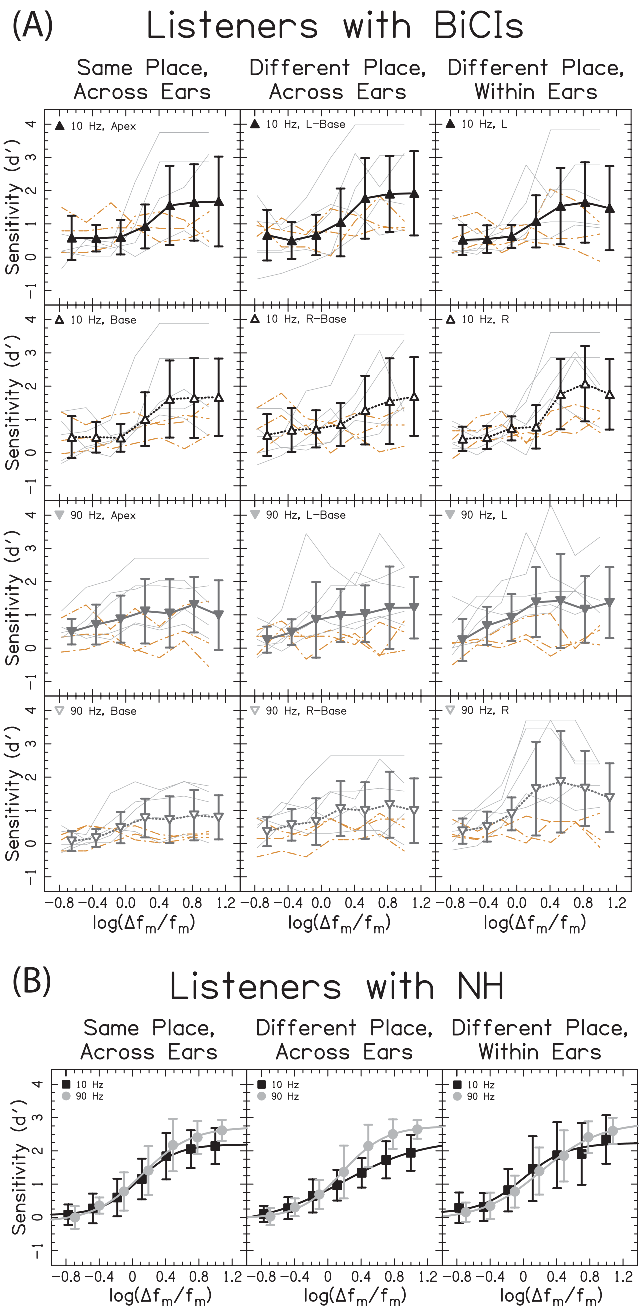


FIG. 2. (Color online) Mean ± 1 standard deviation sensitivity across listeners for all three AM pairing configurations for listeners with (A) BiCIs and (B) NH. Performance for 10-Hz standard rate is shown in black, and performance for 90-Hz standard rate is shown in gray. Each panel corresponds to a different AM pairing configuration. The $x$ axis corresponds to the difference in AM rate between the standard and variable AM rate [see Table II of Anderson *et al.* (2019b) for values of AM rates in Hz]. The $y$ axis corresponds to sensitivity in $d'$ units. (A) Individual performance is shown in thin lines offset to the left. The electrode pair indicated by the shape and line type is given in the figure legend and varied depending upon the AM pairing configuration for listeners with BiCIs. Poorer performers (listeners IBZ, ICM, and IDA) are shown by dashed orange lines.

resulted in greater loudness than other stimuli in the experiment. In the present study, the two greatest variable AM rates [$\log(\Delta f_m/f_m)$] would have resulted in a minimum of two pulses per sinusoidal cycle for listeners with BiCIs. For example, at a standard AM rate of 90 Hz, with the greatest $\log(\Delta f_m/f_m) = 1.057\,08$ (previously rounded to 1.06 for brevity) and largest AM rate rove of +0.12, the variable AM rate would be 1488.55 Hz. The auditory system does not "know" to reconstruct stimuli using sine waves from discrete pulses. For example, with only two pulses per cycle, when the envelope phase was 0, the listener would be presented with a SAM pulse train with pulses at maximum and minimum level. When the envelope phase was $\pi$, the listener would be presented with a constant-amplitude pulse train. Thus, the quality of a SAM pulse train with only two pulses per cycle could change drastically with its sinusoidal phase. During familiarization, some listeners with BiCIs anecdotally described stimuli at highest AM rates (means of 1116 Hz; range of 837–1489 Hz) as changing in quality across presentations, whereas lower AM rates remained consistent across presentations.

Based on psychophysical and physiological experiments, four to five pulses per cycle are recommended (Busby *et al.*, 1993; McKay *et al.*, 1994; Wilson, 1997). Thus, to more fairly compare results in the present study with NH results and to account for undersampling of sinusoids, we replicated the analysis procedure in Anderson *et al.* (2019b) excluding the two highest variable AM rates [$\log(\Delta f_m/f_m)$] from the dataset. The highest possible AM rate analyzed would therefore be 471.9 Hz. Despite the challenges for listeners with BiCIs, there was a significant effect of variable AM rate [$\log(\Delta f_m/f_m)$] on sensitivity [$F(4,443) = 30.472$, $p < 0.0001$], confirming that increasing differences in AM rate between each electrode in a pair resulted in better sensitivity.

#### 1. Effects of standard AM rate

Typically, standard AM rates near 100 Hz for SAM stimuli result in best AM rate discrimination and binaural sensitivity for listeners with BiCIs (Anderson *et al.*, 2019a; Chatterjee and Oberzut, 2011; Chatterjee and Peng, 2008; van Hoesel *et al.*, 2009). Changes relative to the standard AM rate were normalized by measuring variable AM rates in $\log(\Delta f_m/f_m)$ units, allowing for fairer comparisons across standard AM rates. There was no significant difference between standard AM rates [$F(1,443) = 2.571$, $p = 0.110$], in agreement with experiment 1 and previous results using the same task with listeners with NH (Anderson *et al.*, 2019b). There was a significant standard AM rate × variable AM rate [$\log(\Delta f_m/f_m)$] interaction [$F(4,443) = 2.770$, $p < 0.05$], suggesting that the slope of the psychometric function changed with standard AM rate, consistent with results from listeners with NH (Anderson *et al.*, 2019b). In Fig. 2(A), individual traces from listeners IBZ, ICM, and IDA are highlighted in orange because they showed poorer or inconsistent sensitivity to the 90-Hz standard AM rate in experiment 1. The other listeners in the poorer performing group from experiment 1 were unable to complete experiment 2. The results of Fig. 2 showed that these listeners had near or below average sensitivity in experiment 2 at the 10-Hz standard AM rate and were consistently poorer with the 90-Hz standard AM rate. This suggests that there were two groups of listeners: those who could perform both tasks, showing improved sensitivity for the 90-Hz standard AM rate consistent with the previous literature (listeners IAJ, IBF, IBK, IBO, and ICD), and those who showed poorer overall sensitivity at the 90-Hz standard AM rate (IBZ, ICI, ICM, ICP, ICS, and IDA). When each group of listeners who participated in experiment 2 were tested using separate ART ANOVAs, both showed significant effects of standard AM rate. The group with better overall sensitivity showed significantly better performance with the 90-Hz standard AM rate ($p < 0.05$), and the group with lower overall sensitivity showed significantly better performance with the 10-Hz standard AM rate ($p < 0.0001$).[4]

### 2. Effects of AM pairing configuration

Three different AM pairing configurations were tested in the present study representing the possible ways in which the temporal envelope can be compared for listeners with bilateral hearing. The same place, across ears configuration was hypothesized to result in greatest sensitivity because of the addition of a binaural beat cue. Mean performance across the five smallest variable AM rates is shown for listeners with BiCIs and NH in Fig. 3. There was a significant effect of AM pairing configuration [$F(2,443) = 5.213$, $p < 0.01$]. In contrast to our initial hypothesis, *post hoc* analysis indicated that sensitivity was significantly better for the different place, within ears compared to the same place, across ears AM pairing configurations [$t(443) = 3.160$, $p < 0.01$]. This is most visually striking in Figs. 2(A) and 3 for the highest variable AM rates and particularly for the 90-Hz standard AM rates (lower panels). Median sensitivity with the 10-Hz standard AM rate was 0.684 in the same place, across ears configuration, 0.757 in the different place, across ears configuration, and 0.621 in the different place, within ears configuration. Median sensitivity for the 90-Hz standard was 0.423 in the same place, across ears configuration, 0.544 in the different place, across ears configuration, and 0.749 in the different place, within ears configuration. However, there was no significant difference between the different place, within ears compared to the different place, across ears configuration [$t(443) = 2.156$, $p = 0.080$] or the different place, across ears compared to same place, across ears configuration [$t(443) = 1.004$, $p = 0.574$].

There was also no significant AM pairing configuration × standard AM rate interaction [$F(2,443) = 2.691$, $p = 0.069$] or AM pairing configuration × variable AM rate [$\log(\Delta f_m/f_m)$] interaction [$F(8,443) = 0.903$, $p = 0.484$], or three-way AM pairing configuration × standard AM rate × variable AM rate [$\log(\Delta f_m/f_m)$] interaction [$F(8,443) = 0.430$, $p = 0.903$].

### 3. Role of the poorer place of stimulation

We hypothesized that in pairs of electrodes, the electrode yielding poorest temporal sensitivity in experiment 1 would predict the sensitivity of pairs of electrodes in experiment 2. Variability in thresholds from experiment 1 was predicted to be due in part to poorer transmission of temporal information through the auditory system. Accordingly, the poorer of the two electrodes defined based on the thresholds measured in experiment 1 (at the same standard AM rate) was used as the fixed-effect predictor of sensitivity in experiment 2 in the regression.

Results are summarized in Fig. 4. The $x$ axis shows the poorer AM rate discrimination threshold from experiment 1 for the pair of electrodes tested in experiment 2. The $y$ axis shows the average sensitivity across the five highest variable AM rates [$\log(\Delta f_m/f_m)$] tested in experiment 2. There appears to be a negative linear relationship between these two variables within each sub-panel of Fig. 4 when viewed

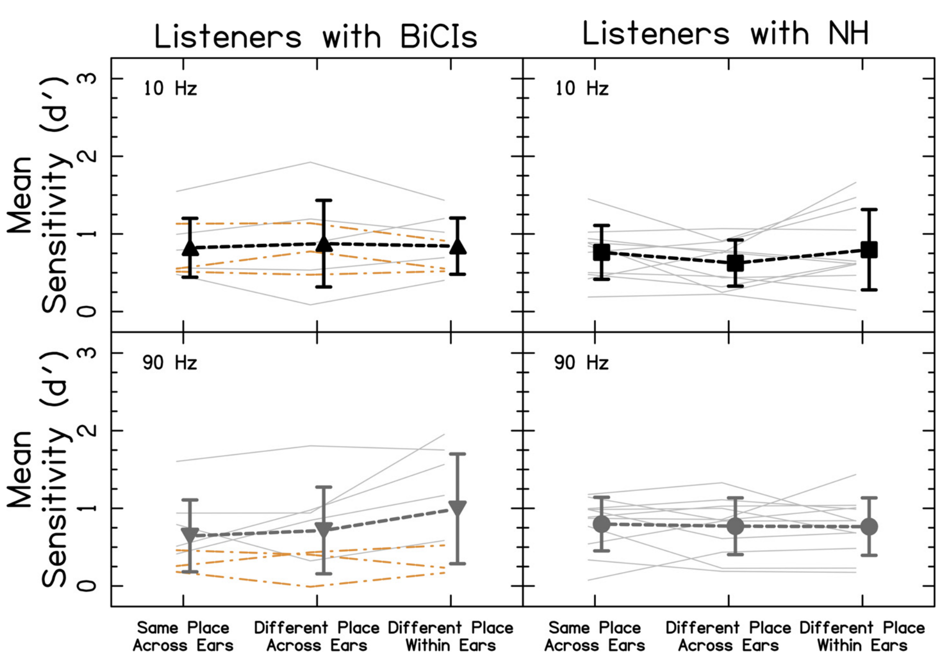


FIG. 3. (Color online) Mean sensitivity in each AM pairing configuration. Mean sensitivity was computed across the five smallest variable AM rates in each AM pairing configuration for listeners with BiCIs and NH shown in the left and right columns, respectively. Performance for 10-Hz standard rate is shown in black, and performance for 90-Hz standard rate is shown in gray. The $x$ axis corresponds to different AM pairing configurations. The $y$ axis corresponds to sensitivity in $d'$ units. Individual performance is shown in thin lines offset to the left. Poorer performers (listeners IBZ, ICM, and IDA) are shown by dashed orange lines.

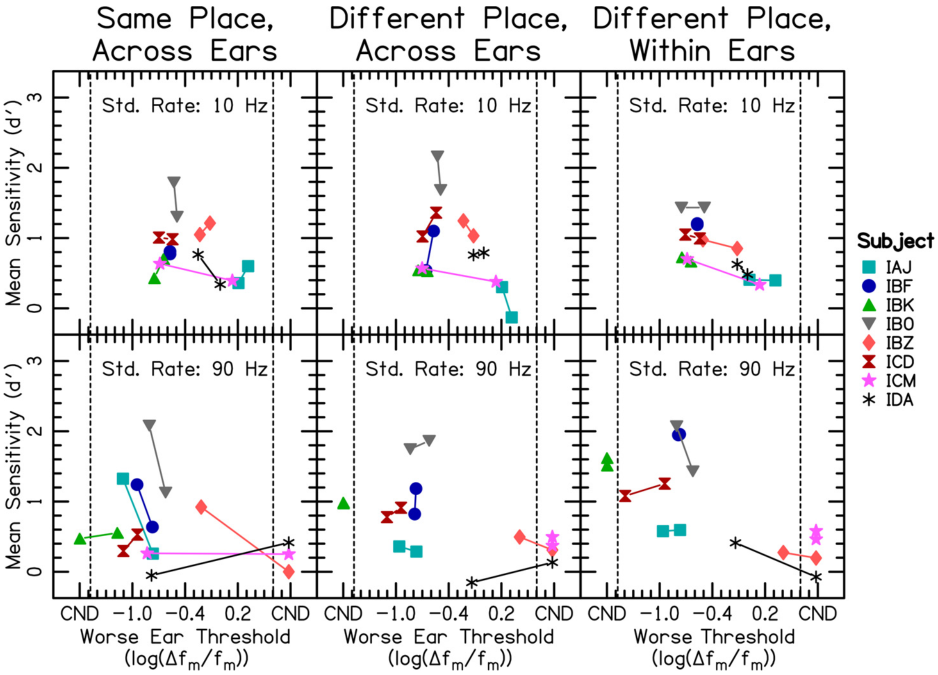


FIG. 4. (Color online) Relationship between experiments 1 and 2. Top and bottom rows correspond to standard AM rates of 10 and 90 Hz, respectively. Each column corresponds to the three AM pairing configurations. Two symbols are shown per listener representing the two possible pairings within each configuration (e.g., apical or basal within the same place, across ears configuration). The *x* axis corresponds to the threshold of the electrode yielding the poorer (higher) threshold in experiment 1 of the pair tested in experiment 2. The *y* axis corresponds to the sensitivity of pairs of electrodes averaged across the five highest variable AM rates. The shape and color given in the figure legend on the right indicate the listener.

within and across individuals. This suggests that as performance became worse (i.e., threshold increased) in experiment 1, sensitivity decreased in experiment 2. Figure 4 does not describe the substantial amount of variability in sensitivity observed within individuals due to changes in variable AM rate [$\log(\Delta f_m/f_m)$] that can be seen more clearly in Fig. 2.

Results from the three regressions for each AM pairing configuration are reported in Table III. Thresholds from experiment 1 that could not be estimated, i.e., the upper and lower "CND" values in Fig. 1, were re-coded as 0.73 or –1.60, respectively, because those values were slightly above and below the maximum and minimum measurable thresholds. Threshold from experiment 1 of the worse electrode in the pair significantly predicted sensitivity in experiment 2 for the same place, across ears ($p < 0.01$), different place, across ears ($p < 0.0001$), and different place, within ears ($p < 0.0001$) configurations. This result is consistent with the hypotheses. The coefficients from the regressions imply that there was a larger decrease in sensitivity associated with thresholds from experiment 1 for the different place, within ears compared to the same place, across ears configurations. Confidence intervals at 95% associated with the predicted decrease in sensitivity for both configurations are [–0.364, –0.042] and [–0.669, –0.363], respectively. This indicates that the sensitivity decreased significantly more with the electrode yielding poorer thresholds in experiment 1 for the different place, within ears compared to the same place, across ears configuration.

An alternative analysis approach provided by Ihlefeld *et al.* (2015) is to fit a similar, fixed-effects model including listener as a fixed effect and excluding interactions, finally computing within-subject correlations for experiments 1 and 2. One benefit of this analysis method is that variability associated with independent measures (variable AM rate, standard AM rate, changes in mean associated with listener) is accounted for before the relationship with experiment 1 thresholds is estimated. For consistency with their report, within-subject correlations are shown in Table IV based on the worst, mean, best, and difference between experiment 1

TABLE III. Results of rank-based, mixed-effects regression relating the electrode yielding the worse threshold in experiment 1 to sensitivity of the pair in experiment 2. Dependent variable was sensitivity in $d'$ units. Categorical variables were coded as 0–1. The value represented by each estimate is shown in parentheses beside the name of the variable. *p*-values were calculated using the normal distribution (as opposed to t-distribution) by default in the rlme package in R.

| | Same place, across ears | | | | Different place, across ears | | | | Different place, within ears | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Effect | Estimate | Standard error | *t*-statistic | *p* | Estimate | Standard error | *t*-statistic | *p* | Estimate | Standard error | *t*-statistic | *p* |
| Intercept | 0.555 | 0.185 | 3.003 | <0.01 | 0.729 | 0.215 | 3.393 | <0.001 | 0.796 | 0.274 | 2.901 | <0.01 |
| Exp. 1 threshold | −0.203 | 0.082 | −2.485 | <0.05 | −0.365 | 0.089 | −4.100 | <0.0001 | −0.516 | 0.078 | −6.587 | <0.0001 |
| Standard rate (90 Hz) | −0.190 | 0.092 | −2.063 | <0.05 | −0.143 | 0.105 | −1.370 | 0.171 | 0.091 | 0.094 | 0.974 | 0.330 |
| $\log(\Delta f_m/f_m)$ (−0.418) | 0.074 | 0.142 | 0.522 | 0.601 | 0.119 | 0.165 | 0.721 | 0.471 | 0.151 | 0.148 | 1.021 | 0.307 |
| $\log(\Delta f_m/f_m)$ (−0.123) | 0.169 | 0.142 | 1.195 | <0.05 | 0.203 | 0.165 | 1.225 | 0.221 | 0.387 | 0.148 | 2.613 | <0.01 |
| $\log(\Delta f_m/f_m)$ (0.172) | 0.496 | 0.142 | 3.505 | <0.001 | 0.466 | 0.165 | 2.818 | <0.01 | 0.656 | 0.148 | 4.429 | <0.0001 |
| $\log(\Delta f_m/f_m)$ (0.467) | 0.639 | 0.142 | 4.515 | <0.0001 | 0.650 | 0.165 | 3.930 | <0.0001 | 1.000 | 0.148 | 6.746 | <0.0001 |

TABLE IV. Within-listener correlations between experiment 1 thresholds and sensitivity in experiment 2. These correlations were calculated using the procedure discussed in Bland and Altman (1995), consistent with Ihlefeld *et al*. (2015). No corrections for multiple comparisons were made to allow for fairer comparisons with the sole relationship analyzed in Ihlefeld *et al*. (2015). Accordingly, *p*-values are not meant to convey "significant" relationships, but correlation effect sizes.

| | Same place, across ears | | Different place, across ears | | Different place, within ears | |
|---|---|---|---|---|---|---|
| Experiment 1 threshold(s) | Pearson *r* | *p* | Pearson *r* | *p* | Pearson *r* | *p* |
| Maximum threshold | –0.149 | 0.092 | –0.272 | <0.01 | –0.253 | <0.01 |
| Mean of thresholds | –0.123 | 0.168 | –0.250 | <0.01 | –0.184 | <0.05 |
| Minimum threshold | –0.075 | 0.399 | 0.201 | <0.05 | 0.060 | 0.516 |
| Difference between thresholds | –0.123 | 0.166 | –0.185 | <0.05 | –0.304 | <0.001 |

thresholds in the pair. The dependent variable was sensitivity in $d'$ values transformed according to Eq. (2). Thresholds that could not be estimated from experiment 1 were removed from analysis. When using the worst threshold from experiment 1 as the predictor, these correlations revealed negative within-subject associations for all pairing configurations except the same place, across ears configuration. The strongest association occurred for the different place, within ears configuration. Since Ihlefeld *et al*. (2015) evaluated sensitivity to ITD cues, the most similar AM pairing configuration is same place, across ears. Our within-subject correlation was weaker than that of Ihlefeld and colleagues (–0.149 vs 0.33, respectively), and other configurations resulted in slightly larger correlation coefficients (–0.272 and –0.253). Since the present study assessed the relationship between threshold from experiment 1 (lower = better) and sensitivity (higher = better), we showed a negative association. Ihlefeld *et al*. (2015) related monaural and binaural temporal sensitivity (higher = better in both cases), so their study showed a positive association. Their study tested three pairs of electrodes rather than two and tested four rates rather than two, which would have provided greater statistical power. Their study also did not need to account for factors varied in the binaural task (i.e., variable AM rate), which could add to residual variance.

Interestingly, the degree of asymmetry in thresholds from experiment 1 (i.e., the difference in threshold between the electrodes) was similarly effective at predicting sensitivity for pairs of electrodes (Table IV). Asymmetry in AM rate discrimination thresholds was only moderately correlated with the worse AM rate discrimination threshold, with Pearson correlation coefficients of –0.123, –0.185, and –0.304 for the three AM pairing configurations. This suggests that a place of stimulation yielding poorer temporal information, the difference in the fidelity of temporal information, or both may play a role in how accurately listeners are able to compare AM rate across place of stimulation in both ears.

### D. Discussion

Results from the present experiment demonstrated that listeners with BiCIs had varying sensitivity to differences in AM rate between pairs of electrodes for SAM pulse trains presented in (1) same place, across ears, (2) different place, across ears, and (3) different place, within ears configurations. We expanded upon previous research on temporal envelope processing in listeners with CIs by examining sensitivity to differences in the temporal envelope across places of stimulation in both ears for the same listeners with BiCIs. The results indicated poor performance for listeners with BiCIs (e.g., non-monotonicities, low overall sensitivity relative to listeners with NH). This finding is consistent with the literature concerning comodulation masking release (i.e., benefit from similar temporal fluctuations in masker stimuli) showing no benefit for listeners with unilateral CIs and attributing the lack of benefit to poor overall performance, reduced spectral resolution, and additional confounding interference to the presence of temporal modulations (Ihlefeld *et al*., 2012; Pierzycki and Seeber, 2014). It has been proposed that auditory object formation begins with the simultaneous comparison of temporal structure across spectral channels (e.g., Shinn-Cunningham, 2008), suggesting that comparison of temporal envelopes might underlie comodulation masking release and other, more complex auditory grouping tasks. Thus, another factor in the lack of comodulation masking release in listeners with CIs may be reduced sensitivity to differences in the temporal envelope across spectral channels compared to listeners with NH. Listeners with BiCIs showed less sensitivity to differences (i.e., decoherence) in the temporal envelope presented to similar places of stimulation in each ear compared to listeners with NH in previous experiments (Goupell, 2015; Goupell and Litovsky, 2015). While performance co-varied with acoustic hearing history, this was not sufficient to explain differences between groups (Goupell, 2015). Findings from the present experiment provide additional evidence to suggest that a lack of comodulation masking release could be due to a poorer ability to compare temporal envelope information between spectral channels (within and across ears) for listeners with CIs compared to NH.

The present study also found that listeners with BiCIs showed better sensitivity to AM rate differences when stimuli were presented to the same ear rather than the same place of stimulation across ears. This contrasts with the results from listeners with NH using the same paradigm, who showed no significant difference between AM pairing configurations (Anderson *et al*., 2019b). At the variable AM rates tested in the present experiment, the use of binaural

https://doi.org/10.1121/10.0016365

beats (cues that could have been useful in the same place, across ears configuration) would only occur for the smallest values of variable AM rate, where listeners showed the poorest sensitivity. There may have been greater differences in sound quality (e.g., timbre or pitch) across rather than within ears given that several additional factors contribute to differences in CI outcomes between ears (e.g., electrode placement, duration of deafness). Listeners with BiCIs are tolerant of large interaural mismatches in place of stimulation for pitch perception, where they fuse stimuli over a large frequency range (∼1 octave; Reiss *et al.*, 2018). However, binaural spatial processing (e.g., sensitivity to ITDs) degrades over much smaller mismatches (e.g., Kan *et al.*, 2013; Kan *et al.*, 2019). Thus, it may be that pitch, timbre, or other sound quality changes were assessed more efficiently within each ear before being compared across ears, and in the absence of sensitivity to spatial cues, this resulted in better sensitivity to temporal differences at different places of stimulation within the same ear. One other possibility is that listeners had access to additional cues when stimuli were presented monaurally rather than binaurally. For example, there may have been a region of overlap in excitation between electrodes when stimulated in the same ear resulting in an envelope beat. Such strategies have been noted in similar experiments with listeners with NH or CIs (Kreft *et al.*, 2013).

The present experiment also showed that sensitivity to differences in AM rate for pairs of electrodes was limited by the electrode yielding poorest sensitivity to temporal information. The previous study by Ihlefeld *et al.* (2015) showed that the sensitivity to temporal information in the worse ear predicted ITD sensitivity. Binaural comparisons in the auditory pathways are completed by a specialized system that relies on precision of temporal inputs (e.g., Golding and Oertel, 2012; Joris and Trussell, 2018). For this reason, we expected that sensitivity to AM rate differences would be best predicted by the ear with poorer sensitivity to temporal information for the same place, different ear compared to other AM pairing configurations. Instead, the evidence of this relationship was strongest in the different place, within ears configuration, with a more consistent and stronger predicted effect. These results imply that comparisons of temporal information across different frequency regions within the same ear were more highly impacted by differences in temporal sensitivity across the electrode array than binaural processing in listeners with BiCIs. Given the small sample size of the present study and lack of literature on this topic, these results should be treated as preliminary evidence. If the binaural system is already considerably taxed by the effects of deafness and nature of CI stimulation, then it seems reasonable that listeners would show limited benefit of improved temporal resolution in the poorer ear (i.e., a weaker relationship between the temporal resolution in the poorer ear and binaural sensitivity). This is supported by the variable sensitivity to ITDs in listeners with BiCIs (Kan and Litovsky, 2015; Laback *et al.*, 2015; Thakkar *et al.*, 2020). Alternatively, the relationship between the place of stimulation yielding poorer sensitivity and the sensitivity of the different place, within ears pair may simply reflect the greater overall sensitivity in the different place, within ears configuration. Because listeners with NH showed a similar relationship but no main effect of AM pairing configuration (Anderson *et al.*, 2019b), it is also possible that a shared mechanism like monaural envelope beating played a role.

The present experiment demonstrates that the degree of asymmetry in temporal fidelity between ears is similarly effective as the poorer ear in predicting sensitivity, especially at different places of stimulation within the same ear (Table IV). In the NH study using the same paradigm, only asymmetric or symmetrically good temporal fidelity was simulated (Anderson *et al.*, 2019b). That is, there was no condition where two poorly performing ears were simulated, making it difficult to disentangle whether the results were driven by the poorer place of stimulation, an asymmetry between places of stimulation, or both. Some research in speech understanding suggests that interaural asymmetries themselves lead to poorer bilateral performance for listeners with BiCIs (e.g., Mosnier *et al.*, 2009; Yoon *et al.*, 2011), but the effect of interaural asymmetry has been largely unexplored and poorly controlled in the literature. Another hypothesis is that attention is mandatorily shifted away from the ear with poorer information when the ears are interaurally asymmetric (e.g., Goupell *et al.*, 2016; Goupell *et al.*, 2021). Thus, it remains of interest to delineate effects of the poorer performing channels of information and the degree of asymmetry between them.

### 1. Comparison with NH results

Compared to listeners with NH completing the same task with very similar stimuli (Anderson *et al.*, 2019b), listeners with BiCIs showed considerably less sensitivity and more unreliable trends across variable AM rates (Fig. 2). In several cases, listeners with BiCIs showed no sensitivity to differences in AM rate at all. More listeners with BiCIs ($n = 3$ of 11; listeners ICI, ICP, and ICS) could not complete the task than listeners with NH ($n = 1$ of 12; testing terminated after familiarization). Many different factors may have played a role in these differences between groups. Sources of differences between listener groups are explored in greater detail in Sec. IV C.

One factor that likely contributed to performance in both groups was the use of visual feedback of the correct answer. It was thought that providing visual feedback would help listeners anchor performance based upon trials where they could clearly hear two different AM rates. However, if the listeners were completing the task correctly and were completely unbiased (i.e., reported “different” on zero trials where the same AM rate was presented to both electrodes), they would have responded “same” more often than “different” and would have been given feedback that, in fact, the correct answer was “different.” These responses would have been provided in trials when the variable AM rate was below identification threshold. Instead of anchoring performance in accordance with the goals of the experiment, visual feedback may have led listeners to question their responses and try new listening strategies. Several listeners were still able to complete the task, but feedback may have played a role in situations where responses were counter-intuitive [e.g., non-monotonic curves in Fig. 2(A)]. Based on these results, it seems that the best course of action may have been to provide feedback during familiarization and remove it during the experiment. Listener-reported difficulty played a role in the decision to include feedback during testing. Listeners with BiCIs and NH reported extreme difficulty with the task, so it is unclear whether excluding feedback would have even been possible.

The present study replicated all of the significant effects previously demonstrated in the same task using similar stimuli in listeners with NH when the two highest variable AM rates were excluded from analysis [Fig. 4; see also Table III of Anderson *et al.* (2019b)]. The present study also found a significant effect of AM pairing configuration, which was not observed in listeners with NH [$p < 0.01$ vs $p = 0.109$ in Anderson *et al.* (2019b)].

The lack of better binaural sensitivity to the standard AM rate of 90 Hz relative to lower rates differs from previous binaural studies showing better sensitivity for SAM stimuli near 90 Hz in listeners with BiCIs and NH (Anderson *et al.*, 2019a; Bernstein and Trahiotis, 2002; Bernstein and Trahiotis, 2009; van Hoesel *et al.*, 2009). When the two highest variable AM rates were included in the analysis of listeners with NH, the 90-Hz standard AM rate resulted in significantly greater sensitivity than the 10-Hz standard AM rate. Results from the present study showed no significant effect of standard AM rate. This resulted because listeners with BiCIs consisted of two distinct groups: poorer performers who were more sensitive at lower (10 Hz) than higher rates (90 Hz) and better performers who were more sensitive at higher than lower rates.

## IV. GENERAL DISCUSSION

Patients with BiCIs are faced with many different challenges that limit access to sound source segregation cues. One important factor is the interface between CI electrodes and the auditory nerve, where a poor interface creates a bottleneck to sound source segregation cues. In the present study, we were interested in whether differences in the temporal fidelity of sounds conveyed via different portions of the auditory nerve contribute to the ability to compare temporal features across frequency (i.e., place of stimulation) and ears for listeners with BiCIs. Experiment 1 investigated monaural temporal thresholds (AM rate discrimination) as a proxy for the fidelity of the temporal information presented to apical and basal electrodes in the left and right ears (Sec. II). Experiment 2 then used these thresholds to predict the sensitivity to differences in AM rate between pairs of electrodes for simultaneously presented SAM pulse trains (Sec. III). The results indicated that the worse threshold in experiment 1 successfully predicted sensitivity of the pair in experiment 2.

Results from the present study expand on previous results showing that pulse rate discrimination is predictive of binaural sensitivity (Ihlefeld *et al.*, 2015) in several important ways. First, we demonstrated that the relationship between the poorer single-channel and across-channel temporal comparisons holds especially when temporal information is compared to disparate places of stimulation within the same ear or across ears. Our results show that this poorer-channel bottleneck exists for all spectro-temporal comparisons, which has critical implications for CI design and programming. For example, some CI processing strategies have shown improvement when poorly performing electrodes (defined differently according to experiment) are deactivated (e.g., Garadat *et al.*, 2013; Zhou and Pfingst, 2012), up to some limit where too many electrodes are deactivated and performance worsens (Schvartz-Leyzac *et al.*, 2017). The findings from the present experiment provide support for those studies, showing that the ability to compare temporal information can be limited by the electrode yielding poorest performance or the difference in performance between electrodes. Second, the present study used lower-rate AM stimuli, the utility of which spans a wide range of perceptual phenomena. Slower temporal envelope fluctuations are useful for speech segmentation and crucial to speech understanding (∼1–15 Hz), are related to the perception of loudness changes or "flutter" (5–15 Hz), are perceived as having a "rough" character (10–300 Hz), and do not elicit a pitch cue [≲100 Hz; for review, see Fig. 9 of Joris *et al.* (2004) and Rosen (1992)]. Faster temporal envelope fluctuations result in the perception of temporal pitch, which is thought to be useful for discriminating voices based upon fundamental frequency (Brungart, 2001; Oxenham, 2008). Consistent with previous reports (Ihlefeld *et al.*, 2015), monaural sensitivity relative to the same AM rate was predictive of simultaneous comparisons of slower (∼10 Hz) and faster (∼90 Hz) AM rates.

### A. Rate limitations

Experiments routinely show that the best performance in temporal pitch and ITD discrimination occurs near 100 Hz. Performance becomes considerably worse for listeners with CIs as rates are increased to around 300 Hz (an "upper-rate" limitation; e.g., Ihlefeld *et al.*, 2015; Kan and Litovsky, 2015; Kong and Carlyon, 2010; Laback *et al.*, 2015). Much less attention has been paid to the lower-rate limitation with respect to AM rate discrimination and sensitivity to ITD (Anderson *et al.*, 2019a; Chatterjee and Oberzut, 2011; Chatterjee and Peng, 2008), where performance becomes considerably worse around 30 Hz. These lower-rate limitations for AM stimuli have been also been shown in listeners with NH (Anderson *et al.*, 2019b; Anderson *et al.*, 2019a; Bernstein and Trahiotis, 2002; Bernstein and Trahiotis, 2009; Krumbholz *et al.*, 2000), suggesting that there is some overlap in the mechanisms involved. The study by Ihlefeld *et al.* (2015) showed that the upper-rate limitation correlates well between monaural and binaural processing. The present study and that by Anderson *et al.* (2019b) expanded on those results, showing that the lower-rate limitation might not apply for SAM stimuli with large rate differences. In particular, the results show that there were two heterogeneous groups of listeners in the present study whose performance could be delineated by examining their threshold at 90-Hz standard AM rate. Poorly performing listeners showed worse sensitivity with the 90-Hz standard AM rate, and well-performing listeners showed better sensitivity with the 90-Hz standard AM rate. In the analysis, this resulted in a non-significant effect when both groups of listeners were pooled.

The lower-rate limitation probably has to do with the slope of the envelope (i.e., amplitude vs time) for listeners with NH. Previous experiments in listeners with NH showed that a sharper slope of the envelope with an equivalent rate results in better discrimination of ITDs (e.g., Bernstein and Trahiotis, 2002; Bernstein and Trahiotis, 2009; Dietz *et al.*, 2015; Klein-Hennig *et al.*, 2011; Laback *et al.*, 2011). In contrast, listeners with CIs show no benefit of sharp slope on AM rate discrimination (Kreft *et al.*, 2010; Landsberger, 2008) or ITD discrimination (Laback *et al.*, 2011). Alternatively, some lower-rate limitations may be due to a "gating effect," where listeners have access to a fewer number of cycles in a stimulus on which to base their perceptual judgment. A gating effect seems unlikely in the present experiment, as even at the lowest roved rate in experiment 2, listeners would have had access to at least 4.5 cycles of AM. If another shared mechanism is at play, it is not yet obvious.

### B. Temporal envelope conundrums

Recordings from the auditory nerve in animals implanted with CIs have shown substantially better phase-locking to stimuli than recordings in animals with NH (Dynes and Delgutte, 1992; Javel and Shepherd, 2000). Based on this finding, one would expect that listeners with CIs would have better sensitivity to some temporal cues than listeners with NH. However, this is not true of the vast majority of listeners with CIs who demonstrate considerable variability depending upon the listener. A small subset of listeners show exceptional performance, better than that of many listeners with NH, and are often referred to as "star" listeners (e.g., Goupell, 2015; Kong and Carlyon, 2010). One listener, IBO, demonstrated star performance in the present experiment (see Figs. 2 and 3), showing consistently better sensitivity than other listeners with BiCIs or NH. Thus, it seems likely that factors associated with deafness limit the representation of temporal information beginning at the auditory periphery. Recent findings show that ITDs are represented with similar fidelity when presented via acoustic or CI stimulation to gerbils with NH (Vollmer, 2018), supporting this hypothesis. Many different attempts have been made to assess the status of the auditory nerve. Some of these include the use of objective measures to predict temporal encoding [e.g., electrically evoked compound action potential; for review, see He *et al.* (2017)], examining the location of the electrode array within the cochlea (e.g., Chakravorti *et al.*, 2019; Wanna *et al.*, 2014), relating psychophysical measures as in the present experiment (e.g., Anderson *et al.*, 2012; Garadat *et al.*, 2012; Garadat *et al.*, 2013; Ihlefeld *et al.*, 2015), and others. Collectively, these studies show that no measure rules all, and when combined with the apparent contrast of animal and human results, suggest that there are heterogeneous outcomes in patients because there are heterogeneous underlying physiological deficits.

There is also a dichotomy in experiments investigating the relative importance of temporal envelope cues to listeners with CIs. On one hand, without access to the temporal envelope, speech becomes unintelligible for simulations of CI processing (Drullman *et al.*, 1994; Shannon *et al.*, 1995). On the other hand, listeners show little to no benefit of or sensitivity to temporal envelope cues to unmask sounds (e.g., Ihlefeld *et al.*, 2012; Pierzycki and Seeber, 2014). The question remains: why are listeners with CIs not extremely sensitive to a sound source segregation cue to which they have considerably greater access than many other cues? While our results cannot directly speak to this question, it may be difficult for listeners to make use of simultaneous differences in the temporal envelope, or these cues may be most useful when combined with good frequency resolution across spectral channels.

### C. Limitations

The results of the present study were compared in depth to a similar study in listeners with NH (Anderson *et al.*, 2019b). While results were similar, poorer performance of listeners with BiCIs could be attributed to many different listener-dependent factors. One obvious difference between listeners with NH and BiCIs is the nature of electrical stimulation and the effects of deafness, which are both suspected to lead to unique spectro-temporal representations in the auditory system compared to listeners with NH. Listeners with BiCIs were also presented with stimuli that were loudness-balanced. While it was not assessed, the listeners with NH likely experienced considerable differences in loudness according to carrier frequency [Fig. 7 of Anderson *et al.* (2019b)]. Increasing level results in better temporal representations of sounds (e.g., phase-locking of the auditory nerve; Joris and Yin, 1992). Thus, using loudness-balanced stimuli makes it difficult to compare the effects of place of stimulation (base vs apex) in listeners with BiCIs to listeners with NH, along with the fact that place of stimulation was a within-subject factor for listeners with BiCIs but not with NH.

Another factor that is a serious limitation to CI research is the demographic homogeneity of the participants. Highly controlled laboratory settings that require listeners to take long periods of time away from home or work heavily bias the population of patients that participate in research. It is likely that this plays a role in the bias toward older age at testing for listeners with CIs shown in many studies. For example, recent research has revealed that older age at testing is associated with poorer utility of spatial cues (Anderson *et al.*, 2019a), suggesting that this confound was affecting the comparison between NH and CI groups. Listeners with BiCIs in the present study were much older (mean 63 years) on average than listeners with NH (mean 22 years). Aging, independent of hearing loss, leads to degradation of sensitivity to temporal cues (e.g., Anderson *et al.*, 2019a; Gallun *et al.*, 2014; Grose and Mamo, 2010). Our laboratory anonymized and pooled demographic data from adults with NH and CIs who have participated in all previous experiments and showed substantial bias toward White, non-Latinx participants (77%) and an underrepresentation of Black (4%) and Indigenous (0.2%) participants. By excluding people of color from CI experiments, we lack awareness of the issues that afflict these clinical populations and contribute to the lack of representation in hearing science. It is difficult to predict how this limitation exactly affects the interpretation of our results as it is a pervasive limitation in the CI literature more generally. Many of the measures in Sec. IV B have not yet been used to relate to sensitivity to psychophysical cues in the clinic, where it is easier to sample from groups of listeners more demographically representative of listeners with hearing loss.

### D. Summary and conclusions

Together from experiments 1 and 2, several conclusions can be drawn with respect to sensitivity to AM rate in listeners with BiCIs:

(1) Listeners showed better (lower) thresholds to sequential presentations of AM rate at apical electrodes compared to basal electrodes, expanding on previous results in listeners with unilateral CIs (Fig. 1) (Chatterjee and Oberzut, 2011; Chatterjee and Peng, 2008; Green *et al.*, 2012; Kreft *et al.*, 2010; Landsberger, 2008).

(2) Several listeners were unable to identify differences in AM rate for SAM pulse trains presented to two electrodes simultaneously (Fig. 2), suggesting that the usefulness of the temporal envelope may be limited in listeners with CIs, in agreement with previous experiments (Ihlefeld *et al.*, 2012; Pierzycki and Seeber, 2014).

(3) Listeners were most sensitive to differences in AM rate for simultaneously presented stimuli when electrodes were paired at different places of stimulation within the same ear compared to the same or different places of stimulation across the ears [Figs. 2(A) and 3]. This finding adds to previous experiments concerning decoherence detection showing that listeners with BiCIs tend to have little sensitivity to these cues (Goupell, 2015; Goupell and Litovsky, 2015).

(4) The electrode with a poorer AM rate discrimination threshold was predictive of the sensitivity of pairs of electrodes to differences in AM rate (Tables III and IV and Fig. 4), in agreement with Ihlefeld *et al.* (2015). The difference in AM rate discrimination thresholds was similarly effective at predicting sensitivity of the pair (Table IV). This finding held when stimuli were presented to pairs of electrodes at different places of stimulation within the same ear or across the ears but was less predictive for pairs of electrodes at similar places of stimulation in both ears.

(5) Two groups of listeners were demonstrated in the present study. Poorer performers showed better sensitivity to low AM rates (10 Hz) and worse sensitivity to high rates (90 Hz). Better performers showed worse sensitivity to low AM rates (10 Hz) and better sensitivity to high rates (90 Hz). This is an important finding as few studies have investigated sensitivity to low AM rates in listeners with CIs.

Together, these results highlight the link between temporal sensitivity in a single spectral channel in one ear and sensitivity to differences within and across channels and ears, suggesting that asymmetry of temporal envelope representations is one mechanism that could limit outcomes of patients with CIs.


### ACKNOWLEDGMENTS

This research was supported by Grant Nos. R01 DC003083 (to R.Y.L.) and R03 DC015321 (to A.K.) from the National Institutes of Health (NIH)-National Institute on Deafness and Other Communication Disorders (NIDCD) and in part by Grant No. P50 HD105353 (to Waisman Center) from NIH-Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD). The authors would like to thank Dr. Donata Oertel, Dr. Matthew Banks, Dr. Monita Chatterjee, Dr. Antje Ihlefeld, and Dr. Frederick Gallun for their helpful feedback as this project has evolved. Portions of this work were presented at the 42nd MidWinter Meeting of the Association for Research in Otolaryngology, Baltimore, MD, 2019. Portions of this work were published in the doctoral dissertation of S.R.A. entitled "Mechanisms that underlie poorer binaural outcomes in patients with asymmetrical hearing and bilateral cochlear implants."


[1]See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0016365 for supplementary tables.

[2]The results of all analyses presented in experiment 2 did not change when these data were included.

[3]The transform used in Eq. (1) is also equivalent to a specific case of the logistic transform where the growth rate parameter is 1 and the midpoint is the minimum value of sensitivity.

[4]Interestingly, for the poorly performing listeners, standard AM rate was the *only* significant effect in the model. In contrast, the better-performing group had no other changes to model predictions. The lack of effects in the poorer performing group is reflective of the flat psychometric functions for these listeners.


Anderson, E. S., Oxenham, A. J., Nelson, P. B., and Nelson, D. A. (**2012**). "Assessing the role of spectral and intensity cues in spectral ripple detection and discrimination in cochlear-implant users," J. Acoust. Soc. Am. **132**(6), 3925–3934.

Anderson, S. R., Easter, K., and Goupell, M. J. (**2019a**). "Effects of rate and age in processing interaural time and level differences in normal-hearing

and bilateral cochlear-implant listeners," J. Acoust. Soc. Am. **146**(5), 3232–3254.
Anderson, S. R., Kan, A., and Litovsky, R. Y. (**2019b**). "Asymmetric temporal envelope encoding: Implications for within- and across-ear envelope comparison," J. Acoust. Soc. Am. **146**(2), 1189–1206.
Baumann, U., and Nobbe, A. (**2004**). "Pulse rate discrimination with deeply inserted electrode arrays," Hear. Res. **196**(1–2), 49–57.
Bernstein, J. G. W., Jensen, K. K., Stakhovskaya, O. A., Noble, J. H., Hoa, M., Kim, H. J., Shih, R., Kolberg, E., Cleary, M., and Goupell, M. J. (**2021**). "Interaural place-of-stimulation mismatch estimates using CT scans and binaural perception, but not pitch, are consistent in cochlear-implant users," J. Neurosci. **41**(49), 10161–10178.
Bernstein, L. R., and Trahiotis, C. (**1992**). "Discrimination of interaural envelope correlation and its relation to binaural unmasking at high frequencies," J. Acoust. Soc. Am. **91**(1), 306–316.
Bernstein, L. R., and Trahiotis, C. (**2002**). "Enhancing sensitivity to interaural delays at high frequencies by using 'transposed stimuli,' " J. Acoust. Soc. Am. **112**(3), 1026–1036.
Bernstein, L. R., and Trahiotis, C. (**2009**). "How sensitivity to ongoing interaural temporal disparities is affected by manipulations of temporal features of the envelopes of high-frequency stimuli," J. Acoust. Soc. Am. **125**(5), 3234–3242.
Bernstein, L. R., and Trahiotis, C. (**2014**). "Sensitivity to envelope-based interaural delays at high frequencies: Center frequency affects the envelope rate-limitation," J. Acoust. Soc. Am. **135**(2), 808–816.
Bierer, J. A., and Nye, A. D. (**2014**). "Comparisons between detection threshold and loudness perception for individual cochlear implant channels," Ear Hear. **35**(6), 641–651.
Bilgic, Y. K., and Susmann, H. (**2013**). "rlme: An R package for rank-based estimation and prediction in random effects nested models," R J. **5**(2), 71–79.
Bland, J. M., and Altman, D. G. (**1995**). "Calculating correlation coefficients with repeated observations: Part 1—Correlation within subjects," Br. Med. J. **310**, 446.
Brungart, D. S. (**2001**). "Informational and energetic masking effects in the perception of two simultaneous talkers," J. Acoust. Soc. Am. **109**(3), 1101–1109.
Busby, P. A., Tong, Y. C., and Clark, G. M. (**1993**). "The perception of temporal modulations by cochlear implant patients," J. Acoust. Soc. Am. **94**(1), 124–131.
Chakravorti, S., Noble, J. H., Gifford, R. H., Dawant, B. M., O'Connell, B. P., Wang, J., and Labadie, R. F. (**2019**). "Further evidence of the relationship between cochlear implant electrode positioning and hearing outcomes," Otol. Neurotol. **40**(5), 617–624.
Chatterjee, M., and Oberzut, C. (**2011**). "Detection and rate discrimination of amplitude modulation in electrical hearing," J. Acoust. Soc. Am. **130**(3), 1567–1580.
Chatterjee, M., and Peng, S.-C. (**2008**). "Processing F0 with cochlear implants: Modulation frequency discrimination and speech intonation recognition," Hear. Res. **235**(1–2), 143–156.
Dietz, M., Klein-Hennig, M., and Hohmann, V. (**2015**). "The influence of pause, attack, and decay duration of the ongoing envelope on sound lateralization," J. Acoust. Soc. Am. **137**(2), EL137–EL143.
Drullman, R., Festen, J. M., and Plomp, R. (**1994**). "Effect of temporal envelope smearing on speech reception," J. Acoust. Soc. Am. **95**(2), 1053–1064.
Dynes, S. B. C., and Delgutte, B. (**1992**). "Phase-locking of auditory-nerve discharges to sinusoidal electric stimulation of the cochlea," Hear. Res. **58**, 79–90.
Gallun, F. J., McMillan, G. P., Molis, M. R., Kampel, S. D., Dann, S. M., and Konrad-Martin, D. L. (**2014**). "Relating age and hearing loss to monaural, bilateral, and binaural temporal sensitivity," Front. Neurol. **8**(172), 172.
Galvin, J. J., III, Oba, S., Başkent, D., and Fu, Q. J. (**2015**). "Modulation frequency discrimination with single and multiple channels in cochlear implant users," Hear. Res. **324**, 7–18.
Garadat, S. N., Zwolan, T. A., and Pfingst, B. E. (**2012**). "Across-site patterns of modulation detection: Relation to speech recognition," J. Acoust. Soc. Am. **131**(5), 4030–4041.
Garadat, S. N., Zwolan, T. A., and Pfingst, B. E. (**2013**). "Using temporal modulation sensitivity to select stimulation sites for processor MAPs in cochlear implant listeners," Audiol. Neurootol. **18**(4), 247–260.
Geurts, L., and Wouters, J. (**2001**). "Coding of the fundamental frequency in continuous interleaved sampling processors for cochlear implants," J. Acoust. Soc. Am. **109**(2), 713–726.
Golding, N. L., and Oertel, D. (**2012**). "Synaptic integration in dendrites: Exceptional need for speed," J. Physiol. **590**(22), 5563–5569.
Goldsworthy, R. L., Bissmeyer, S. R. S., and Camarena, A. (**2022**). "Advantages of pulse rate compared to modulation frequency for temporal pitch perception in cochlear implant users," J. Assoc. Res. Otolaryngol. **23**(1), 137–150.
Goupell, M. J. (**2015**). "Interaural envelope correlation change discrimination in bilateral cochlear implantees: Effects of mismatch, centering, and onset of deafness," J. Acoust. Soc. Am. **137**(3), 1282–1297.
Goupell, M. J., Eisenberg, D., and DeRoy Milvae, K. (**2021**). "Dichotic listening performance with cochlear-implant simulations of ear asymmetry is consistent with difficulty ignoring clearer speech," Atten. Percept. Psychophys. **83**(5), 2083–2101.
Goupell, M. J., Kan, A., and Litovsky, R. Y. (**2016**). "Spatial attention in bilateral cochlear-implant users," J. Acoust. Soc. Am. **140**(3), 1652–1662.
Goupell, M. J., and Litovsky, R. Y. (**2015**). "Sensitivity to interaural envelope correlation changes in bilateral cochlear-implant users," J. Acoust. Soc. Am. **137**(1), 335–349.
Goupell, M. J., Noble, J. H., Phatak, S. A., Kolberg, E., Cleary, M., Stakhovskaya, O. A., Jensen, K. K., Hoa, M., Kim, H. J., and Bernstein, J. G. W. (**2022**). "Computed-tomography estimates of interaural mismatch in insertion depth and scalar location in bilateral cochlear-implant users," Otol. Neurotol. **43**(6), 666–675.
Green, T., Faulkner, A., and Rosen, S. (**2012**). "Variations in carrier pulse rate and the perception of amplitude modulation in cochlear implant users," Ear Hear. **33**(2), 221–230.
Grose, J. H., Hall, J. W., III, and Buss, E. (**2005**). "Across-channel spectral processing," Int. Rev. Neurobiol. **70**, 87–119.
Grose, J. H., and Mamo, S. K. (**2010**). "Processing of temporal fine structure as a function of age," Ear Hear. **31**(6), 755–760.
He, S., Teagle, H. F. B., and Buchman, C. A. (**2017**). "The electrically evoked compound action potential: From laboratory to clinic," Front. Neurosci. **11**, 339.
Ihlefeld, A., Carlyon, R. P., Kan, A., Churchill, T. H., and Litovsky, R. Y. (**2015**). "Limitations on monaural and binaural temporal processing in bilateral cochlear implant listeners," J. Assoc. Res. Otolaryngol. **16**(5), 641–652.
Ihlefeld, A., Shinn-Cunningham, B. G., and Carlyon, R. P. (**2012**). "Comodulation masking release in speech identification with real and simulated cochlear-implant hearing," J. Acoust. Soc. Am. **131**(2), 1315–1324.
Javel, E., and Shepherd, R. K. (**2000**). "Electrical stimulation of the auditory nerve in man," Hear. Res. **140**, 45–76.
Joris, P. X., Carney, H., Smith, H., and Yin, T. C. T. (**1994**). "Enhancement of neural synchronization in the anteroventral cochlear nucleus. I. Responses to tones at the characteristic frequency," J. Neurophysiol. **71**(3), 1022–1036.
Joris, P. X., Schreiner, C. E., and Rees, A. (**2004**). "Neural processing of amplitude-modulated sounds," Physiol. Rev. **84**(2), 541–577.
Joris, P. X., and Trussell, L. O. (**2018**). "The calyx of Held: A hypothesis on the need for reliable timing in an intensity-difference encoder," Neuron **100**(3), 534–549.
Joris, P. X., and Yin, T. C. T. (**1992**). "Responses to amplitude-modulated tones in the auditory nerve of the cat," J. Acoust. Soc. Am. **91**(1), 215–232.
Kan, A., Goupell, M. J., and Litovsky, R. Y. (**2019**). "Effect of channel separation and interaural mismatch on fusion and lateralization in normal-hearing and cochlear-implant listeners," J. Acoust. Soc. Am. **146**(2), 1448–1463.
Kan, A., and Litovsky, R. Y. (**2015**). "Binaural hearing with electrical stimulation," Hear. Res. **322**, 127–137.
Kan, A., Stoelb, C., Litovsky, R. Y., and Goupell, M. J. (**2013**). "Effect of mismatched place-of-stimulation on binaural fusion and lateralization in bilateral cochlear-implant users," J. Acoust. Soc. Am. **134**(4), 2923–2936.
Kay, M., Elkin, L. A., Higgins, J. J., and Wobbrock, J. O. (**2021**). "ARTool: Aligned rank transform nonparametric factorial ANOVAs [computer program]," https://github.com/mjskay/ARTool (Last viewed November 28, 2022).

Kenward, M. G., and Roger, J. H. (**1997**). "Small sample inference for fixed effects from restricted maximum likelihood," Biometrics **53**(3), 983–997.

Klein-Hennig, M., Dietz, M., Hohmann, V., and Ewert, S. D. (**2011**). "The influence of different segments of the ongoing envelope on sensitivity to interaural time delays," J. Acoust. Soc. Am. **129**(6), 3856–3872.

Kong, Y.-Y., and Carlyon, R. P. (**2010**). "Temporal pitch perception at high rates in cochlear implants," J. Acoust. Soc. Am. **127**(5), 3114–3123.

Kong, Y.-Y., Deeks, J. M., Axon, P. R., and Carlyon, R. P. (**2009**). "Limits of temporal pitch in cochlear implants," J. Acoust. Soc. Am. **125**(3), 1649–1657.

Kreft, H. A., Nelson, D. A., and Oxenham, A. J. (**2013**). "Modulation frequency discrimination with modulated and unmodulated interference in normal hearing and in cochlear-implant users," J. Assoc. Res. Otolaryngol. **14**(4), 591–601.

Kreft, H. A., Oxenham, A. J., and Nelson, D. A. (**2010**). "Modulation rate discrimination using half-wave rectified and sinusoidally amplitude modulated stimuli in cochlear-implant users," J. Acoust. Soc. Am. **127**(2), 656–659.

Krumbholz, K., Patterson, R. D., and Pressnitzer, D. (**2000**). "The lower limit of pitch as determined by rate discrimination," J. Acoust. Soc. Am. **108**(3), 1170–1180.

Laback, B., Egger, K., and Majdak, P. (**2015**). "Perception and coding of interaural time differences with bilateral cochlear implants," Hear. Res. **322**, 138–150.

Laback, B., Zimmermann, I., Majdak, P., Baumgartner, W.-D., and Pok, S.-M. (**2011**). "Effects of envelope shape on interaural envelope delay sensitivity in acoustic and electric hearing," J. Acoust. Soc. Am **130**(3), 1515–1529.

Landsberger, D. M. (**2008**). "Effects of modulation wave shape on modulation frequency discrimination with electrical hearing," J. Acoust. Soc. Am. **124**(2), EL21–EL27.

Lee, J. (**1994**). "Amplitude modulation rate discrimination with sinusoidal carriers," J. Acoust. Soc. Am. **96**(4), 2140–2147.

Levitt, H. (**1971**). "Transformed up-down methods in psychoacoustics," J. Acoust. Soc. Am. **49**(2), 467–477.

Lindenbeck, M. J., Laback, B., Majdak, P., and Srinivasan, S. (**2020**). "Temporal-pitch sensitivity in electric hearing with amplitude modulation and inserted pulses with short inter-pulse intervals," J. Acoust. Soc. Am. **147**(2), 777–793.

Litovsky, R. Y. (**1997**). "Developmental changes in the precedence effect: Estimates of minimum audible angle," J. Acoust. Soc. Am. **102**(3), 1739–1745.

Litovsky, R. Y., Goupell, M. J., Godar, S., Grieco-Calub, T., Jones, G. L., Garadat, S. N., Agrawal, S., Kan, A., Todd, A., Hess, C., and Misurelli, S. (**2012**). "Studies on bilateral cochlear implants at the University of Wisconsin Binaural Hearing and Speech Lab," J. Am. Acad. Audiol. **23**, 476–494.

Litovsky, R. Y., Goupell, M. J., Kan, A., and Landsberger, D. M. (**2017**). "Use of research interfaces for psychophysical studies with cochlear-implant users," Trends Hear. **21**, 2331216517736464.

Loizou, P. C. (**2006**). "Speech processing in vocoder-centric cochlear implants," Adv Otorhinolaryngol. **64**, 109–143.

Macmillan, N. A., and Creelman, C. D. (**2005**). *Detection Theory: A User's Guide*, 2nd ed. (Cambridge University, Cambridge, UK), 341 pp.

McFadden, D., and Pasanen, E. G. (**1975**). "Binaural beats at high frequencies," Science **190**(4212), 394–396.

McKay, C. M., McDermott, H. J., and Clark, G. M. (**1994**). "Pitch percepts associated with amplitude-modulated current pulse trains in cochlear implantees," J. Acoust. Soc. Am. **96**(5), 2664–2673.

Monaghan, J. J. M., Bleeck, S., and McAlpine, D. (**2015**). "Sensitivity to envelope interaural time differences at high modulation rates," Trends Hear. **19**, 2331216515619331.

Moore, B. C. J. (**2008**). "The role of temporal fine structure processing in pitch perception, masking, and speech perception for normal-hearing and hearing-impaired people," J. Assoc. Res. Otolaryngol. **9**(4), 399–406.

Mosnier, I., Sterkers, O., Bebear, J. P., Godey, B., Robier, A., Deguine, O., Fraysse, B., Bordure, P., Mondain, M., Bouccara, D., Bozorg-Grayeli, A., Borel, S., Ambert-Dahan, E., and Ferrary, E. (**2009**). "Speech performance and sound localization in a complex noisy environment in bilaterally implanted adult patients," Audiol. Neurootol. **14**(2), 106–114.

Oxenham, A. J. (**2008**). "Pitch perception and auditory stream segregation: Implications for hearing loss and cochlear implants," Trends Amplif. **12**(4), 316–331.

Pierzycki, R. H., and Seeber, B. U. (**2014**). "Comodulation masking release in electric hearing," J. Assoc. Res. Otolaryngol. **15**(2), 279–291.

R Core Team (**2019**). *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, Vienna, Austria).

Reiss, L. A. J., Fowler, J. R., Hartling, C. L., and Oh, Y. (**2018**). "Binaural pitch fusion in bilateral cochlear implant users," Ear Hear. **39**(2), 390–397.

Rhode, W. S., and Greenberg, S. (**1994**). "Encoding of amplitude modulation in the cochlear nucleus of the cat," J. Neurophysiol. **71**(5), 1797–1825.

Richards, V. M. (**1987**). "Monaural envelope correlation perception," J. Acoust. Soc. Am. **82**(5), 1621–1630.

Rosen, S. (**1992**). "Temporal information in speech: Acoustic, auditory and linguistic aspects," Philos. Trans. R. Soc. London, B: Biol. Sci. **336**, 367–373.

Rothman, J. S., Young, E. D., and Manis, P. B. (**1993**). "Convergence of auditory nerve fibers onto bushy cells in the ventral cochlear nucleus: Implications of a computational model," J. Neurophysiol. **70**(6), 2562–2583.

Rubinstein, J. T. Y., Wilson, B. S., Finley, C. C., and Abbas, P. J. (**1999**). "Pseudospontaneous activity: Stochastic independence of auditory nerve fibers with electrical stimulation," Hear. Res. **127**(1–2), 108–118.

Schvartz-Leyzac, K. C., Holden, T. A., Zwolan, T. A., Arts, H. A., Firszt, J. B., Buswinka, C. J., and Pfingst, B. E. (**2020**). "Effects of electrode location on estimates of neural health in humans with cochlear implants," J. Assoc. Res. Otolaryngol. **21**(3), 259–275.

Schvartz-Leyzac, K. C., Zwolan, T. A., and Pfingst, B. E. (**2017**). "Effects of electrode deactivation on speech recognition in multichannel cochlear implant recipients," Cochlear Implants Int. **18**(6), 324–334.

Shannon, R. V., Zeng, F., Kamath, V., Wygonski, J., and Ekelid, M. (**1995**). "Speech recognition with primarily temporal cues," Science **270**(5234), 303–304.

Shinn-Cunningham, B. G. (**2008**). "Object-based auditory and visual attention," Trends Cogn. Sci. **12**(5), 182–186.

Thakkar, T., Anderson, S. R., Kan, A., and Litovsky, R. Y. (**2020**). "Evaluating the impact of age, acoustic exposure, and electrical stimulation on binaural sensitivity in adult bilateral cochlear implant patients," Brain Sci. **10**, 406–426.

Vandali, A., Sly, D., Cowan, R., and Van Hoesel, R. (**2013**). "Pitch and loudness matching of unmodulated and modulated stimuli in cochlear implantees," Hear. Res. **302**, 32–49.

van Hoesel, R. J. M., Jones, G. L., and Litovsky, R. Y. (**2009**). "Interaural time delay sensitivity in bilateral cochear implant users: Effects of pulse rate, modulation rate, and place of stimulation," J. Assoc. Res. Otolaryngol. **10**(4), 557–567.

van Hoesel, R. J. M., and Tyler, R. S. (**2003**). "Speech perception, localization, and lateralization with bilateral cochlear implants," J. Acoust. Soc. Am. **113**(3), 1617–1630.

Vollmer, M. (**2018**). "Neural processing of acoustic and electric interaural time differences in normal-hearing gerbils," J. Neurosci. **38**(31), 6949–6966.

Wanna, G. B., Noble, J. H., Carlson, M. L., Gifford, R. H., Dietrich, M. S., Haynes, D. S., Dawant, B. M., and Labadie, R. F. (**2014**). "Impact of electrode design and surgical approach on scalar location and cochlear implant outcomes," Laryngoscope **124**(S6), S1–S7.

Wichmann, A. F., and Hill, N. J. (**2001**). "The psychometric function: I. Fitting, sampling, and goodness of fit," Percept. Psyhophys. **63**(8), 1293–1313.

Wilson, B. S. (**1997**). "Thirty years of the British Journal of Audiology: Guest editorial. The future of cochlear implants," Br. J. Audiol. **31**(4), 205–225.

Wobbrock, J. O., Findlater, L., Gergle, D., and Higgins, J. J. (**2011**). "The aligned rank transform for nonparametric factorial analyses using only ANOVA procedures," in *Proceedings of ACM Conference on Human Factors in Computing Systems*, May 7–12, Vancouver, Canada, pp. 143–146.

Yoon, Y. S., Li, Y., Kang, H. Y., and Fu, Q. J. (**2011**). "The relationship between binaural benefit and difference in unilateral speech recognition performance for bilateral cochlear implant users," Int. J. Audiol. **50**(8), 554–565.

Zhou, N., and Pfingst, B. E. (**2012**). "Psychophysically based site selection coupled with dichotic stimulation improves speech recognition in noise with bilateral cochlear implants," J. Acoust. Soc. Am. **132**(2), 994–1008.