Magnified interaural level differences enhance spatial release from masking in bilateral cochlear implant users

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Bilateral cochlear implant (BiCI) usage makes binaural benefits a possibility. However, access to interaural time difference (ITD) cues is limited, leaving users reliant on interaural level difference (ILD) cues for binaural tasks. But even ILD cues may not be as salient for BiCI users as for normal-hearing (NH) listeners. Thus, the benefits that BiCI listeners obtain when target and masker are spatially separated are limited. Here, we explore whether magnifying ILD cues improves masked speech intelligibility for BiCI listeners in a "symmetrical-masker" configuration, which controls for improvements to target-to-masker ratio (TMR) at the ear nearer the target from naturally occurring ILD cues. We magnified ILDs by estimating moment-to-moment ITDs in 1-octave-wide frequency bands and applying corresponding ILDs to the target-masker mixtures at each ear in two experiments: with NH listeners using vocoded stimuli and with BiCI users. ILD magnification significantly improved intelligibility in both experiments. CI listeners showed no improvement with natural ILDs, even for the largest target-masker separation. Because ILD magnification is applied to the mixed signals at each ear, the strategy does not alter the TMR; therefore, the improvements to masked speech intelligibility observed are not due to improved TMR, but likely from improved perceptual separation of the competing sources.

I. INTRODUCTION

Bilateral cochlear implant (BiCI) use has become more common in recent years, in part because of the potential of providing CI users access to binaural cues. Because cochlear implant (CI) devices do not deliver a robust representation of temporal fine structure (TFS; Lorenzi et al., 2006; Moore, 2008), CI users are insensitive to cues important for good speech understanding in noise, including pitch (Brown and Bacon, 2010) and interaural time differences (ITDs; (Noel and Eddington, 2013). Indeed, BiCI users are less accurate than their normal-hearing peers on sound localization tasks (Grantham et al., 2008; Jones et al., 2014; Dorman et al., 2016) and on spatial release from masking (SRM) tasks (Loizou et al., 2009; D'Onofrio et al., 2020), even though they retain some sensitivity to interaural level differences (ILDs; (Grantham et al., 2008).

Alternative CI stimulation strategies have attempted to re-introduce or extend ITD information in BiCIs (Long et al., 2003; van Hoesel et al., 2009; Srinivasan et al., 2020; Thakkar et al., 2023). However, BiCI users show limited ITD sensitivity even using such strategies. These outcomes likely reflect limitations inherent to electrical stimulation, such as current spread, frequency limitations on phase locking, and interaural asymmetry in electrode position (Laback et al., 2015; Gray et al., 2021). ILD cues, on the other hand, are simple to introduce into existing BiCI strategies because they only require sensitivity to differences in stimulation intensity at each ear, which is better preserved than timing information in electric hearing.

In normal hearing (NH) listeners, naturally occurring ILDs can contribute to SRM in several ways. When two competing sound sources arrive at a listener's head from different directions, the target sound is closer to one ear than is the masker, resulting in a greater acoustic target-to-masker energy ratio (TMR) in that ear, termed the better-ear effect (Glyde et al., 2013a, 2013b). Even in situations where there is not a long-term average TMR benefit, ILDs can provide

dynamic short term better-ear advantages ("glimpses") at moments when one of the maskers has a "dip" (Glyde et al., 2013a, 2013b). Beyond better-ear effects, ILD cues also contribute to the perception of spatial differences in competing sources, which can contribute to SRM by promoting sound segregation and supporting selective attention based on perceived source laterality (Best et al., 2005; Ihlefeld and Shinn-Cunningham, 2008; Middlebrooks and Waters, 2020). This suggests that naturally occurring ILDs can support SRM in NH listeners when target and masker sound sources are sufficiently spatially separated, through long-term and dynamic better-ear effects and by promoting sound source segregation and enabling spatial selective attention.

ILD cues are encoded in BiCI devices, and thus may provide a positive TMR at the ear nearer the target (Litovsky et al., 2006, 2009; Loizou et al., 2009). However, they are reduced after processing (Gray et al., 2021), likely due to a number of factors including dynamic range compression associated with frontend automatic gain control that operates independently at the two ears (Spencer et al., 2019), backend mapping (Khing et al., 2013), and independent peak picking (Gray et al., 2021). In addition, CI vocoding reduces glimpsing (Hu et al., 2018; Gibbs et al., 2022). Finally, the reduced representation of binaural cues in BiCI configurations reduces the ability of these users to selectively attend to a target in the presence of a spatially separated masker (Goupell et al., 2016; Akbarzadeh et al., 2020). As a result, ILD cues alone are not sufficient to support SRM in BiCI users (Ihlefeld and Litovsky, 2012).

A previous study from our group demonstrated that magnification of low-frequency ILD information (i.e., increasing ILD cue magnitudes to be larger than what occurs naturally) significantly improves speech intelligibility in BiCI users compared to when they are presented with naturally occurring ILDs alone (Brown, 2014). Briefly, the approach applies ILDs based on

the ITDs in the signal at a given time and frequency. Specifically, the target-masker mixtures at each ear are first band-pass filtered. The moment-to-moment ITD in each band is estimated by cross-correlating the left and right ear band-passed signals and taking the interaural delay resulting in the strongest correlation. A lookup table assigns an ILD to each band at each moment based on the computed ITD, mapping small ITDs to small ILDs and large ITDs to large ILDs. ILDs are then applied via attenuation at the ear with the delayed signal.

In the previous study (Brown, 2014), the low-frequency region (< 2 kHz) was targeted for ILD magnification because naturally occurring ILD cues are small at these frequencies. However, the mid-frequencies (i.e., 1-5 kHz) are important for speech understanding (DePaolis et al., 1996). One of the goals of the current study was to compare performance in two ILD magnification conditions: one in which magnification was restricted to frequency bands below 2 kHz (as in Brown, 2014), and one in which ILDs were magnified across the entire frequency spectrum available to most CI users.

A second goal of the current study was to examine the benefit of magnified ILD cues as a function of spatial separation of target and masker. To control for better-ear benefits from target-masker separation, we employed a symmetrical-masker spatial configuration. Specifically, we positioned the target talker at 0° (midline) and presented two competing maskers, one from the left and one from the right of the listener, and varied the masker location to be ±0, 15, 30, 45, 60, 75, and 90°. For the tested spatial configurations, naturally occurring ILDs cause the target-to-masker ratio (TMR) to vary with the masker eccentricity; however, the ILD magnification algorithm will not change the TMR at either ear in any meaningful way, because magnification is applied to the target-masker mixture reaching each ear. For example, if the algorithm indicates a

left-leading ITD in a particular spectro-temporal bin, an ILD will be applied by attenuating the target-masker mixture in the right ear, preserving the TMR in that ear.

We were also interested in the symmetrical-masker configuration because it is more acoustically complex than the single-masker configuration used previously, and we wanted to observe the effectiveness of the algorithm in this more acoustically complex scene. This spatial configuration increases the difficulty of the task and reduces the impact of better-ear glimpsing (Bronkhorst and Plomp, 1992; Gibbs et al., 2022).

We presented listeners with an SRM task in three ILD magnification conditions. The first (No Magnification) used naturally occurring spatial cues via non-individualized head-related transfer functions (Gardner and Martin, 1994). The second (Low-Frequency Magnification) applied the same HRTF-based natural cues, then applied ILD magnification in frequency bands below 2 kHz, as was done previously (Brown, 2014), where naturally occurring ILDs are perceptually negligible. The third condition (Broadband Magnification) applied ILD magnification in frequency bands spread across the entire usable frequency spectrum.

The current low-frequency implementation of ILD magnification differs from that in the previous study in that ILD magnification was applied independently to four 1-octave-wide frequency bands between 100 and 2000 Hz, rather than independently in 32 bands below 2 kHz. We considered using one processing band per vocoder channel, but this would have made across-participant comparisons difficult since BiCI users may have different numbers of channels, and in any event it would have resulted in a number of processing bands that was almost certainly higher than needed. If the strategy were implemented in actual CI devices, computational load would be an issue. Load scales linearly with the number of processing bands, since ITD estimation must be computed in each band, and that stage of processing represents the

vast majority of the total processing requirements. As a result, we decided to use only 4 processing bands, based on a previous study that showed that 1-octave wide processing bandwidths are sufficient to achieve significant benefits to localization performance from magnified ILD cues (Brown, 2018).

We were also interested in the extent to which applying ILD magnification across the entire usable frequency spectrum would be beneficial. As noted above, frequencies above 2 kHz convey significant speech information (DePaolis et al., 1996). We chose to fix the number of processing bands, and let bandwidth vary. Thus, this condition applied ILD magnification in four roughly equally spaced (on a logarithmic scale) contiguous frequency bands with cutoff frequencies of 100, 300, 900, 3500, and 5500 Hz. In all conditions, stimuli were ultimately bandpassed to between 100 and 5500 Hz, to approximate the bandwidth of typical CI processing, and to maintain a relatively consistent bandwidth across participants, especially as the BiCI group may have devices with different bandwidths.

In NH listeners, we predicted that naturally occurring ILDs alone would be insufficient for SRM at small target-masker separations since ILDs are small for sources within 30 degrees of midline but would be sufficient at large separations where ILDs are significant. We expected magnification of ILDs to increase SRM by increasing the perceived spatial separation of target and maskers, increasing the efficacy of spatial selective attention. Specifically, we expected Low-frequency magnification to yield better performance than naturally occurring ILDs and that Broadband magnification would produce the best performance (and the strongest SRM).

For BiCI listeners, we expected no SRM with naturally occurring ILDs (Ihlefeld and Litovsky, 2012), even for large target-masker separations. We hypothesized that Low-frequency

ILD magnification would enhance spatial perception and support SRM, and that Broadband ILD magnification would produce even better perceptual spatial separation and greater SRM.

II. EXPERIMENT 1

A. Methods

1. Participants

Sixteen normal-hearing subjects participated. A hearing screening confirmed that all participants had audiometric thresholds of 25 dB HL or better at octave frequencies up to 8 kHz. All participants were compensated either monetarily or with course credit for their participation. All procedures were approved by the Institutional Review Board of the University of Pittsburgh.

2. Equipment and Procedures

All digital signals (sampling frequency 44.1 kHz) were converted to analog signals with an RME Fireface UFX+ soundcard and attenuated to an overall sound pressure level of 70 dB with Atlas AT100-RM passive attenuators. Listeners wore Etymotic ER-3 insert phones. All participants sat in an audiometric booth during testing while the experimenter sat in an acoustically isolated, but physically adjoined booth with a window between and an intercom allowing verbal communication.

Participants first heard ten target sentences presented in quiet to familiarize them with the normal acoustic voice of the target talker, and then heard 10 vocoded target sentences. All participants were instructed to verbally repeat back as many of the words as possible produced by the centrally located "target" talker and to guess if they were not sure. Masker sentences were spatialized to the left and the right at various simulated locations (see next section). Ten sentences, each with an average of five keywords (nouns, verbs, adjectives) for a total of 50 keywords, were presented in each condition. No participant ever heard a sentence more than

once. For each condition, we quantified performance by calculating the total number of target keywords out of 50 that were correctly identified.

3. Stimuli and Signal Processing

Target speech stimuli were drawn from the CUNY sentence corpus (Boothroyd et al., 1985) produced by a female talker. Masker stimuli were drawn from the IEEE corpus (IEEE Recommended Practice for Speech Quality Measurements, 1969), which were produced by a different female talker. Masker sentences were concatenated if needed and then truncated to be equal in length to the target.

Stimulus processing and presentation, as well as experiment control, were accomplished using the Python programming language. All signal processing was performed offline. To generate stimuli, each masker sentence was first adjusted in level relative to the target sentence level to achieve a TMR of +2 dB. Then, naturally occurring binaural cues were applied separately to the target and maskers by convolving each with appropriate non-individualized HRTFs to simulate the target sentence at midline and the maskers symmetrically positioned around midline at azimuths of +/- 0, 15, 30, 45, 60, 75, and 90 degrees, all at ear height (0 degrees elevation). The 0-degree conditions (where target and maskers were all co-located) served as a reference for the spatial configurations using the same type of processing. Next, spatialized target and masker tokens were summed into left and right channels. Finally, stimuli were bandpass filtered between 125 and 5500 Hz to simulate the limited bandwidth of CI processing and to set the effective bandwidth of the signals to be comparable to that available to typically BiCI users (Exp 2).

In the No Magnification condition, no further spatial processing was performed. In the other (ILD-magnified) conditions, target-masker mixtures were filtered into different frequency bands,

with the number depending on the processing condition. In the Low-Frequency Magnification condition, the filter bank used 4th-order Butterworth filters, and consisted of five contiguous bands with cutoff frequencies of 125, 250, 500, 1000, 2000, and 5500 Hz. ILD magnification was applied to the lowest four bands. In the Broadband Magnification condition, four contiguous bands were created using cutoff frequencies of 125, 300, 900, 3500, and 5500, and ILD magnification was applied to all four bands. These parameters were chosen in order to fix the number of frequency bands in which ILD magnification occurred to four. Note that we opted not to implement one processing band per vocoder channel, as that would have made comparisons across BiCI users difficult since individuals may have different numbers of channels available. Moreover, ILD magnification with processing bandwidths of one octave significantly improves sound localization performance (Brown, 2018). Given this, we expected ILD magnification using the same processing bandwidths to enhance SRM.

To implement ILD magnification, non-overlapping 20-ms boxcar-shaped windows of data were created within each frequency band. While applying level changes to each contiguous window creates audible static, pilot testing indicates that this static is not audible after vocoding by listeners with NH, or by CI users. In each window, an ITD was estimated by finding the interaural delay corresponding to the peak in the cross-correlation of the left and right channels. A lookup table was used to convert the ITDs to ILDs. Specifically, a zero-μs ITD corresponded to a 0-dB ILD, a 750-μs ITD corresponded to a 32 dB ILD, and intermediate values were linearly interpolated. The resulting ILD in each 20-ms segment was then achieved by attenuating the signal for the ear contralateral to the direction of the ITD, leaving the ipsilateral ear segment unchanged. Although this processing approach often causes intensity transitions from window to

window, pilot testing indicated that these are not audible after vocoding by either NH listeners or BiCI users.

Finally, stimuli were processed with an 8-channel sinusoidal vocoder to make the available information similar to what a CI user could access. The first stage of the vocoder was a filterbank with cutoff frequencies logarithmically spaced between 125 and 5500 Hz. In each band, the amplitude envelope was extracted via half-wave rectification and low-pass filtering at the lesser of 400 Hz or half the bandwidth. These envelopes were then applied to sine tones with frequencies at the logarithmic center of the bands, which were then summed.

B. Results

Figure 1 presents the across-subject average results for Experiment 1, showing the raw percent correct speech intelligibility for each condition as a function of target-masker separation. As expected, performance in the co-located control conditions is similar across all types of ILD magnification, with about 50% of the keywords correctly identified. In the No Magnification condition, performance does not improve from the co-located configuration for less lateral maskers (±15, 30 & 45°), but is better for more lateral masker locations (±60, 75 & 90°). In contrast, performance is better and similar for all spatially separated masker conditions in both of the ILD magnification conditions. As a result, target speech intelligibility is consistently better with ILD magnification than with naturally occurring ILDs when the maskers are spatially separated from the target but relatively close to midline.

A 2-factor repeated-measures ANOVA was computed, with Masker location and ILD Magnification as the two main factors and percent correct speech intelligibility as the dependent factor. We excluded the co-located conditions from the analysis, because it was intended as a

control condition, and we were primarily interested in whether performance depended on the degree of spatial separation between target and maskers.

Significant effects were observed for the main factors of ILD Magnification ($F(2,30) = 5.4$, $p = 0.01$) and Masker Location ($F(5,75) = 3.9$, $p = .003$), as was the interaction between them ($F(10,150) = 2.1$, $p = 0.027$). Post hoc pairwise analyses with Bonferroni corrections revealed a significant difference between Broadband and No magnification ($p=.018$). However, Low-frequency magnification was not significantly different than either No Magnification or Broadband Magnification ($p > .05$). To understand the significant interaction, we conducted follow-up one-way ANOVAs separately for each magnification condition. We found no significant effect of masker location for the Low-Frequency and Broadband Magnification conditions. Importantly, however, there was a significant effect of spatial separation in the No Magnification condition ($p < 0.001$). Pairwise t-tests showed that performance in the 15-, 30-, and 45-degree masker locations was significantly lower than in the 60- and 75-degree masker locations. This pattern of results clearly drives the interaction between target-masker separation and magnification conditions.

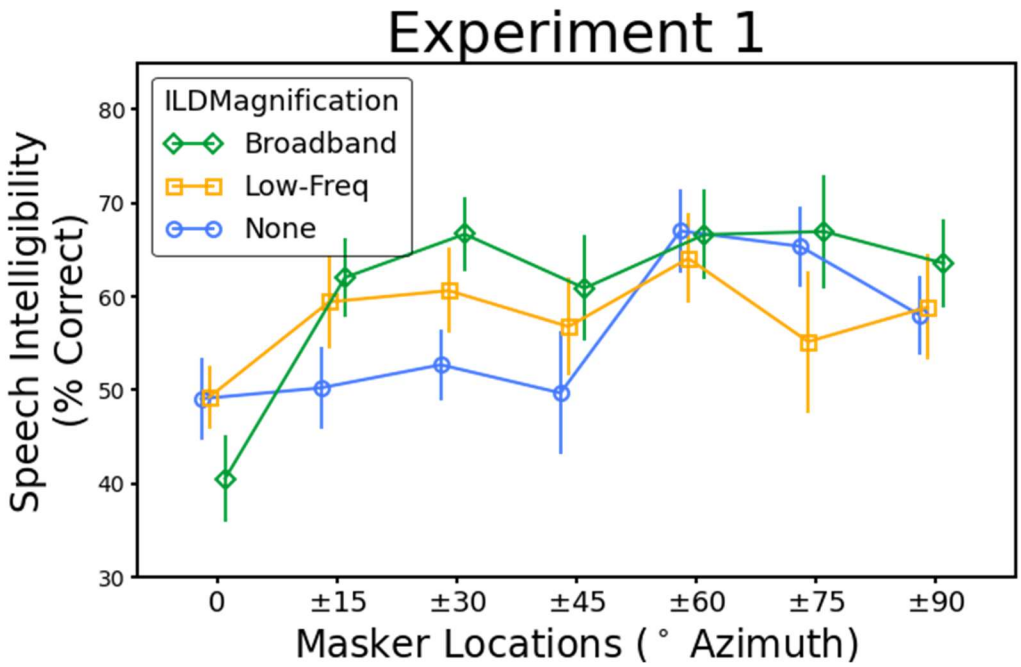

FIG. 1. Experiment 1 Results. Average percent keywords correct as a function of masker location for sixteen NH participants in a BiCI (vocoded) simulation. Data are shown for the three ILD Magnification conditions: None (circles), Low-frequency (square), and Broadband (diamonds). The symbols show the across -subject average and the error bars show the across-subject standard error.

C. Discussion

We hypothesized that both Low-frequency and Broadband magnification would significantly improve performance compared to naturally occurring ILD cues (No magnification). Supporting these hypotheses, we observed a significant benefit from Broadband magnification, and a small, albeit non-significant benefit from Low-frequency ILD magnification. These results are in line with a previous study that showed a statistically significant increase in intelligibility even for low-frequency ILD magnification using different ILD magnification algorithm parameters and a different spatial configuration (Brown, 2014). The fact that the current study found no significant benefit with low-frequency amplification may be a question of statistical power; however, the

spatial configuration used here, with a masker to either side of the target, poses much greater challenges, both for the algorithm and for the listener, than in the previous study. Thus, this more challenging listening situation may require greater spatial separation in higher frequency regions important for speech intelligibility (DePaolis et al., 1996; Hogan and Turner, 1998; Vickers et al., 2001). Consistent with this hypothesis, the Broadband condition yielded significantly greater benefit than Low-frequency magnification.

The only condition in which performance was not flat across azimuth in this experiment was in the No Magnification case. In this case, listeners performed well at large target-masker separations, but at smaller target-masker separations, performance was equivalent to the co-located configuration. This suggests that naturally occurring ILD information at small masker eccentricities does not support SRM. For these vocoded stimuli, only azimuths greater than 45 degrees provided enough perceptual separation for NH listeners to selectively attend to the target. Performance improved with ILD magnification for these conditions, indicating that the magnification provides a spatial perceptual benefit when natural cues are insufficient to support SRM.

III. EXPERIMENT 2

A. Methods

1. Participants

Seven BiCI patients participated, using their everyday program without modification, except for a minor adjustment to ensure that sounds were at a comfortable overall level. All participants were compensated monetarily. All procedures were approved by the Institutional Review Board of the University of Pittsburgh.

2. Equipment and Procedures

All equipment and procedures were identical to those used in Exp. 1, except for a few minor differences. Specifically, instead of a 70-dB SPL presentation level, BiCI participants used the attenuators to adjust the presentation level to most comfortable. In addition, instead of Etymotic ER-3 insert phones, direct-connect accessory cables delivered sound to participants. Participants used their everyday programs with no adjustments, including for automatic gain control. Finally, practice consisted of 10 unprocessed target sentences in quiet, with no vocoder practice.

3. Stimuli and Signal Processing

Stimuli and signal processing were identical to that used in Exp. 1, except that no vocoding was performed on the stimuli.

B. Results

Figure 2 presents the across-subject average results for Exp. 2 in 7 BiCI users, showing the raw percent correct speech intelligibility for each condition as a function of target-masker separation. In this population, performance in the co-located condition (about 40 percentage points) was generally lower than in the spatially separated conditions.

A 2-factor repeated-measures ANOVA was conducted with dependent factors of masker location and ILD magnification, and percent-correct speech intelligibility as the dependent variable. As with Experiment 1, co-located conditions were excluded from the analysis. The ANOVA revealed a significant main effect of ILD Magnification ($F(2,12) = 11.4$, $p = 0.009$). However, neither Masker Location ($F(5,30) = 2.15$, $p = .116$) nor the interaction term ($F(10,60) = 1.18$, $p = 0.342$) were significant. Post hoc pairwise analyses with a Bonferonni correction revealed that the Broadband ILD magnification strategy produced performance that was significantly better than both No Magnification ($p = 0.041$), and Low-Frequency Magnification (p

= .011). However, there was no significant difference between No Magnification and Low-Frequency Magnification (p = 0.629).

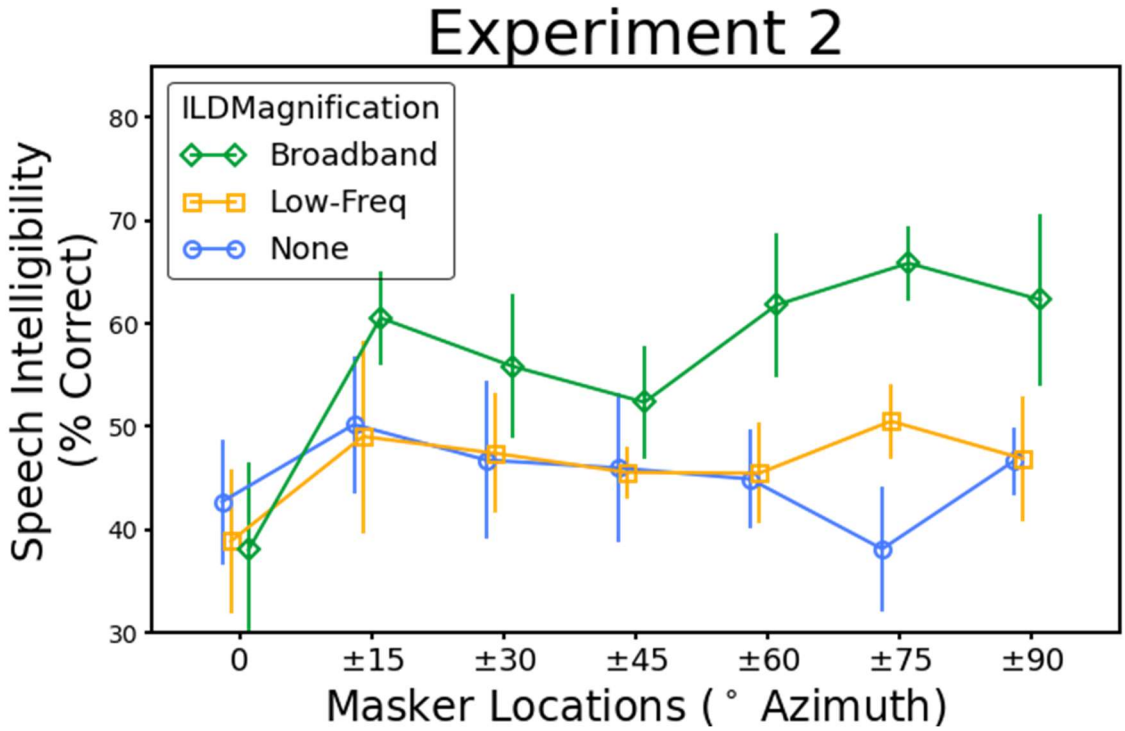

FIG. 2. Experiment 2 Results. Average percent keywords correct as a function of masker location for seven BiCI patients. Data are shown for the three ILD Magnification conditions: None , low-frequency, and Broadband. The symbols show the across -subject average and the error bars show the across-subject standard error in each condition.

C. Discussion

In BiCI users, we hypothesized that both Low-frequency and Broadband magnification would allow for greater benefit than naturally occurring ILD cues. We observed a significant improvement in performance with Broadband magnification over No magnification; however, Low-frequency magnification provided no statistically significant benefit.

The effect of ILD magnification was relatively consistent across azimuth in the BiCI group. In all three conditions, percent correct in spatially separated conditions did not vary much with

increased spatial separation. This effect was confirmed by the ANOVA, which revealed no significant effect of masker location.

Naturally occurring cues provided insufficient perceptual separation to observe a benefit, even with maskers at ±90°. This result supports our hypothesis that BiCI users require greater ILDs to perceive a separation between target and maskers. This is consistent with the literature (Ihlefeld and Litovsky, 2012; Brown, 2014), and is likely due to the compressed perceptual space they experience in the horizontal plane with naturally occurring cues (Grantham et al., 2007). ILD Magnification can mitigate this limitation for BiCI users however, by expanding the perceptual space (Brown, 2018). These BiCI users showed a consistent benefit of target-masker separation with the Broadband ILD magnification across masker azimuth. Given that our ILD magnification does not alter the TMR at either ear, these results suggest that Broadband ILD magnification allows BiCI listeners to focus on the target speech and suppress the maskers by deploying spatial selective attention. However, neither naturally occurring ILDs nor Low frequency ILD magnification allowed the BiCI users to effectively deploy spatial attention.

IV. GENERAL DISCUSSION

Both NH and BiCI listeners benefitted from magnifying ILD cues. For NH listeners, Broadband magnification improved performance compared to naturally occurring ILDs when symmetrically positioned maskers were close to midline and natural ILDs were too small to support SRM. For BiCI users, Broadband magnification significantly improved performance compared to both Low frequency Magnification and No Magnification conditions.

The overall benefit of ILD magnification observed in the current study is less than what was observed previously with a single masker (Brown, 2014). That is, previous results showed a masking release of about 30 percentage points from ILD magnification, while the amount of

benefit in the current study is around 20 percentage points with Broadband magnification. This difference is almost certainly due to the perceptual difficulty associated with the symmetrical masker configuration used in the current study. Nevertheless, 20 percentage points of masking release represents a substantial benefit and indicates that ILD magnification can be effective in relatively complex auditory scenes.

A. ILD Magnification Enhances Spatial Differences, Thereby Supporting Spatial Attention

In natural listening conditions, the better-ear effect contributes to improved speech intelligibility, and this effect grows as the eccentricity of the masker increases. However, our algorithm does not alter the acoustic TMR at either ear, precluding better-ear benefit. This is due to the fact that our algorithm achieves ILD magnification by attenuating the target-masker mixture at each ear, as dictated by the ITD in that frequency band and time point: both target and masker are attenuated by the same amount. This fact is not changed by the spatial configuration (ie., it is true even in the case where the target and masker are in opposite hemifields, as in Brown, 2014). As a result, the benefits observed from ILD magnification cannot be explained by either increases in the TMR at the better ear or increased opportunities for dip listening. Even when magnified, ILD cues are not likely to facilitate dip listening by BiCI listeners in any event, as the perceptual ability has been shown to be reliant on TFS information, which is reduced in vocoded stimuli (Hopkins and Moore, 2009; Brown and Bacon, 2010; Gibbs et al., 2022).

Consistent with this observation, our results do not show a significant effect of target-masker separation in any magnified condition (Low-frequency or Broadband). If ILD magnification improved performance by increasing TMR, percent correct should increase as a function of target-masker separation. Instead, we found that performance improved over co-located

conditions when ILDs were “large enough,” but did not increase monotonically with increasing masker eccentricity. Given this, the observed benefits of ILD magnification must reflect other mechanisms. Specifically, we propose that magnified ILDs enhance spatial perception of the vocoded / BiCI stimuli, allowing listeners to filter out masker-dominated frequencies / time instances that are perceived as off midline and focus attention on the target. When spatial cues do not meaningfully change the TMR, as in experiments in which only ITDs are manipulated, spatial selective auditory attention allows NH listeners to attend to a target amongst spatially separated maskers (Shinn-Cunningham and Best, 2008; Shinn-Cunningham, 2017; Noyce et al., 2021). Such spatial auditory selective attention occurs through coordinated activity in multiple areas of the brain, including prefrontal cortex, parietal cortex, and auditory cortex (Alho et al., 2014; Choi et al., 2014; Deng et al., 2019, 2020; Noyce et al., 2022). Attention modulates the information represented in auditory cortex, enhancing the representation of a target and suppressing the representation of maskers (Noyce et al., 2021; Auerbach and Gritton, 2022). Spatial auditory attention is less effective in listeners with hearing loss; indeed, performance is inversely correlated with spatial discrimination thresholds (Dai et al., 2018; Bonacci et al., 2019). Similarly, limitations of electrical stimulation reduce CI users’ ability to capitalize on naturally occurring spatial cues to direct selective attention (Goupell et al., 2016; Akbarzadeh et al., 2020). ILD magnification, which yields an SRM benefit without changing TMR, enhances the perceived spatial separation of target and maskers, thereby supporting spatial attentional processes. This underscores the need for processing algorithms that facilitate greater perceptual segregation and easier deployment of attention.

360 **B. Corrective ILD Magnification**

361 ILD magnification has the potential to be corrective; that is, to improve spatial hearing
362 outcomes in BiCI users in a targeted, individualized way. Individualized corrective ILD
363 processing benefits users by magnifying cues according to baseline frequency- and azimuth-
364 specific localization abilities (Brown, 2018). While this corrective approach works well for
365 optimizing sound source localization and making spatial perception veridical, tasks with multiple
366 sound sources may require a different level of magnification. In a cocktail-party like
367 environment, increased perceptual separation between target and masker may improve speech
368 reception, even if sources are not perceived at their veridical locations. When a target and masker
369 are on either side of the head (as in Brown, 2014), magnifying ILD cues will likely support
370 SRM even though the perceived spatial locations of the target and masker are incorrect (i.e.,
371 large ILD cues will lead to hyper-lateralization, in which perceived locations will be at or near
372 ±90 degrees azimuth). Exaggerated ILD magnification also works well for speech understanding
373 in the spatial configuration used in the current study, in which the target is at midline and the
374 maskers are on either side of the head. Because the target is at 0 degrees azimuth, its perceived
375 location does not change after ILD magnification, so perceived spatial separation between it and
376 the maskers increases from ILD magnification, which accentuates the eccentricity of the
377 maskers. If a target and masker are both off midline and on the same side of the head, however,
378 ILD magnification may actually decrease the perceived spatial separation between them.

379 **C. Future Work**

380 Future experiments will explore the frequency-, azimuth-, and subject-specific benefits of
381 magnified ILD cues in an SRM paradigm. This will include an examination of the effects of
382 parameters such as the number of magnification bands, the cutoff frequencies of those

magnification bands, and the ITD to ILD mapping function (lookup table). Four magnification bands were used in this study, as we wanted to explore if fewer, broader bands than used in Brown (2014) could elicit SRM benefits. Fewer bands would be easier to implement in BiCI configurations as it is computationally less expensive. We also used a bandwidth of about 2 octaves in the Broadband magnification, which yielded the largest benefit. Future work will be needed to determine the optimal bandwidth for magnification. Both the number of bands and the bandwidth may be frequency-, azimuth-, or subject specific.

Ongoing extensions of this work will also measure neural responses to sound in both normal hearing listeners and BiCI users completing spatial selective attention tasks. This is motivated by a need to understand the perceptual and neural mechanisms that underlie the benefit observed in this experiment. If the magnified ILD cues used here do, in fact, allow for attentional modulation of responses to target and masker sounds, this will provide strong motivation for the use of ILD magnification in bilateral cochlear implant processing.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts of interest to disclose.

Ethics Approval

All procedures were approved by the Institutional Review Board of the University of Pittsburgh. All participants gave written informed consent and were compensated for their participation.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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