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Contralateral interference caused by binaurally presented competing speech in adult bilateral cochlear-implant users

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Abstract

OBJECTIVE—Bilateral cochlear implants (BI-CIs) are intended to improve sound localization and speech understanding in the presence of interfering sounds. For normal-hearing listeners, improved speech understanding in the presence of interfering sounds can be achieved with monaural head shadow and binaural unmasking. While some BI-CI listeners experience binaural unmasking under certain testing conditions, others appear to not. This study tested a group of BI-CI users with hearing histories that have been linked to poor binaural processing – early onset of deafness or long duration of deafness in just one ear. We predicted that these listeners would experience the opposite of binaural unmasking (i.e., contralateral interference) when trying to understand speech in the presence of a competing talker.

DESIGN—Nine adult BI-CI users who were deafened early in life or had an asymmetric hearing history (e.g., a much longer duration of deafness in one ear) participated in this study. The coordinate response-measure (CRM) corpus was used to assess speech understanding for a male target talker in quiet or in the presence of one male competing talker. Experiment 1 measured binaural unmasking in a paradigm that provided no head-shadow component. The target was always presented monaurally while the interferer was presented either monaurally or diotically. Experiment 2 measured spatial release from masking in a paradigm that included both a head-shadow component and possible binaural-unmasking component. Non-individualized head-related transfer functions were used to simulate talker locations in the front or 90° to the left or right.

RESULTS—In experiment 1, all nine listeners experienced contralateral interference (9 dB on average). Four listeners demonstrated roughly symmetric contralateral interference; five listeners experienced asymmetrical contralateral interference. In experiment 2, the listeners experienced only 1 dB of spatial release from masking on average; this small amount was possibly a result of the contralateral interference observed in experiment 1. The results were best explained by individual differences in speech understanding in quiet, which significantly correlated with the duration of deafness in the ipsilateral ear. Specifically, instances of asymmetrical contralateral interference could correspond to asymmetrical hearing histories.

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CONCLUSION—Bilateral cochlear implantation should provide a hearing benefit to the recipient. For the BI-CI listeners specifically recruited for this study, there seems to be a conflict with processing the auditory information across the two ears, which produced the opposite of the desired hearing benefit. This suggests that there may be a subset of potential BI-CI users for whom contralateral interference offsets much of the potential head-shadow benefit. If so, earlier implantation in the second implanted ear might have produced larger binaural benefits, which is important information for clinicians advising patients considering bilateral implantation.

Keywords

cochlear implant; binaural hearing; speech understanding

Introduction

One of the most critical functions of the auditory system is to organize complex auditory scenes, such as attending to a single target talker of interest in a room with interfering sounds. People with normal hearing (NH) perform this task exceedingly well because they receive multiple advantages from having access to sound in both ears when sounds are separated in space. One of these advantages is “head shadow,” a mechanism that is monaural in nature and results in an acoustically favored or “better ear” (BE) from the diffraction of the physical acoustical signal by the head. Another of these advantages is “binaural unmasking” (sometimes called “squelch” or “the binaural intelligibility level difference”; Van Hoesel 2012), a mechanism that is binaural in nature and likely results from the neural computation of interaural differences that help listeners perceive sound sources at different locations in space. The magnitudes of these advantages vary depending on the situation, but it is not uncommon for NH listeners to experience about 5 dB of head shadow and 5 dB of binaural unmasking (Hawley et al. 2004).

People with severe-to-profound hearing impairment who receive bilateral cochlear implants (BI-CIs) to partially restore their hearing show much less benefit than NH listeners from having two ears in these situations. Head-shadow advantages have been well documented for BI-CI users, but until recently there has been minimal evidence of binaural unmasking (e.g., Goupell et al. 2016; Litovsky et al. 2006; Loizou et al. 2009; Schleich et al. 2004; van Hoesel et al. 2008). One possible reason that binaural unmasking of speech is limited for BI-CI listeners is because of stimulus-encoding factors, whereby signals are likely distorted differently across the two ears (“interaural decorrelation”, see Goupell and Litovsky 2015 for a description; see also Kan and Litovsky 2015; Laback et al. 2015; Litovsky et al. 2012). For example, binaural processing of complex sounds might be stunted by interaural mismatch in the cochlear place-of-stimulation (Kan et al. 2015; Kan et al. 2013) and a reliance on across-ear differences in the level (interaural level differences, ILDs) rather than in the arrival time (interaural time differences, ITDs) for a given sound (Aronoff et al. 2010).

A second possible reason for limited evidence of the binaural unmasking of speech for BI-CI listeners is that the nature of the testing conditions plays an important role in the amount of unmasking observed. In other words, larger binaural unmasking benefits can be observed in BI-CI listeners under certain optimized testing conditions. For example, Bernstein et al.

(2016) measured binaural unmasking using speech targets and interferers in a contralateral-unmasking paradigm. Speech understanding performance for a monaural target and monaural interferer in the same ear was compared to performance for a monaural target and a diotic interferer. This configuration provides no possible head-shadow (i.e., BE) advantage because only masking energy is added to the ear contralateral to the target, and yet NH listeners experience less masking because the talkers are perceived at different intracranial locations. The paradigm employed the coordinate response-measure (CRM) corpus (Bolia et al. 2000; Brungart 2001), which has a small closed set of possible responses along with an identical sentence structure for both the target and the interfering talkers. Using such a speech corpus is thought to produce larger effects from perceived spatial separation (i.e., increased binaural unmasking) because NH and CI listeners appear to experience difficulty in perceptually separating the similar speech streams in the absence of binaural cues (i.e., “informational masking,” Brungart 2001; Durlach et al. 2003). Under these testing conditions, Bernstein et al. (2016) showed nine BI-CI listeners could achieve 5 dB of binaural unmasking on average. It may be that the speech corpus used to measure binaural unmasking was critical, because another study by Goupell et al. (2016) measured no unmasking on average when using some of the same target-interferer configurations but with targets and interferers taken from a different closed-set matrix sentence test (Kidd et al. 2008).

Even though Bernstein et al. (2016) study revealed a substantial amount of binaural unmasking for BI-CI listeners on average, it is important to note that the amount of unmasking varied greatly across listeners, including one BI-CI listener (BI5) who systematically showed contralateral interference¹ (i.e., a decrease in performance for the binaural condition). This listener had a unique hearing history compared to the other eight listeners in the study, with an early onset of deafness, followed by a relatively long duration of deafness, which was finally followed by bilateral cochlear implantation as an adult. This inter-subject variability suggests that the timeline of hearing history may play a role in determining whether a particular BI-CI listener or group of BI-CI listeners will experience binaural unmasking. The purpose of this study was to determine if adult BI-CI listeners with certain hearing histories that have been linked to poor binaural processing – in particular, early onset of deafness (as was the case with BI5) or long durations of deafness in one ear – would also demonstrate contralateral interference rather than binaural unmasking of speech in the presence of a competing talker. It can be argued that these two subpopulations of adult BI-CI listeners are relatively less represented in the literature than those with a late-onset and more symmetrical duration of deafness, perhaps because these may be relatively poor performers (Kan and Litovsky 2015; Laback et al. 2015).

We recruited adult BI-CI listeners with early onsets of deafness and late implantation because binaural processing seems to be diminished or non-existent in this population. Only a few reports have compared adult BI-CI listeners with early and late onset of deafness, and

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¹Here we are careful not to use the term “binaural interference,” which was originally used by McFadden and Pasanen (1976) to discuss the differential effect of low- vs. high-frequency stimuli when measuring sensitivity to interaural differences for a target in the presence of a remote diotic interferer. Rather, we discuss “contralateral interference” for understanding speech, which is defined as the opposite of “contralateral unmasking.”

for only a handful of listeners. For example, Schleich et al. (2004) showed notably poor sound-localization abilities for one BI-CI listener that had an early onset of deafness. Litovsky et al. (2010) showed that eight BI-CI listeners with late onset-of-deafness perceived a change in intracranial lateral position with changes in ITD or ILD for stimulation on a single electrode pair, whereas three BI-CI listeners with early onset-of-deafness perceived a change in intracranial lateral position only with changes in ILDs. Note that perceiving a change in intracranial lateral position with ILDs could be achieved by monitoring the level in only one ear and thus does not necessarily provide evidence of binaural processing. Goupell (2015) compared eight BI-CI listeners with late onset to three BI-CI listeners with early onset of deafness in a correlation-change discrimination task on a single electrode pair and found that most of the early-onset listeners were not sensitive to changes in interaural correlation, unlike the late-onset listeners. The small number of early onset listeners in these studies limit any strong conclusions. Nonetheless, these findings in adults are consistent with findings in children with BI-CIs for whom ILD sensitivity has been demonstrated often (Gordon et al. 2014). ITD sensitivity, however, seems much more difficult to achieve in children with BI-CIs; it seems to depend on whether there was any hearing at birth and on the duration of time between implantations (Bennett 2016). To summarize, acoustic hearing early in life might be critical to achieving certain binaural-hearing benefits.

We also recruited adult BI-CI listeners with relatively long inter-implant durations because there is neurological evidence that an asymmetric hearing history could affect binaural processing. For example, Gordon et al. (2013) found that abnormal lateralization of activity in the auditory cortex occurs for children with unilateral implantation, but not for children with bilateral implantation. This reorganization required a sufficiently long duration of unilateral stimulation. Subsequent bilateral implantation after 1.5 yrs of unilateral CI experience could not counteract the cortical reorganization, even after 3–4 yrs of bilateral stimulation. Similar results are mirrored in a cat model where long durations of unilateral hearing negatively affect processing of ITDs (Tillein et al. 2016). Finally, Reeder et al. (2014) showed that BI-CI listeners with relatively long inter-implant durations have poorer sound localization abilities than those with shorter inter-implant durations. In summary, the evidence from the literature suggests that BI-CI listeners with asymmetric hearing history may have difficulty understanding speech in noise and experiencing binaural unmasking of speech.

In this study, we specifically recruited nine adult BI-CI users that might have impaired binaural processing resulting from either little exposure to acoustic hearing as a young child or a relatively asymmetric hearing history, such as a long (>5–10 year) duration of deafness in one ear compared to the other or a long duration of unilateral CI use². We hypothesized that these BI-CI listeners would demonstrate contralateral interference in a competing speech-understanding task, similar to the one listener from Bernstein et al. (2016), who had an early onset of deafness, and unlike the other listeners from that study who experienced binaural unmasking of speech.

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²)It is also possible that the effects of asymmetric hearing history and early onset of deafness with late implantation could interact, although with the limited size of the population tested, addressing this issue was outside of the scope of the current study.

Methods

Three types of measurements were made in this study. First, monaural and diotic speech understanding in quiet was measured to assess baseline performance. Second, binaural unmasking was measured using the contralateral-unmasking paradigm, which has no head-shadow component. This was the measurement of primary interest in this study. Third, spatial release from masking, which includes both binaural unmasking and head-shadow components, was measured with a target talker placed in front and an interfering talker placed in front or on the side of the listener. Reasons to test this condition were: (1) this listening configuration is more ecologically valid; (2) there are limited measurements of the magnitude of spatial release from masking with head shadow with the type of BI-CI listener that was recruited for this study, but many studies include such a measurement (e.g., Litovsky et al. 2006; Loizou et al. 2009; Schleich et al. 2004; van Hoesel et al. 2008), and hence the results can be compared more broadly to the literature; (3) head shadow is produced by the physical diffraction of sound waves by the head, and thus this benefit should be relatively unaffected by hearing status (i.e., someone with NH or a CI should experience about 4–6 dB of head-shadow benefit for co-located talkers from the front and spatially separated talkers at the front and side). Head shadow typically causes an acoustically favored ear (i.e., better ear = BE). For the purposes of this study, we distinguish between a BE caused by physical acoustics and head shadow, defined as the ear with the better signal-to-noise ratio (SNR) (i.e., better ear as measured by SNR from head shadow = BE_{HS}) and a BE related to listener performance, defined as the ear with better speech understanding in quiet (better ear as measured by performance = BE_P). Correspondingly, we also distinguish between the poorer ear in terms of SNR (i.e., poorer ear as measured by SNR from head shadow = PE_{HS}) and the poorer ear in terms of speech understanding in quiet (i.e., poorer ear as measured by performance = PE_P). BE_P and PE_P would capture large asymmetries in speech understanding in quiet that could result, for example, from asymmetrical durations of deafness.

Listeners

Nine BI-CI listeners participated in this study. The hearing histories and demographic information for these listeners are provided in Table 1. All listeners were tested at the University of Maryland – College Park. One listener, CBA, was listener BI5 in Bernstein et al. (2016) and was retested for this study. Five of the BI-CI listeners were postlingually deafened. Some had a much longer duration of deafness in one ear (CAX, CCA), had a long amount of time (>5 yrs) between implantations (CBC, CBF), or experienced both (CAK). Four were pre- or peri-lingually deafened (CAW, CBA, CCD, CCE). All nine BI-CI listeners were implanted sequentially with Cochlear Ltd. devices. Eight of the listeners were implanted in both ears as adults. There was no evidence or self-report of stroke in the listeners. There was no evidence of greater than mild cognitive decline as measured by the Montreal Cognitive Examination (MOCA; Nasreddine et al. 2005); all listeners had a score of at least 22 (Anderson et al. 2012). The study procedures were approved by the Institutional Review Board at the University of Maryland – College Park.

Stimuli

Two types of speech stimuli were tested in this study. The first was an open set of Institute for Electronics and Electrical Engineers (IEEE) sentences (Rothausen et al. 1969) spoken by a male talker and presented in quiet using circumaural headphones or Freedom TV/HiFi Cables (Cochlear Ltd; Sydney, Australia). The second was the call-sign based word-identification task using the CRM corpus (Bolia et al. 2000; Brungart 2001). The CRM sentences were spoken by a male talker presented in quiet or in the presence of a competing different male talker. The CRM corpus was used because it contains a carrier phrase and a small set of key words (colors and numbers) that CI listeners can identify even if they have poor speech understanding with an open set of sentences. Another reason the CRM was used is that the identical sentence structures of the target and interfering sentences make it difficult to perceptually separate the concurrent voices (i.e., there is a relatively large amount of “informational masking,” Durlach et al. 2003). As argued in Bernstein et al. (2016), the use of the CRM may have contributed to the relatively large binaural unmasking effects for their BI-CI listeners compared to other similar studies.

Stimuli were presented using circumaural headphones (HD650, Sennheiser; Hannover, Germany). Previous studies have used circumaural headphones placed over CI sound processors to perform binaural experiments (Grantham et al. 2008). We decided to use circumaural headphones for two reasons. First, using the direct audio input of a sound processor is difficult to calibrate. For this study, we presented the speech stimuli at 65 dB-A over headphones (Brüel & Kjær Sound & Vibration Measurement A/S, Naerum, Denmark), although listeners could still independently adjust their volume on their processors to achieve a comfortable and balanced loudness in both ears. Second, there is an increasing prevalence of personal sound processors without a direct audio input port. Because we wanted to use the sound processor and processing strategy that the listener experienced on a daily basis, this was another reason we decided to use circumaural headphones. Any noise-reduction strategy or beamforming was disabled before testing. Before testing, we verified that crosstalk from the contralateral headphone was not audible.

Procedure

Listeners were seated in a double-walled sound attenuating booth (Industrial Acoustics, Inc.; Bronx, NY) to perform all the tests. Experiments were controlled by a personal computer running MATLAB (the Mathworks; Natick, MA). Stimuli were delivered over a soundcard (UA-25 EX, Edirol/Roland Corp.; Los Angeles, CA) and an amplifier (D-75A, Crown Audio; Elkhart, IN).

Listeners used their everyday sound-processing program and set both of their sound processors to a typical and comfortable loudness. Listeners were then presented with sentences sequentially and simultaneously in order to adjust the volume between the ears so that they were approximately loudness balanced.

As a baseline measurement, speech understanding in quiet was measured using IEEE sentences³. Listeners repeated the words they heard and five keywords were scored by an experimenter who was also seated in the sound booth. They were presented with 20

sentences in each of the three conditions tested: unilateral (right or left ear alone) and bilateral (right and left ears together). The order of testing these conditions was randomized across listeners.

Testing of the CRM sentences in quiet and with an interferer followed the procedure used by Bernstein et al. (2016). The CRM sentences have a fixed structure: “Ready <call sign>, go to <color> <number> now.” Listeners were instructed to follow the speech of the talker who used the call sign “Baron” and to identify the color and number spoken by this target talker while ignoring the interfering talker that used other call signs (e.g., “Laker” or “Ringo”) and coordinates. The target and interferer never said the same color or number in a given trial.

There were two experiments that used the CRM sentences. Experiment 1 measured binaural unmasking without head shadow. For the monaural conditions, target and interfering talker were presented to one ear. For the binaural conditions, the target talker was presented monaurally and the interfering talker was presented diotically. Such a target-interferer configuration leads to “contralateral unmasking” as it only adds masking energy in the contralateral ear (i.e., there is no BE_{HS}), but reduces the amount of masking experienced by most NH listeners. If the listener is able to perceptually fuse the copies of the interfering speech presented diotically, this should lead to the target being perceived nearer the right or left ear, and the interferer perceived nearer the center of the head. Testing was performed in blocks. In each block, the ear that received the target speech was held constant. The listener was explicitly instructed to selectively attend to the appropriate target ear. All of the blocks with the target placed in one ear were completed before testing with the target in the other ear. The ear that was tested first was randomly assigned for each listener. Within each block, the target-to-masker ratio (TMR: -8, -4, 0, +4, +8, +12 dB, and quiet)⁴ and the presentation mode (monaural/binaural) were randomly varied. There were five trials per TMR and the testing was repeated for at least five blocks, yielding at least 25 trials per condition.

Experiment 2 measured spatial release from masking for a target talker in front of the listener and an interfering talker spatially separated from the front to the side of the head. Such configurations are similar to other studies that measured both head shadow and binaural unmasking effects together (e.g., Loizou et al. 2009). The purpose of this experiment was to test the hypothesis that BE_{HS} , which is simply a result of acoustical interference of the head, would produce a benefit to a BI-CI user. Placing the target talker in front of the listener is a more realistic configuration than placing the target talker to the side as was done in experiment 1. Spatial locations were simulated by filtering the stimuli using non-individualized head-related transfer functions (HRTFs) measured in an anechoic environment (Wightman and Kistler 1989a, 1989b) for front (0°), right ($+90^\circ$), or left (-90°) locations. The target talker was presented diotically (0°). The interfering talker was either co-located (0°) or spatially separated ($+90^\circ$ or -90°) from the target talker. As in experiment

³)Some of the speech-understanding data in quiet using IEEE sentences were collected in a larger study on the effect of time compression in CI users. The 0% compression conditions reported here were intermixed with conditions with 20, 40, and 60% time compression. We verified that the presentation mode, circumaural headphones or TV/HiFi cable, produced equivalent speech-understanding scores in a subset of listeners.

⁴)Listener CAX had much lower thresholds than the other eight listeners and therefore was also tested at -12-dB TMR for some conditions.

1, TMRs were varied, a block design was used, and data from at least 25 trials per condition were collected. The co-located and two spatially separated conditions were performed in three separate blocks, unlike experiment 1 where the monaural and binaural conditions were performed in the same block. The order of spatial conditions was randomized across listeners.

Data Analysis

Five keywords per sentence were scored for the IEEE sentences. Two keywords (color and number) per sentence were scored for the CRM sentences. Performance differences between test conditions were evaluated using repeated-measures binomial logistic regression. This analysis provides a set of results that can be interpreted analogously to a repeated-measures analysis of variance, in that it provides an assessment of the main effects and interactions between independent variables that influence the dependent variable. The main advantages of the logistic regression analysis are that (1) it does not violate test assumptions related to the non-normally distributed percent-correct (PC) scores and (2) it takes into account the number of trials completed for each listener and condition when evaluating the difference between PC scores. Speech-reception thresholds (SRTs; the TMR required to produce PC=50%), were estimated by fitting the data with a logistic function (psignifit; Wichmann and Hill 2001). In cases where the function did not exceed PC=50%, the threshold was set to an arbitrarily large number, 15 dB. For experiment 2, spatial release from masking was calculated as the difference in co-located and separated SRTs at PC=50%.

RESULTS

Speech understanding in quiet

Speech understanding in quiet was performed as a baseline measurement. We expected to see inter-subject variability and some open-set speech understanding for at least one ear for each listener. Figure 1 shows PC scores in quiet for individual listeners' for the BE_P (panel A) and PE_P (panels B); the IEEE speech understanding scores were used to define the BE_P and PE_P. A repeated-measures binomial logistic regression analysis of PC scores with factors ear and corpus was performed. Three important trends can be observed in these data. First, the listeners achieved a range of open-set speech understanding comparable to that expected from the literature (Gifford et al. 2008). Second, speech understanding was much higher for the CRM sentences than for the IEEE sentences [$\chi^2(1)=112$, $p<0.0005$], as expected when comparing closed- and open-set speech corpora. Third, scores for the IEEE sentences were highly variable across listeners and in some cases were variable across ears for individual listeners. There was a significant effect of ear of presentation [BE_P, PE_P, or diotic, Fig. 1B; $\chi^2(2)=28.1$, $p<0.0005$] but no significant corpus $\times$ ear interaction [$\chi^2(2)=0.093$, $p=0.96$].

Figure 1A and Table 2 highlight important individual differences in speech-understanding scores. Figure 1A and the second half of Table 2 show that some listeners had very asymmetric open-set speech-understanding scores. Focusing only on the IEEE sentences, the direction of the asymmetry was different across individuals (four listeners better in the right ear, five listeners better in the left ear). Bonferroni-corrected binomial tests carried out for

each individual listener revealed that six listeners had significant across-ear differences in speech understanding ($p < 0.005$), while the other three did not ($p > 0.05$). For each of the six listeners with a significant asymmetry, the asymmetry was larger than 20 percentage points which was the criterion used by Mosnier et al. (2009) to be considered to have “asymmetrical” hearing. Presenting the IEEE sentences to both ears improved speech understanding for only six listeners, resulting in no significant difference between diotic performance and monaural presentation for the BE_p [$PC = 2.2 \pm 7.5\%$, post-hoc pairwise comparison, $p = 1.00$]⁵. Separating the symmetrical and asymmetrical listeners, the symmetrical listeners improved ($PC = 8.2\%$) more than the asymmetrical listeners ($PC = -0.8\%$) for diotic compared to BE_p-monaural presentation. There was a much larger and significant improvement from PE_p-monaural to diotic presentation [$PC = 38.5 \pm 25.9\%$, post-hoc pairwise comparison $p < 0.0005$]. Similar trends in performance were observed for the CRM sentences presented in quiet, albeit with smaller differences between the ears due to ceiling effects. There was a significant difference between diotic and PE_p monaural presentation [$PC = 14.2 \pm 10.8\%$, post-hoc pairwise comparison $p < 0.0005$], but not between diotic and PE_p monaural presentation [$PC = -0.2 \pm 2.0\%$, post-hoc pairwise comparison $p = 1.00$]. In summary, the listeners demonstrated a wide range of speech understanding and some demonstrated significant, large ($> 20\%$) asymmetries for open-set sentences.

Experiment 1: Binaural unmasking

Figure 2 shows average data for eight of the BI-CI listeners from Bernstein et al. (2016; panel A) and for the nine listeners from this study (panels B–D)⁶. For the listeners from Bernstein et al. (2016), performance improved for the binaural compared to the monaural condition. In contrast, performance for the listeners in the current study was substantially poorer for the binaural compared to the monaural condition. The data from the current study (Fig. 2B) were analyzed with a repeated-measures binary logistic regression analysis with two within-subjects factors: configuration (monaural or binaural) and TMR (six levels: -8 to $+12$ dB). Each ear was treated as a separate case. There was a significant main effect of configuration [$\chi^2(1) = 31.2$, $p < 0.0005$] confirming the observation that performance was substantially lower for the binaural than for the monaural condition. There was also a significant main effect of TMR [$\chi^2(5) = 218$, $p < 0.0005$], as expected. Finally, there was a significant interaction between the two factors [$\chi^2(5) = 33.7$, $p < 0.0005$], reflecting the fact that contralateral interference became much larger with increasing TMR. Bonferroni-corrected post-hoc pairwise comparisons found a significant contralateral interference effect for TMRs between -4 and $+12$ dB ($p < 0.005$ for all), but no significant difference between monaural and binaural performance at -8 dB ($p > 0.05$). Separate binomial logistic regression analyses conducted on the data for the BE_p and (Fig. 2C) and PE_p (Fig. 2D) also identified significant main effects of configuration and TMR and configuration, as well as significant interactions between these factors ($p < 0.005$ in both cases).

⁵)We acknowledge that choosing the BE_p and PE_p introduces a potential statistical bias or a “regression to the mean” effect (van Hoesel and Litovsky 2011). This is likely a small effect, however, given the clearly large asymmetries for most of listeners, particularly the ones that show small deficits in speech understanding between the BE_p alone and both ears together.

⁶)Note that listener BI5 from Bernstein et al. (2016) was retested in the present study as CBA. Her data was not included in Fig. 2A, only in Figs. 2B–D.

Figures 3–5 show the individual data from experiment 1 (rows A–C). Row A shows the results when the target speech was presented to the BE_p. Row B shows the results when the target was presented to the PE_p. Row C shows the magnitude of contralateral unmasking, defined as the difference between the binaural and monaural conditions. The top half of Table 3 summarizes the SRTs and magnitude of contralateral unmasking for each individual listener and for the group average.

Two common features were observed for all of the listeners in Experiment 1. First, monaural PC scores at +12-dB TMR were similar to monaural PC scores in quiet (horizontal dashed lines in Figs. 3–5, rows A and B). Although there was a significant main effect of TMR [12 dB vs quiet; $\chi^2(1)=5.10$, $p<0.05$], there was also a significant interaction between ear of presentation (BE_p or PE_p) and TMR [$\chi^2(1)=12.6$, $p<0.0005$], with performance slightly better in quiet for the BE_p but slightly better at +12 dB for the PE_p. On average, the difference between quiet and +12-dB performance was only 3%.

Second, all nine listeners showed contralateral interference – lower performance for the binaural compared to the monaural condition – for at least one ear. There was, however, variation in the pattern of contralateral interference effects across listeners, with each listener showing one of two patterns. Four of the listeners demonstrated contralateral interference in only one ear: CAX (Fig. 3), CCA (Fig. 5), CCD (Fig. 5), and CCE (Fig. 5). Three of these four listeners (except for CAX) had near 0% speech understanding for the open-set IEEE sentences in one ear in quiet and relatively poorer CRM performance for that ear compared to their other ear (Fig. 1). The other five listeners showed contralateral interference in both ears: CAK (Fig. 3), CAW (Fig. 3), CBA (Fig. 4), CBC (Fig. 4), and CBF (Fig. 4). These five listeners had non-zero speech understanding for IEEE sentences in quiet in both ears. Listener CBA is noteworthy because this was the listener from Bernstein et al. (2016) and she showed the largest total contralateral interference of all of the listeners in the current study.

A correlation analysis was carried out to investigate the factors that might have influenced the magnitude of interference (i.e., negative binaural unmasking) experienced by each listener and ear. The magnitude of interference was calculated as the average difference between monaural and binaural PC scores across all of the TMRs tested. This was done – rather than using the SRT-based values reported in Table 3 – because the SRTs were arbitrarily set to 15 dB for many of the listeners who did not achieve 50% correct at any TMR. Six different factors were examined, three each for the ears ipsilateral and contralateral to the target speech: (1) speech-understanding scores for IEEE sentences, (2) duration of deafness before implantation, and (3) age at onset of deafness. Bonferroni corrections were applied for multiple comparisons (3 factors $\times$ 2 ears = 6 total comparisons). Three of these factors were found to be significantly correlated with the magnitude of interference in a given ear⁷. The magnitude of the interference was negatively correlated to

⁷This analysis treated the 18 tested ears (9 ears $\times$ 2 listeners) as independent. The analysis was repeated separately for the nine better ears (BE_p, as determined by the IEEE score in quiet) and nine poorer ears (PE_p) for each listener. With the target presented to the BE_p, the IEEE speech-understanding score in the PE_p was found to be positively correlated with the magnitude of the interference ($r = -0.95$, $p<0.0005$). With the target presented to the PE_p, none of the factors were significantly correlated with the magnitude of the interference.

speech understanding in the ear ipsilateral to the target ($r = -0.64$, $p < 0.005$) but was positively correlated to speech understanding in the contralateral ear ($r = 0.61$, $p < 0.01$). In other words, better speech understanding in the target ear reduced interference, but better speech understanding in the contralateral ear increased it. The magnitude of the interference was also positively correlated to duration of deafness in the ipsilateral ear ($r = 0.69$, $p < 0.005$), meaning that an ear with a longer duration of deafness was more susceptible to interference.

One additional analysis was performed to examine whether the magnitude of the interference was related to the inter-implantation duration (i.e., the amount of time between the activation of the two CIs). Because this analysis involved a difference metric between the ears, unmasking was considered for nine ears at a time (the first or the second implanted ear). There were no significant correlations between the inter-implant duration and the magnitude of the interference for either the first or second ear implanted.

Experiment 2: Spatial release from masking

Figures 3–5 (rows D–F) show individual data from experiment 2, where spatial release from masking was measured. This paradigm involved a combination of monaural head shadow and potential binaural unmasking. The PC score is plotted as a function of TMR for the spatial conditions where the ear corresponding to the BE_p (row D) or ear corresponding to the PE_p (row E) had the better signal-to-noise ratio (BE_{HS}). Performance in the co-located condition (white squares) is re-plotted in both rows for comparison with the spatially separated condition (blue circles or red triangles). Row F plots the spatial release from masking (i.e., the difference in performance between the co-located and spatially separated conditions). Table 3 also summarizes the SRTs and amount of spatial release from masking for each individual listener and for the group average. In the bottom four rows of Table 3, the magnitude of spatial release from masking is delineated based on which ear was the BE_{HS} (i.e., which ear had the better TMR).

All listeners experienced a positive spatial release from masking, sometimes as much as 25–30% at a specific TMR, for one or both ears (Figs. 3–5, row F). In a few cases, listeners showed a small negative spatial release from masking (e.g., CAK when head shadow favored the left ear, Fig. 3F). Using the difference in SRTs at PC=50%, the average spatial release from masking across ears and listeners was only 1.6 ± 1.6 dB, which is much smaller than the 4–6 dB measured in numerous other studies (Loizou et al. 2009; Schleich et al. 2004). Sorting the data into BE_p and PE_p , listeners experienced an average of 2.6 dB of spatial release from masking when the BE_p was the BE_{HS} (i.e., the listener relied mainly on their BE_p to understand speech) but only 0.7 dB when the PE_p was the BE_{HS} (Table 3). A repeated-measures binomial logistic regression analyses revealed a significant improvement in performance relative to the co-located condition when the BE_{HS} was also the BE_p [$\chi^2(1)=19.4$, $p<0.0005$], but no significant improvement when the BE_{HS} was the PE_p [$\chi^2(1)=0.90$, $p=0.34$].

As was done for the interference data in Experiment 1, a correlation analysis investigated the factors that might have contributed to variability in spatial release from masking (speech understanding in quiet, duration of deafness before implantation, and age at onset of

deafness in each ear). Bonferroni corrections were applied for multiple comparisons (3 factors $\times$ 2 ears = 6 total comparisons). Both the duration of deafness ($r = 0.69$, $p < 0.05$) and speech understanding in quiet ($r = -0.64$, $p < 0.05$) in the PE_{HS} were significantly correlated with spatial release from masking. In other words, an ear with a shorter duration of deafness or better speech-understanding score was more likely to reduce spatial release from masking in the other ear. This result is similar to the correlation identified in experiment 1, where presenting the interfering speech to an ear with better speech intelligibility was more likely to cause interference.

DISCUSSION

Access to sound in both ears usually produces benefits for NH, hearing-impaired, and CI listeners, even in cases of sequential bilateral implantation (Reeder et al. 2014). For people with hearing impairment who use hearing aids or CIs, most show improvements for speech understanding in both quiet and noise; however, there are cases and certain testing conditions where people do not (Bernstein et al. 2016; Walden and Walden 2005). The purpose of this study was to determine if there are BI-CI users that experience contralateral interference in a binaural speech-on-speech masking test, the opposite of what occurs in normal-hearing and many other BI-CI listeners. We tested nine BI-CI listeners with either an early onset of deafness or an asymmetrical hearing history, and they experienced contralateral interference when trying to understand speech when target and interferer should have been perceived at different locations.

To verify that this was an otherwise typically performing group of BI-CI listeners, speech understanding in quiet was measured for both an open set of sentences (IEEE) and a closed set of responses (CRM) (Fig. 1). There was a range of performance for the open set of sentences, comparable to what is expected from the literature (Blamey et al. 2013; Gifford et al. 2008). Most BI-CI listeners had near perfect performance in quiet for the CRM corpus. On average, the listeners in the current study showed a significant asymmetry in speech understanding when comparing their speech-understanding performance across the ears, greater than 30% on average for best vs worst. Some listeners, however, showed relatively symmetric performance between the two ears. Some listeners showed improved speech understanding with both ears compared to monaural performance for the better ear, and a small number showed worse, resulting in no significant difference between the better-ear and both-ear conditions. BI-CI listeners generally show improved speech understanding in quiet with both ears compared to one (Mosnier et al. 2009); however, listeners with longer inter-implant durations may not (Reeder et al. 2014). For example, when Mosnier et al. (2009) separated listeners into groups with symmetrical ($n=16$; $<20\%$ difference in quiet) and asymmetrical ($n=11$) speech-understanding scores, they found that two ears were not better than one for the asymmetrical group, consistent with our results. Finally, one last piece of evidence that the listeners in this study were relatively typical CI users is that they performed similarly to the BI-CI listeners in the Bernstein et al. (2016) study for monaural CRM sentences in noise (compare white circles and white squares in Fig. 2B).

The main result of experiment 1, where we compared speech-understanding scores between a monaural condition (target and interferer in one ear) and a binaural condition (target in one

ear, interferer in both ears), is shown in Fig. 2. Here one group of BI-CI listeners (eight listeners' data taken from Bernstein et al. 2016; Fig 2A) benefited greatly from bilateral inputs for this task, demonstrating contralateral unmasking of speech. In comparison, a second group of nine BI-CI listeners (data collected for this study; Fig. 2B) had a large decrease in speech understanding in the binaural condition, demonstrating contralateral interference in the ability to understand the speech. The primary difference between the two groups was their hearing histories. Most of the BI-CI listeners from Bernstein et al. (2016) were high-performing, experienced, late-deafened BI-CI users. The BI-CI listeners in the current study had earlier onsets of deafness, long durations of deafness in one or both ears, or longer inter-implant durations (Table 1). Some listeners demonstrated contralateral interference in only one ear while others did in both (see individual data, Figs. 3–5 and Table 3). There is no reason to believe that this latter group of listeners had their clinical devices programmed appreciably differently than the first, and thus the explanation for the difference between the two listener groups must come after the sound processor, at the stage of neural encoding. It is generally assumed that to achieve good binaural hearing requires ITDs and ILDs to be conveyed with a certain level of fidelity. It may be that the encoding of those cues are more distorted at the level of the auditory nerve for the listeners in the current study compared to the former one. Alternatively, in some cases (e.g., this is more likely in the listeners with an early onset of deafness), it may be that the more central binaural circuits of the superior olivary complex and higher cannot make use of the binaural information because those circuits are inadequately developed (Litovsky et al. 2010).

Note that the results from Bernstein et al. (2016) and the current study are markedly different than previous studies for BI-CI listeners that found neither binaural unmasking nor interference. This discrepancy may have happened for several possible reasons. First, previous studies did not use a contralateral unmasking task. This task specifically avoided the contribution of any head shadow benefits to speech perception and likely also produced larger perceived differences in spatial location (at least for the listeners that showed binaural unmasking). Second, previous studies did not use the CRM corpus, which is intended to produce a large amount of informational masking. The results of this study can be compared to a study that tested normal-hearing listeners (Iyer et al. 2010). It was found that the addition of a third talker can substantially interfere with speech perception in an informational masking condition. Importantly, the interference was observed regardless of whether the third talker was presented to the ear ipsilateral or contralateral to the ear that was presented with the target talker and the other masking talker. The interference effect in the current study could have arisen if the BI-CI listeners were unable to fuse the diotic masking speech, and instead perceived the speech in the contralateral ear as a third talker. The choice of masker may also important. Bernstein et al. (2016) found that for BI-CI listeners, a single-interfering talker maximizes binaural unmasking benefits compared to more than one talker or noise.

Finally, for the current study (where contralateral interference was observed), the BI-CI listeners might be considered relatively atypical for the CI literature that tends to test listeners with considerable experience participating in long psychoacoustical experiments. The adult BI-CI listeners in the current study had relatively little experience with psychoacoustic research (in contrast to e.g., Bernstein et al. 2016; Goupell 2015; Goupell

and Litovsky 2015; Litovsky et al. 2010). It is possible that performing other binaural tasks trains a BI-CI listener in a way that generalizes to binaural unmasking of speech.

A correlation analysis found that the magnitude of the interference was correlated with speech scores in quiet and duration of deafness in the ear ipsilateral to the target, as well as speech in quiet in the ear contralateral to the target speech. This result makes intuitive sense – the more robust the auditory representation in a given ear (i.e., a high speech-understanding score or a short duration of deafness in BE_p), the more impervious that ear is to interference from the other ear. Also, an ear with a high speech-understanding score is more likely to cause interference in the opposite ear. These opposing relationships suggest that asymmetry is an important factor in determining whether interference will occur – a high-functioning ear will tend to interfere with a low-functioning ear. Nevertheless, the fact that some of the listeners in the study did not have asymmetrically performing ears suggests that asymmetry is not the sole factor that determines whether a listener will experience contralateral interference.

The paradigm employed in Experiment 1, where contralateral interference was directly observed, was specifically designed to test the binaural computations that result from having binaural inputs from the BI-CIs. To accomplish this, the paradigm eliminated any head-shadow advantages. Experiment 2 tested a more realistic set of spatial configurations that contained a monaural head-shadow component and the potential for a binaural component. Using HRTFs, the target speech was always presented from the front and the interferers were presented from front, left, or right side of the head. The differences between the co-located (front-front) and the two spatially separated conditions (front-left and front-right) provide a measure of spatial release from masking. Many previous studies show that differences in performance for these spatial configurations should provide approximately 4–6 dB of spatial release from masking, primarily from head shadow (Culling et al. 2012; Loizou et al. 2009; Schleich et al. 2004; Van Hoesel 2012). Table 3 shows that several listeners experienced 3–4 dB of spatial release from masking, but on average there was only 1 dB. Since head shadow is a result of sound physically diffracting around the head and primarily producing attenuation at the ear farther from the source (Culling et al. 2012; Grange and Culling 2016), it should be independent of the hearing status of our BI-CI listeners. Therefore, the results are remarkable in that the spatial release from masking including head shadow is reduced or absent for many of our listeners. Based on the results of Experiment 1 that showed 9-dB of contralateral interference in the absence of any head-shadow advantage, one interpretation of the results from experiment 2 is that these listeners experience a reduction in spatial release from masking caused by contralateral interference. This interpretation is supported by the fact that the magnitude of spatial release from masking was negatively correlated with speech-understanding scores in quiet and positively correlated with duration of deafness in the contralateral ear (i.e., the ear opposite from the likely attended BE_{HS}). In other words, a high-functioning ear was more likely to cause interference that diminishes the head-shadow advantage in the other ear.

While all nine listeners in this study demonstrated some contralateral interference in Experiment 1, the contralateral interference was particularly strong for seven of the listeners who were almost completely unable to complete the task in the binaural condition (scores

near 0% correct; Figs. 3–5). In these cases, such a result might occur if the listener was unable to attend to the target ear in the presence of the signal in the interfering ear, even though there was no problem for the monaural conditions. An inability to attend to the target ear has been previously shown in two BI-CI listeners in a dichotic listening task (Goupell et al. 2016). Anecdotal self-reports from the listeners in the current study suggest that the signal from the target ear disappeared completely from their perception. Extinction of a perception from one of two sensory inputs, where the weaker input vanishes in the presence of the stronger, has been reported both for the visual system (called amblyopia) and the auditory system (see Kaplan et al. 2016 for a review). These studies are often performed on children and viewed through a developmental lens, where unilateral sensory deprivation during a critical developmental sensitive period will cause an abnormal strengthening of some of the neural pathways and alter perception of the stimulated input. Similarly, the current results might suggest that an assumed abnormally strong pathway can extinguish the perception in the weakened ear through sensory deprivation, either from a long duration of unilateral hearing loss. Some of the listeners in the current study fall within the developmental explanation; for example, listener CCE was implanted in one ear at the age of 1 year and in the other ear at the age of 11 years (Table 1). However, developmental deprivation may not be a pre-requisite for this phenomenon. Listener CCA had typical acoustic hearing until the age of 13 years and experienced more than 60 years of hearing loss in only one ear. This listener was strongly dominant in one ear in the speech-understanding task (Fig. 5), and also reported extinction.

It is unclear whether the contralateral interference observed here would become reduced over time as a result of neural plasticity and reorganization. Some of these listeners had recently received their second implant and CI performance has been shown to significantly improve over the first year after activation of a second implant (Mosnier et al. 2009; Reeder et al. 2014). Binaural unmasking of speech may continue to increase up to four years after activation (Eapen et al. 2009). Some of our listeners, however, have been BI-CI users for a number of years and still demonstrated contralateral interference. It is therefore unlikely that all of these listeners will benefit from neural plasticity to the point that all of their contralateral interference would vanish at some time in the future. It is also possible that binaural processing may have been impeded, for example, by large interaural differences in insertion depth. This would cause interaural place-of-stimulation mismatch, which is known to degrade binaural performance for single-electrode stimulation (Goupell 2015; Hu and Dietz 2015; Kan et al. 2015; Kan et al. 2013). In such a scenario, the listeners from this study might have had relatively large amounts of interaural mismatch, so much so that adaptation was not possible. Under such an explanation, the listeners from Bernstein et al. (2016) (except for BI5) might have less interaural mismatch and therefore adaptation and training allowed them to improve in this binaural-hearing task. Teasing apart the contributions of duration of deafness, mismatch, and adaptation would be a worthwhile future area of research.

Based on these results, one conclusion is that reducing the duration of deafness is advisable for both ears. It is possible that if the type of listener that was tested in the current study had been implanted earlier, they might not have experienced contralateral interference but instead a binaural-unmasking benefit, like the listeners in the Bernstein et al. (2016) study.

In other words, it is well established that “sooner is better” for outcomes for the first ear, meaning that shorter durations of deafness tend to yield better outcomes with a first CI (Blamey et al. 2013). We argue that sooner may also be better for improved outcomes for the second CI, specifically for tasks that involve binaural hearing. One possible clinical solution to this problem is to make simultaneous implantation or sequential implantation within a short time interval the standard of care for adults. Our results agree with the results of other authors who have also argued for shorter inter-implantation durations in children and adults (Gordon et al. 2013; Jiواني et al. 2015; Reeder et al. 2014).

The purpose of BI-CIs is not solely to provide maximum speech understanding in the presence of interfering talkers in a contralateral unmasking paradigm. For example, two inputs also provide other hearing benefits such as improved sound localization. Also, the results from experiment 2 (Table 3) showed some head-shadow benefit in a free-field listening conditions when the target talker was located in front of the listener and interferer was located to the side of the head. Therefore, having two inputs is still better than having only one, even for these listeners who experience relatively large levels of contralateral interference for speech understanding from bilateral inputs. As the field moves forward, it should consider how to provide the best hearing in both ears, and not view the two ears as simply two independent inputs. Such an approach provides the hope of producing larger amounts of the supra-additive benefits that binaural hearing has to offer.

CONCLUSIONS

Nine BI-CI users who were deafened early in life or had an asymmetrical hearing history were tested in two separate speech-understanding experiments where there was a competing talker that was either co-located or spatially separated. In the first experiment, listeners showed large decreases in speech understanding (i.e., contralateral interference) in the spatially separated conditions in at least one ear. On average, there was 9 dB of contralateral interference that was presumed to be binaural in origin. In a second experiment, only 1 dB of spatial release from masking was observed in a virtual free-field listening task. Although this shows that these BI-CI still received a speech-understanding benefit from having a second CI, this reduced advantage from what is often reported in the literature could be attributable to the contralateral interference measured in experiment 1. These data suggest that earlier implantation in the second implanted ear might be necessary for achieving larger binaural-hearing benefits.

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Figure 1.

Speech-understanding performance in quiet for the CRM and IEEE sentences. Panel (A) shows the individual data for the poorer ear based on performance (PE_p), the better ear based on performance (BE_p), and both ears. Panel (B) shows the corresponding average data. Error bars in panel (B) are ± 1 standard error in length. BE_p indicates better ear as measured by performance; CRM, coordinate response measure sentences; IEEE, Institute for Electronics and Electrical Engineers sentences; PEP, poorer ear as measured by performance.

Figure 2.

Average speech understanding in the presence of an interfering talker using the CRM corpus for the monaural (open symbols) and binaural (closed symbols). The data in panel (A) are taken from eight listeners in Bernstein et al. (2016). The data in panels (B–D) are from the current study, where panel (B) shows the data from all nine listeners, panel (C) shows the data from just the better ear based on performance (BE_p), and panel (D) shows the data from just the poorer ear based on performance (PE_p). The monaural condition from panel (A) is replotted as small squares in panel (B) for comparison. The error bars in both panels are ± 1 standard error in length. BE_p indicates better ear as measured by performance; PE_p, poorer ear as measured by performance; TMR, target-to-masker ratio.

Figure 3.

Data for listeners CAK, CAX, and CAW on the speech-understanding task in the presence of an interfering talker using the CRM corpus. Each column represents a different listener. Each condition is shown in a different row. In all rows, circles denote performance for the situation with the target speech presented to the better ear as defined by speech understanding in quiet for IEEE sentences (BE_p) or with the better TMR occurring in the BE_p due to head shadow; triangles denote the same for the poorer ear (PE_p); red symbols for the right ear; and blue symbols for the left ear. Row (A) shows data from experiment 1

(binaural unmasking without head shadow) when the target was presented to the BE_p. CRM performance in quiet is represented by the thick horizontal dashed line. Performance for the monaural conditions is shown by open symbols. Performance for the binaural conditions is shown by closed symbols. Row (B) shows data from experiment 1 when the target was presented to PE_p. Row (C) shows the difference in performance between the monaural and binaural conditions for both ears. The duration of deafness for each ear and the inter-implant duration are also reported in this row. Rows (D) and (E) show the data from experiment 2 (spatial release from masking with head shadow) for the co-located (open squares) and spatially separated (closed symbols) conditions. Row (D) shows the data for the conditions where the head-shadow advantage (BE_{HS}) favors the better ear as defined by speech scores in quiet (BE_p). Row (E) shows the data for the conditions where the head-shadow advantage (BE_{HS}) favors the PE_p. Row (F) shows the difference in performance spatial release from masking between the co-located (Front-Front) and spatially separated (Front-Left or Front-Right) conditions. BE_{HS} indicates the ear with the better signal-to-noise ratio; BE_p, better ear as measured by performance; DOD, duration of deafness; PE_p, poorer ear as measured by performance; SRM, spatial release from masking; TMR, target-to-masker ratio.

Figure 4.

Data for experiments 1 and 2 for listeners CBA, CBC, and CBF. The figure has the same conventions as Fig. 3.

Figure 5.

Data for experiments 1 and 2 for listeners CCA, CCD, and CCE. The figure has the same conventions as Fig. 3.

Table 1

Listener hearing history and demographic information.

Listener	Sex	Age (Years)	Age of Onset of Deafness (Years)				CI Experience (Years)				Internal Device		Etiology
			Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	
CAK	M	70	35	57	1	12	CI422	CI24R (CS)	CI24RE (CA)	CI24RE (CA)	CI422	CI24R (CS)	Surgery
CAW	M	54	0	0	7	4	CI24RE (CA)	CI24RE (CA)	CI24RE (CA)	CI24RE (CA)	CI422	CI24R (CS)	Unknown
CAX	M	55	49	7	5	2	CI512	CI422	CI512	CI422	CI422	CI24R (CS)	Unknown
CBA	F	56	0	0	4	5	CI24RE (CA)	CI512	CI24RE (CA)	CI512	CI512	CI24R (CS)	Stickler's Syndrome
CBC	F	79	70	59	9	3	CI24RE (CA)	CI24RE (CA)	CI24RE (CA)	CI24RE (CA)	CI422	CI24R (CS)	Measles
CBF	M	59	5	5	7	2	CI24RE	CI422	CI24RE	CI422	CI422	CI24R (CS)	Unknown
CCA	M	77	13	70	3	6	CI24RE	CI512	CI24RE	CI512	CI512	CI24R (CS)	Measles/Antibiotics
CCD	M	46	3	3	11	22	CI24RE	N22	CI24RE	N22	N22	CI24R (CS)	Unknown
CCE	F	20	0	0	9	19	CI24RE	N22	CI24RE	N22	N22	CI24R (CS)	Unknown

CI, cochlear implant

Table 2

Speech understanding in quiet for the CRM and IEEE sentences for the left ear (L), the right ear (R), and both ears (B). The asymmetry in speech understanding between the ears (R-L) and the magnitude of this asymmetry [$\text{abs}(\text{R-L})$] is reported. The difference in speech understanding between both ears and the better of the single ears [$\text{B-max}(\text{R-L})$], and between both ears and the poorer of the single ears [$\text{B-min}(\text{R-L})$] is also reported.

Corpus	Ear	CAK	CAW	CAX	CBA	CBC	CBF	CCA	CCD	CCE	Average	Std. Dev.
CRM	Left	81.0	100.0	100.0	98.0	90.2	100.0	78.9	96.0	66.0	90.0	12.1
	Right	95.0	86.0	72.0	100.0	78.0	92.5	96.7	100.0	100.0	91.1	10.3
	Both	98.3	100.0	98.0	100.0	86.0	100.0	96.7	100.0	100.0	97.7	4.5
	R-L	14.0	-14.0	-28.0	2.0	-12.2	-7.5	17.8	4.0	34.0	1.1	18.9
	abs(R-L)	14.0	14.0	28.0	2.0	12.2	7.5	17.8	4.0	34.0	14.8	10.6
	B-max(R,L)	3.3	0.0	-2.0	0.0	-4.2	0.0	0.0	0.0	0.0	-0.3	2.0
	B-min(R,L)	17.3	14.0	26.0	2.0	8.0	7.5	17.8	4.0	34.0	14.5	10.5
IEEE	Left	18.0	17.0	80.0	38.5	21.0	45.0	0.0	1.0	0.5	24.6	26.3
	Right	48.0	7.5	4.0	33	18.0	24.0	53.0	37.5	93.0	35.3	27.4
	Both	44.0	26.5	81.0	45.5	29.0	54.0	50.0	42.0	80.5	50.3	19.4
	R-L	30.0	-9.5	-76.0	-5.5	-3.0	-21.0	53.0	36.5	92.5	10.8	48.6
	abs(R-L)	30.0	9.5	76.0	5.5	3.0	21.0	53.0	36.5	92.5	36.3	31.7
	B-max(R,L)	-4.0	9.5	1.0	7.0	8.0	9.0	-3.0	4.5	-12.5	2.2	7.5
	B-min(R,L)	26.0	19.0	77.0	12.5	11.0	30.0	50.0	41.0	80.0	38.5	25.9

CRM, coordinate response measure sentences; IEEE, Institute for Electronics and Electrical Engineers sentences; L, left; R, right

Table 3

Speech reception thresholds, contralateral unmasking, and spatial release from masking. All values are in dB.

Experiment 1	CAK	CAW	CAX	CBA	CBC	CBF	CCA	CCD	CCE	Mean	Std. Dev.
<u>Target ear</u>											
SRT	Left, Monaural	2.6	0.7	-4.2	-1.3	2.3	1.2	3.7	0.1	4.2	2.6
	Left, Binaural	15.0	7.3	-4.6	15.0	10.6	15.0	15.0	15.0	11.5	6.6
	Right, Monaural	1.8	5.8	3.2	-1.5	2.8	1.7	0.7	0.4	1.7	2.1
	Right, Binaural	8.4	15.0	15.0	13.4	12.6	15.0	2.3	0.7	-0.7	6.6
Unmasking	Left	-12.5	-6.6	0.5	-16.3	-8.3	-13.8	-11.3	-14.9	-10.8	5.1
	Right	-6.5	-9.2	-11.8	-14.9	-9.8	-13.3	-1.5	-0.3	1.1	5.9
	BE _p	-6.5	-6.6	0.5	-16.3	-8.3	-13.8	-1.5	-0.3	1.1	6.3
	PE _p	-12.5	-9.2	-11.8	-14.9	-9.8	-13.3	-11.3	-14.9	-10.8	2.1
Experiment 2	CAK	CAW	CAX	CBA	CBC	CBF	CCA	CCD	CCE	Mean	Std. Dev.
<u>Configuration</u>											
SRT	Front-Front	0.5	1.1	-3.9	-1.3	1.7	0.1	0.7	-0.7	-0.3	1.7
	Front-Left	-0.1	0.3	-3.9	-3.5	0.7	-3.2	-3.4	-4.0	-3.5	2.0
	Front-Right	3.0	-2.7	-6.5	-2.8	0.0	-2.6	-0.1	-1.3	-0.5	2.6
<u>BE_{US}</u>											
SRM	Left	-2.4	3.8	2.6	1.6	1.7	2.7	0.8	0.6	-0.2	1.8
	Right	0.6	0.8	0.0	2.2	1.0	3.3	4.0	3.3	2.8	1.4
	BE _p	0.6	3.8	2.6	1.6	1.7	2.7	4.0	3.3	2.8	1.1
	PE _p	-2.4	0.8	0.0	2.2	1.0	3.3	0.8	0.6	-0.2	1.6

BE_p, better ear as measured by performance; BE_{US}, the ear with the better signal-to-noise ratio; PE_p, poorer ear as measured by performance; SRT, speech-reception threshold; SRM, spatial release from masking