Binaural interference with simulated electric acoustic stimulation

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Preserved low-frequency acoustic hearing in cochlear implant (CI) recipients affords combined electric-acoustic stimulation (EAS) that could improve access to low-frequency acoustic binaural cues and enhance spatial hearing. Such benefits, however, could be undermined by interactions between electrical and acoustical inputs to adjacent (spectral overlap) or distant (binaural interference) cochlear places in EAS. This study simulated EAS in normal-hearing listeners, measuring interaural time difference (ITD) and interaural level difference (ILD) discrimination thresholds for a low-frequency noise (simulated acoustic target) in the presence or absence of a pulsatile high-frequency complex presented monotically or diotically (simulated unilateral or bilateral electric distractor). Unilateral distractors impaired thresholds for both cue types, suggesting influences of both binaural interference (which appeared more consistently for ITD than ILD) and physical spectral overlap (for both cue types). Reducing spectral overlap with an EAS gap between 1 and 3 kHz consistently improved binaural sensitivity. Finally, listeners displayed significantly lower thresholds with simulated bilateral versus unilateral electric stimulation. The combined effects revealed similar or better thresholds in bilateral full spectral overlap than in unilateral EAS gap conditions, suggesting that bilateral implantation with bilateral acoustic hearing preservation could allow for higher tolerance of spectral overlap in CI users and improved binaural sensitivity over unilateral EAS. © 2019 Acoustical Society of America.

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I. INTRODUCTION

In the last decade, the prevalence of preserved low-frequency acoustic hearing in cochlear implant (CI) recipients has increased (e.g., Büchner *et al.*, 2009; Gantz *et al.*, 2009; Lenarz *et al.*, 2009; Pillsbury *et al.*, 2018). Studies have found that mean threshold elevations after implantation range from 10 to 25 dB for shorter electrode arrays (10 mm; Gantz *et al.*, 2005; Gantz *et al.*, 2009; 16 mm, Lenarz *et al.*, 2009), and 10 to 40+ dB for longer arrays (16 to 30+ mm; Gstoettner *et al.*, 2008; Gstoettner *et al.*, 2009; Carlson *et al.*, 2011; Gifford *et al.*, 2013). Improved surgical techniques, steroid use, and electrode dimensions are all contributing factors to these improved post-operative outcomes (e.g., Zanetti *et al.*, 2015; Wanna *et al.*, 2018). Increasing availability of atraumatic arrays and electric-acoustic stimulation (EAS)/hybrid systems has also resulted in a greater prevalence of post-operative preserved hearing. Furthermore, altered CI criteria over the years have allowed individuals with better low-frequency hearing to qualify for CIs. EAS devices provide low-frequency acoustic stimulation to apical

cochlear regions and electric stimulation to basal regions coding mid-to-high frequencies. At the time of manuscript preparation, EAS systems included the Nucleus N7 (Cochlear Ltd, Sydney, Australia) with acoustic component combined with the Hybrid-L24, CI522, or CI532 electrode (Cochlear Ltd., Sydney, Australia), MED-EL Sonnet EAS processor (MED-EL, Innsbruck, Austria) combined with FLEX24, FLEX28, or FLEXsoft electrode arrays, and Advanced Bionics Naida EAS processor (Advanced Bionics, Valencia, CA) combined with mid-scala or slim j electrode array.

There has been a significant amount of research on the benefits of amplifying preserved low-frequency hearing. Studies have observed improved localization and improved speech in noise perception for CI users with amplified residual low-frequency hearing (Loiselle *et al.*, 2015; Loiselle *et al.*, 2016; Gifford *et al.*, 2013; Gifford *et al.*, 2014; Dunn *et al.*, 2010). Gifford and colleagues (Gifford *et al.*, 2013; Gifford *et al.*, 2014; Gifford *et al.*, 2017) found that CI recipients using bilateral hearing aids achieved significantly higher speech recognition than observed with a single hearing aid on the non-implanted side (the latter condition commonly termed *bimodal hearing*). With bilateral acoustic amplification, patients have a greater potential to access binaural cues such as interaural time differences (ITDs) and low-frequency interaural level differences (ILDs). Studies investigating speech understanding in semi-diffuse noise for

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CI recipients with various listening configurations (e.g., hearing preservation CI, bimodal, and bilateral CI) have demonstrated that bilateral acoustic hearing along with either unilateral or bilateral CIs provides an advantage over simply using either bilateral CIs alone or bimodal hearing (e.g., Gifford *et al.*, 2014; Gifford *et al.*, 2015). This bilateral acoustic benefit for speech recognition in noise is significantly correlated with underlying ITD sensitivity afforded by the amplified low-frequency acoustic hearing (Gifford *et al.*, 2013; Gifford *et al.*, 2014). Research has also been done on localization ability in CI users with preserved acoustic hearing in the implanted ear (e.g., Dunn *et al.*, 2010; Gifford *et al.*, 2014; Loisel *et al.*, 2015; Loisel *et al.*, 2016). Studies have demonstrated that CI recipients using bilateral hearing aids and a unilateral CI performed significantly better on tasks of horizontal plane localization as compared to the bimodal listening condition (Dunn *et al.*, 2010; Gifford *et al.*, 2014) or even as compared to the bilateral acoustic hearing condition without the use of the CI (Dunn *et al.*, 2010; Loisel *et al.*, 2015). This research indicates that use of a unilateral CI does not impair localization abilities.

Any stimulation mode that provides audibility of bilateral acoustic stimuli (see Table I) could potentially support good binaural sensitivity, particularly because low-frequency hearing—which involves structures nearer the cochlear apex that are most likely to be preserved—plays a dominant role in binaural processing by normal-hearing (NH) individuals. However, because electrical stimulation does not preserve binaural cues to the same extent, EAS presents conflicting cues in basal versus apical regions of the cochlea. In regions where electrical and acoustical stimuli overlap, information may be distorted or masked directly. Even the presence of conflicting cues in remote spectral regions presents a potential concern. In acoustic listening by NH listeners, binaural-cue conflicts across frequency result in *binaural interference*: interaural-difference thresholds can be elevated by a factor of 2 or more when a diotic interferer is presented at a frequency well below (or in some cases, above) that of the target (McFadden and Pasanen, 1976; Heller and Trahiotis, 1995; Heller and Richards, 2010; Bibee and Stecker, 2016). Potentially, then, electrical stimulation of the cochlear base could produce binaural interference that reduces sensitivity to preserved low-frequency acoustic cues. This study investigated that possibility by measuring low-frequency ITD and ILD thresholds in the presence of concurrent high-frequency stimuli designed to mimic pulsatile stimulation delivered by a multi-channel CI.

TABLE I. Examples of EAS and related binaural configurations. Designations in the right column indicate the stimulation mode in each of two ears: acoustical (A), electrical (E), hybrid/EAS (E+A), or none (–).

Terminology	Designation (primary/secondary ear)
Normal or aided hearing	A/A
Unilateral CI	E/–
Bilateral CI	E/E
Bimodal	E/A
Hybrid / EAS	E+A/–
Unilateral EAS	E+A/A
Bilateral EAS	E+A/E+A

With a better understanding of the specific benefits of EAS-based localization and speech perception, it also becomes important to consider optimal programming of the CIs and hearing aids to maximize this listening benefit for both speech perception and spatial hearing. When using EAS, the spectral-overlap levels can be varied to investigate the optimal listening condition. Previous literature has hypothesized that binaural interference can vary as a function of this spectral overlap (Brown and Yost, 2015). This study simulates EAS to determine how the presence of an electric stimulus affects the ability to detect low-frequency ILD and ITD cues. Previous studies have assessed the localization ability of patients with bilateral hearing aids and bilateral CIs; however, they were unable to definitively determine whether the listeners were using ITD cues or low-frequency ILD cues (e.g., Gifford *et al.*, 2014; Loisel *et al.*, 2016; Plant and Babic, 2016). This study directly investigates the effect of a simulated electric stimulus on the perception of binaural cues. These data will provide a better understanding of underlying mechanisms that EAS patients are using for improved localization and speech understanding in complex listening environments.

II. METHODS

A. Participants

Participants included seven inexperienced listeners between the ages of 21 and 25 years (three male, four female) who reported normal hearing. An additional three participants with experience in lateralization tasks were also tested (one female aged 45 years, two males aged 30 and 32 years). Their hearing status was verified by pure-tone audiometry [<15 dB hearing level (HL) from 250 to 8000 Hz and <10 dB variation between left and right ears at any frequency].

B. Stimuli and procedure

The target stimulus was a rectangular band of flat-spectrum noise (100–1000 Hz) simulating the typical range of preserved low-frequency acoustic hearing for EAS users. Distractor stimuli were complex Gabor click trains with a 500 Hz click rate that simulated electric input via a CI (Fig. 1). Distractors were presented in three different spectral-overlap conditions. The *full* overlap condition combined stimulation centered at four center frequencies (CFs: 1000 Hz, 2000 Hz, 4000 Hz, 8000 Hz), the *meet* condition omitted the 1000 Hz distractor channel (CFs: 2000 Hz, 4000 Hz, 8000 Hz), and the *gap* condition omitted both the 1000 Hz and 2000 Hz distractor channels (CFs: 4000 Hz, 8000 Hz; Fig. 2). As illustrated in Fig. 1, clicks were temporally interleaved across CF (ascending-frequency order) to achieve flatter broadband envelopes and mimic interleaved electrical stimulation. In separate conditions, distractor stimuli were delivered bilaterally to both ears or *unilaterally* to the left ear (six individuals) or the right ear (four individuals). Target and distractor stimuli were gated on and off simultaneously with a duration of 500 ms, including 5 ms onset/offset ramps applied to the target.

FIG. 1. Distractor stimuli were complex Gabor click trains consisting of components centered at 1, 2, 4, and 8 kHz (a). Individual frequency components were offset in time (interleaved) to reduce temporal overlap across frequencies. Three spectral-overlap conditions were defined (b): *full* included all components (1, 2, 4, and 8 kHz); *meet* included 2, 4, and 8 kHz components; *gap* included only the 4 and 8 kHz components. A fourth condition (*none*) omitted distractors entirely, presenting target stimuli alone. Waveforms (c) and spectra (d) of the combined distractors are shown for each condition. Shaded region in (d) indicates the target stimulus: a rectangular band of noise spanning 100–1000 Hz.

Target stimuli were delivered via headphones (Stax SR-307, Saitama, Japan) at 52 dB sound pressure level (SPL; A-weighted). Distractor components were presented at 57 dB SPL each. Thus, overall levels were 63 dB SPL in the full condition and 60 dB SPL in the gap condition.

Thresholds for ITDs and ILDs were measured in separate trial runs using an adaptive three-interval two-alternative forced-choice task. Listeners were seated in a double-walled sound booth with a touchscreen interface (Apple iPad Mini 2, Cupertino, CA) mounted on a desk in front of them. Each interval included a noise burst as described above, which was diotic in two of the intervals. The target interval (either the second or third) carried an ITD or ILD favoring the right ear. Distractor stimuli, when presented, were gated on and off with the noise burst in each interval. Participants were instructed to ignore the distractor (if present) and select the interval in which the low-frequency target noise lateralized farthest to the right. Three buttons, labeled 1, 2, and 3, were displayed on the touch screen. Before initial testing, individuals were familiarized with the task in quiet with 4–5 practice runs until they showed understanding of the task (i.e., when participants displayed consistent responses that cumulated to a reliable threshold).

A total of seven conditions were tested for each cue type (ITD and ILD): unilateral full, unilateral meet, unilateral gap,

bilateral full, bilateral meet, bilateral gap, and no distractor (control condition). Separately, both ITD and ILD cues were measured in each such condition. Thresholds were measured on each run using a two-down, one-up adaptive procedure (Levitt, 1971). In ILD conditions, the step size was ± 2 dB ILD for the initial four reversals decreasing to ± 0.5 dB for the final eight reversals. Equivalently, ITD values were adjusted by a logarithmic scaling factor (Saberi, 1995) of $10^{\pm 0.2}$ [± 2 decilog (dg)] initially, and $10^{\pm 0.05}$ (± 0.5 dg) for the final 8 of 12 reversals. ITD or ILD values of the last eight reversals were averaged to compute each adaptive threshold. The procedure was repeated to obtain an average across four threshold runs per condition and participant. A single run lasted 5–6 min for each subject. Testing order of conditions and whether the unilateral EAS condition was presented to the right or left ear was randomized for each participant.

C. Statistical methods

Mean thresholds obtained in each condition were used to quantify the ITD interference ratio (ratio of threshold ITD obtained in the presence versus absence of a distractor) and ILD interference magnitude (dB difference in threshold ILD obtained with and without distractor) for each participant and condition. Two-way, repeated-measures analysis of

FIG. 2. Mean normalized ITD (upper) and ILD (lower) thresholds plotted against distractor condition ($n = 10$). Thresholds are plotted after normalizing by each participant's no-distractor threshold ("reference"; dotted line). The normalized value corresponds to the ITD interference ratio or ILD interference magnitude as indicated on the right axis. Scaling by the group-mean reference gives the equivalent threshold value as indicated on the left axis. Error bars indicate bootstrapped 95% confidence intervals. Asterisks (*) at bottom of each bar indicate significant threshold differences from no-interferer conditions: * $p < 0.05$, ** $p < 0.005$, *** $p < 0.0005$, ns = not significant. Horizontal bars with asterisks indicate significant differences between conditions.

variance (ANOVA) was completed in MATLAB (Mathworks, Natick, MA) to analyze data. Separate analyses were conducted with dependent variables of ITD interference ratio and ILD interference magnitude. Factors were the spectral-overlap condition and binaural condition (unilateral or bilateral presentation of distractor). Follow-up analyses, also conducted in MATLAB, used paired bootstrap tests to compare pairs of distractor conditions. Pairwise differences in threshold or interference measures across conditions were computed for each participant. Difference values were resampled (bootstrapped) across subjects 10 000 times to estimate the sampling distribution of the difference. The statistical significance of the difference (i.e., the p -value) is given by the proportion of bootstrap samples with mean less than or equal to zero and is expressed to one significant digit (i.e., $p < 0.004$). Tests in which no bootstrap sample fell at or below zero are indicated by the minimum obtainable value of $p < 0.0001$.

III. RESULTS

A. Binaural interference

Results indicate significant threshold elevations, consistent with binaural and/or structural interference, at least with unilaterally presented distractors. Repeated-measures ANOVA revealed significant main effects of the spectral-overlap [$F_{(2,18)} = 7.84$, $p < 0.005$, $\eta_p^2 = 0.47$] and bilateral conditions [$F_{(1,9)} = 15.77$, $p < 0.005$, $\eta_p^2 = 0.64$] on ITD interference ratio. For ILD interference magnitude, we observed significant main effects of the spectral-overlap

condition [$F_{(2,18)} = 4.57$, $p < 0.05$, $\eta_p^2 = 0.34$] and bilateral condition [$F_{(1,9)} = 12.69$, $p < 0.01$, $\eta_p^2 = 0.59$] along with a significant interaction between the two [$F_{(2,18)} = 3.68$, $p < 0.05$, $\eta_p^2 = 0.29$] that was driven mainly by the significant difference between full and gap for unilateral but not bilateral distractors (see Fig. 2).

B. Bilateral and unilateral interferers

Figure 2 plots mean thresholds (left axis) and corresponding interference measures (right axis) obtained in each distractor condition. For ITD (upper plot) significant threshold elevations (relative to no-interferer) were observed with unilateral distractors in the full ($p < 0.0001$), meet ($p < 0.0001$), and gap ($p < 0.0008$) conditions (dark bars). Thresholds with bilaterally presented distractors (light bars) were lower and did not significantly differ from the no-distractor condition ($p > 0.05$). Results for ILD were broadly similar but varied across spectral-overlap conditions: significant interference was observed in unilateral-full ($p < 0.0001$), unilateral-meet ($p < 0.0001$), and bilateral-meet ($p < 0.05$) conditions, but not in other conditions. Greater ILD interference under bilateral than unilateral presentation was observed only for full ($p < 0.0001$) and gap ($p < 0.05$) conditions.

Figure 3 plots thresholds obtained in all conditions for individual listeners (symbols). Greater individual variation in baseline thresholds was observed among naive listeners than among the three experienced listeners (indicated by stars and diamonds), whose baseline thresholds fell within the lower half of naive listeners. Reiterating the mean data plotted in Fig. 2, the majority of both groups exhibited threshold elevations in the presence of unilateral distractors (symbols above the diagonal in left panels). The effects of bilateral distractors were less consistent; some of the highest no-distractor thresholds actually improved in the presence of bilateral distractors (points below the diagonal in right panels in Fig. 3).

C. Effect of spectral-overlap conditions

Thresholds and interference measures varied significantly across spectral-overlap conditions. When distractors were presented unilaterally, significant differences were observed between full and meet ($p < 0.05$ for ITD, $p < 0.03$ for ILD), between meet and gap ($p < 0.0001$ for ITD, $p < 0.04$ for ILD), and between full and gap ($p < 0.0007$ for both cues). Bilateral presentation of distractors revealed a similar trend in that the gap condition resulted in the best (lowest) thresholds; interference was significantly weaker for gap than meet ($p < 0.0001$ for ITD, $p < 0.01$ for ILD). ITD interference was also greater in full than gap ($p < 0.0001$), but ILD interference was not ($p > 0.05$). Interference did not significantly differ between full and meet for either cue ($p > 0.05$).

IV. DISCUSSION

A. Spectral overlap between simulated electric and acoustic stimuli

This study examined the effect of a high-frequency simulated electric stimulus on a listener's ability to lateralize a

FIG. 3. Threshold ITD (upper panels) and ILD (lower panels) obtained by individual participants (symbols). Experienced listeners are indicated by stars and diamonds; other symbols indicate data for naive listeners. Each panel plots thresholds obtained under distractor conditions (vertical axis) against thresholds obtained for targets in isolation (horizontal axis). Symbols plot values for spectral-overlap conditions: full (black symbols), meet (gray), gap (white). Diagonal line in each plot indicates equality (no interference). Overall, greater interference was observed when distractors were presented unilaterally (left panels) than bilaterally (right panels).

low-frequency sound using ITD and ILD cues with varying degrees of spectral overlap. Results indicated that access to both types of binaural cues was negatively affected by the high-frequency distractor in most conditions. The best lateralization thresholds were obtained when the spectral configuration of acoustic and electric stimuli was presented in the gap condition, defined as an unstimulated frequency region from 1 to 3 kHz, presumably by reducing structural/energetic interference in regions of overlap. The gap condition reduced interference to non-significant levels in both bilateral-distractor conditions and also in the unilateral condition for ILD. Generally, optimizing speech perception is the most important consideration when programming CIs and hearing aids. Therefore, it would be ideal to find a spectral-overlap ratio that is optimal for both speech perception and localization. [Karsten et al. \(2013\)](#) investigated the effect of EAS overlap for ten Nucleus Hybrid (Cochlear Ltd., Sydney, Australia) recipients with a 10-mm electrode insertion depth. They found that the meet condition yielded significantly higher speech recognition compared to the full condition. They also found no significant difference between the meet and gap conditions. [Gifford et al. \(2017\)](#) investigated the effects of varying EAS overlap for 11 standard electrode implant recipients (13 ears). They found that

the highest speech recognition was observed for minimal overlap and meet conditions and the gap condition was nearly always significantly poorer than some degree of overlap. To date, no study has investigated the effect of EAS overlap on tasks of binaural sensitivity or spatial hearing.

Throughout the psychophysical literature on binaural interference in normal hearing, studies have been careful to limit the spectral proximity of targets and distractors so as to minimize the physical/structural interference that might produce masking or distortion of binaural cues in the overlapping spectral region. In contrast, the current study manipulated spectral overlap as an experimental variable. The greater interference observed in full and meet versus gap conditions suggests that structural interference does play a significant role. That significant interference persisted even in the gap condition, however, strongly supports the view that binaural interference due to central interactions between remote frequencies also contributes.

B. Comparison to binaural interference in past studies

It is notable, with respect to the existing psychophysical literature on binaural interference, that significant threshold

elevations were observed in several conditions of the current study. In particular, we observed significant effects of high-frequency distractors on both ITD and ILD sensitivity in low-frequency targets. Previous literature has suggested large frequency asymmetries in binaural interference, with stronger effects of a low-frequency distractor on a high-frequency ITD target (McFadden and Pasanen, 1976; Heller and Trahiotis, 1995) or a high-frequency distractor on a low-frequency ILD target (Heller and Richards, 2010). Those observed asymmetries are thought to reflect the greater potency of ITD cues at low versus high frequencies and vice versa for ILD. The current results are not consistent with that idea in that high-frequency distractors impacted low-frequency targets in a manner that was actually more robust for ITD than ILD.

The result is also noteworthy because of the inherent stimulus differences between the target (a relatively wide band of noise) and the distractor (a high-frequency harmonic complex). Previous work has suggested stronger interference effects when the target and interferer share stimulus features, such as harmonicity and common onsets, that facilitate fusion or grouping (Buell and Hafter, 1991; Stellmack and Dye, 1993; Best *et al.*, 2007; Camalier *et al.*, 2014; Bibee and Stecker, 2016). It is possible that greater interference would be observed when distractors better match the features of the target, as might be expected for EAS stimuli modulated by a common sound source.

C. Bilateral versus unilateral presentation of distractors

The results of this study revealed significantly greater interference when distractors were presented unilaterally rather than bilaterally, as is more typical of existing literature on binaural interference. Only a handful of studies have manipulated the binaural configuration of distractors. Buell and Hafter (1991) measured ITD discrimination in one of two low-frequency tones, and found interference to be unaffected by manipulation of the non-target (i.e., interferer) ITD. Buell and Trahiotis (1993) similarly measured ITD discrimination in one of two high-frequency (2 or 4 kHz) amplitude-modulated tones. Regardless of frequency, discrimination of a target ITD near 0 μ s was poorer when the non-target tone (i.e., the distractor) carried a 600- μ s ITD than when the distractor was diotic. However, the diotic condition produced significant interference (relative to target alone) only for the 4-kHz target (2-kHz distractor). When the target was lower in frequency than the distractor—as in the current study—performance was slightly *better* in the presence of the diotic high-frequency distractor than in the baseline condition. The lateralized configuration produced significant interference effects regardless of the frequency relationship of target and distractor. A similar result was described by Heller and Richards (2010), who reported greater ITD and ILD threshold elevations for distractors lateralized via random ITD or ILD than for diotic distractors. That effect was greatest when 4-kHz distractors varied in ILD or 500-Hz distractors varied in ITD, conditions that presumably produced the greatest lateralization in each case.

Together, the observations of these studies are consistent with the current results and suggest important differences between interference produced by lateral versus central distractors.

One possible explanation for these differences is that bilateral presentation of the distractor provides listeners with an additional cue for performance on the binaural discrimination task—specifically, a robust midline intracranial reference in the vicinity of the target. If so, the observed effects in bilateral conditions reflect a combination of the negative effects of interference and positive effects of the midline anchor. By this account, the apparent facilitation observed by Buell and Trahiotis (1993) represents a case where the benefit exceeded any negative effects of interference *per se*. Lateralized or unilateral presentation of the distractor, in contrast, does not provide such a reference and, thus, more clearly reveals the interfering effects.

D. Potent binaural cues in pulsatile interferers

This study also differs from much of the literature in its use of pulsatile stimuli, rather than tones or noise bands, as distractors. As discussed by Bibee and Stecker (2016), the class of “pulsatile” stimuli includes Gabor click trains (Buell and Hafter, 1988), transposed tones (van de Par and Kohlrausch, 1997), and raised-sine amplitude-modulated (AM) sounds (Bernstein and Trahiotis, 2009), all of which provide more potent binaural information than tones with slow, steady, or sinusoidal envelopes. That greater potency is thought to underlie the reduced susceptibility of envelope-ITD targets to binaural interference when carried by transposed tones (Bernstein and Trahiotis, 2004) or the onsets of Gabor click trains (Bibee and Stecker, 2016). The availability of potent binaural cues may also mediate the relative effectiveness of stimuli as interferers themselves, and thus may have contributed to the significant levels of interference produced by high-frequency Gabor click trains in the current study. Further testing in CI users is necessary to determine if interference effects might be reduced by their relatively poorer access to binaural cues in electrical stimuli.

E. Clinical implications

The data suggest that bilateral electrical stimulation in the presence of low-frequency acoustic hearing could potentially improve access to ITD cues and low-frequency ILD cues. Of course, sensitivity may remain limited by a lack of temporal synchronization and independent automatic gain characteristics of the hearing aids and CIs alike. Furthermore, the degree of hearing loss and symmetry in aidable acoustic bandwidth will all affect the accessibility of these binaural cues. Nevertheless, these results suggest that bilateral CI users with bilateral hearing preservation may localize better with bilateral CIs (as opposed to a single CI) regardless of degree of spectral overlap (e.g., Gifford *et al.*, 2013; Loiselle *et al.*, 2016).

This simulation study can provide insight on how to ideally program CIs and hearing aids for EAS patients, considerations for stimulus delivery such as frequency allocation for all electrodes, or perhaps what electrodes to activate or

deactivate in the presence of EAS. Since average thresholds were lower in the bilateral full condition (simulating bilateral hearing aids and CIs) than the unilateral gap condition (bilateral hearing aids with unilateral CI) across all spectral-overlap conditions, a potential real-world implication is that bilateral implants allow for a higher tolerance of spectral overlap and improved localization abilities over unilateral implantation. Furthermore, it may be extrapolated that if only one implant is feasible then best localization would be obtained by amplification with a gap since this was the optimal spectral overlap for lateralization of a low-frequency stimulus in this study. However, research has found that providing a gap in the speech spectrum yields significantly poorer speech understanding (Karsten *et al.*, 2013; Gifford *et al.*, 2017).

A key motivator of the current study was the realization that electrical stimulation in EAS might, in some cases, interfere with sensitivity to binaural cues in preserved acoustic hearing. The results of this simulation study support that possibility, despite important differences in frequency content and target-distractor similarity between this and earlier studies of binaural interference. The clear influence of spectral overlap suggests that some interference effects may be limited to cases of structural (i.e., physical) interactions between targets and interfering sounds, and further motivates the need to limit such interactions in clinical EAS. Finally, the strong differences between the effects of bilaterally and unilaterally presented distractors—although not without precedent—suggest that there could be important spatial benefits of bilateral over unilateral EAS beyond the often-limited expectations for binaural electrical hearing.

F. Limitations of the NH EAS simulation

Although the distractor stimuli employed here were designed to mimic several key features of electrical stimuli in EAS listening, a number of important differences between binaural hearing by NH and CI listeners should be considered. First, many (though not all) studies have described relatively poor binaural sensitivity among bilateral CI users, particularly for regular, high-rate stimulation. The 500-Hz pulse rate simulated in this study is above the maximum rate at which most NH listeners—and possibly all CI users—experience potent lateralization cues based on the ongoing ITD of a pulsatile stimulus, forcing both groups to rely more heavily on cues associated with sound onsets (van Hoesel and Clark, 1997; Brown and Stecker, 2010; Stecker *et al.*, 2013; Hu *et al.*, 2017; Baumgärtel *et al.*, 2017). Additional factors such as device limitations, hearing impairment, and neuronal survival also suggest that distractors might produce a clearer midline impression—and potentially greater binaural interference—in NH than CI listeners.

Other important differences arise in the frequency regions stimulated by the simulated EAS distractors. The spread of excitation at each cochlear place, the spacing of components (octave versus regular cochlear length), harmonicity, and potential place mismatches in bilateral CI stimulation all suggest differences in the nature of simulated versus actual electrical stimulation. It is not known whether

these factors could enhance or reduce binaural interference on a low-frequency acoustic target, but future research could address these questions.

V. SUMMARY AND CONCLUSIONS

This study presented a simulation of EAS to study the impact of electrical stimulation of the cochlear base on binaural discrimination of acoustic stimuli near the cochlear apex. Low-frequency target threshold ITD and ILD values were measured in the presence and absence of simulated electrical stimuli (*distractors*) that varied in degree of spectral overlap with the target and in binaural configuration. Major observations of the study include the following:

- (1) In several tested conditions, threshold ITD and threshold ILD values were significantly elevated in the presence of high-frequency pulsatile distractors. Threshold elevations are presumed to reflect a combination of remote-frequency *binaural interference* (McFadden and Pasanen, 1976) and spectrally overlapping excitation that produces *structural/energetic interference* (e.g., Gifford *et al.*, 2017).
- (2) Threshold elevations were greater for unilateral distractors than for bilateral distractors. Listeners may plausibly have benefited from the bilateral presentation as a diotic reference upon which to base discrimination judgments (cf. Buell and Trahiotis, 1993).
- (3) Threshold elevations were greater when distractors were spectrally proximate or overlapping the target region, presumably due to greater structural/energetic interference in regions of overlap. However, unilateral distractors produced significant elevations of threshold ITD even with a spectral gap of a few kHz between target and distractor.
- (4) Overall, thresholds in bilateral full spectral-overlap conditions were similar or better than in unilateral EAS gap conditions, suggesting that bilateral implantation with bilateral acoustic hearing preservation could allow for higher tolerance of spectral overlap in CI users and improved localization abilities over unilateral EAS.

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