2018

Effects of cochlear implantation on binaural hearing in adults with unilateral hearing loss

Emily Buss
University of North Carolina at Chapel Hill

Margaret T. Dillon
University of North Carolina at Chapel Hill

Meredith A. Rooth
University of North Carolina at Chapel Hill

English R. King
UNC Health Care

Ellen J. Deres
UNC Health Care

See next page for additional authors

Recommended Citation

Buss, Emily; Dillon, Margaret T.; Rooth, Meredith A.; King, English R.; Deres, Ellen J.; Buchman, Craig A.; Pillsbury, Harold C.; and Brown, Kevin D., ,"Effects of cochlear implantation on binaural hearing in adults with unilateral hearing loss." Trends in Hearing.22,. 1-15. (2018).
https://digitalcommons.wustl.edu/open_access_pubs/6848

Authors

Emily Buss, Margaret T. Dillon, Meredith A. Rooth, English R. King, Ellen J. Deres, Craig A. Buchman, Harold C. Pillsbury, and Kevin D. Brown

Trends in Hearing
Volume 22: 1–15
© The Author(s) 2018
Reprints and permissions:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/2331216518771173
journals.sagepub.com/home/tia
SAGE

Effects of Cochlear Implantation on Binaural Hearing in Adults With Unilateral Hearing Loss

Emily Buss[1], Margaret T. Dillon[1], Meredith A. Rooth[1], English R. King[2], Ellen J. Deres[2], Craig A. Buchman[3], Harold C. Pillsbury[1], and Kevin D. Brown[1]

Abstract

A FDA clinical trial was carried out to evaluate the potential benefit of cochlear implant (CI) use for adults with unilateral moderate-to-profound sensorineural hearing loss. Subjects were 20 adults with moderate-to-profound unilateral sensorineural hearing loss and normal or near-normal hearing on the other side. A MED-EL standard electrode was implanted in the impaired ear. Outcome measures included: (a) sound localization on the horizontal plane (11 positions, −90° to 90°), (b) word recognition in quiet with the CI alone, and (c) masked sentence recognition with the target at 0° and the masker at −90°, 0°, or 90°. This battery was completed preoperatively and at 1, 3, 6, 9, and 12 months after CI activation. Normative data were also collected for 20 age-matched control subjects with normal or near-normal hearing bilaterally. The CI improved localization accuracy and reduced side bias. Word recognition with the CI alone was similar to performance of traditional CI recipients. The CI improved masked sentence recognition when the masker was presented from the front or from the side of normal or near-normal hearing. The binaural benefits observed with the CI increased between the 1- and 3-month intervals but appeared stable thereafter. In contrast to previous reports on localization and speech perception in patients with unilateral sensorineural hearing loss, CI benefits were consistently observed across individual subjects, and performance was at asymptote by the 3-month test interval. Cochlear implant settings, consistent CI use, and short duration of deafness could play a role in this result.

Keywords

single-sided deafness, spatial hearing, localization

Date received: 26 December 2017; revised: 19 March 2018; accepted: 21 March 2018

Introduction

Binaural hearing provides spatial cues that support sound source localization and facilitate masked speech recognition in complex listening environments. An accurate sense of auditory space helps a listener avoid environmental hazards and orient toward sound sources of interest. Of particular importance, spatial cues can help a listener selectively attend to one talker in the context of one or more background talkers located at different points on the horizontal plane, a benefit described as spatial release from masking (Bronkhorst, 2015). Adults with unilateral hearing loss (UHL) report substantial difficulties listening in their everyday lives, despite good access to sound in one ear (Dwyer, Firszt, & Reeder, 2014; Firszt, Reeder, & Holden, 2017). This observation has prompted more aggressive treatment of UHL, with the goal of restoring spatial hearing abilities. The present study evaluates spatial hearing abilities in a group of adults with moderate-to-profound UHL who received

---

[1] Department of Otolaryngology/Head and Neck Surgery, University of North Carolina School of Medicine, Chapel Hill, NC, USA
[2] Department of Audiology, UNC Health Care, Chapel Hill, NC, USA
[3] Department of Otolaryngology/Head and Neck Surgery, Washington University School of Medicine in St. Louis, St. Louis, MO, USA

Corresponding author:
Emily Buss, Department of Otolaryngology/Head and Neck Surgery, University of North Carolina School of Medicine, 170 Manning Drive, Chapel Hill, NC 27599, USA.
Email: ebuss@med.unc.edu

cochlear implants (CI) as part of a clinical trial conducted at the University of North Carolina at Chapel Hill.

Traditionally, moderate-to-profound UHL has either gone untreated or it has been treated with a conventional hearing aid, Contralateral Routing of the Signal (CROS) hearing aid, or Bone-Conduction Hearing Aid (BCHA). Although some patients with moderate-to-profound UHL report an overall improvement in quality of life when using CROS or BCHA devices (Desmet, Wouters, De Bodt, & Van de Heyning, 2012; Saroul, Akkari, Pavier, Gilain, & Mom, 2013), these devices fail to restore spatial hearing (Peters, Smit, Stegeman, & Grolman, 2015). Both CROS and BCHA devices provide increased access to sound from the side of the hearing loss, but they do so by presenting sound from that side to the contralateral ear. This results in masking of sound presented on the side with better hearing. Not surprisingly, these devices improve masked speech recognition under some conditions but degrade it under other conditions: A benefit in masked speech perception is observed when the masker is presented on the side with better hearing thresholds, but a decrement in performance occurs when the masker is presented on the side of the UHL (Kitterick, Smith, & Lucas, 2016; Linstrom, Silverman, & Yu, 2009). CROS and BCHA devices also fail to improve sound localization for listeners with moderate-to-profound sensorineural UHL and may degrade performance (Grantham et al., 2012). In contrast, cochlear implantation has the potential to provide spatial hearing by providing ear-specific stimulation on the side of the UHL.

Results obtained with patients who meet current CI candidacy—bilateral sensorineural hearing loss and poor speech perception in the best aided condition—indicate that CIs can provide a binaural benefit, although this benefit is often less than observed with normal-hearing listeners. Compared with a unilateral CI listening condition, bilateral CIs improve both localization and masked speech perception, particularly when the target and masker are separated on the horizontal plane (Buss et al., 2008; Grantham, Ashmead, Ricketts, Labadie, & Haynes, 2007; Litovsky, Parkinson, & Arcaroli, 2009; Rana et al., 2017; Smulders et al., 2016). Similarly, some unilateral CI patients with modest contralateral residual hearing derive benefit from wearing a hearing aid on the contralateral ear, despite the fact that this residual hearing is too limited to support good speech perception with a hearing aid alone. While localization and masked speech perception tend to be better with the combination of a CI and contralateral hearing aid than either device alone (Dunn, Tyler, & Witt, 2005; Gifford et al., 2014; Morera et al., 2012; Potts, Skinner, Litovsky, Strube, & Kuk, 2009), there are large individual differences in patient outcomes.

It has been suggested that the limited binaural abilities of CI patients are at least partly due to the degraded cues provided by the speech processor, and in particular the elimination of interaural time difference (ITD) cues (Ihlefeld & Litovsky, 2012; Jones, Kan, & Litovsky, 2014; Schoof, Green, Faulkner, & Rosen, 2013). Whereas ITD cues play an important role in localization for normal-hearing listeners (Wightman & Kistler, 1992), localization cues available through a CI are thought to be based solely on interaural level difference cues (Dorman et al., 2014). Interaural level cues may be degraded by amplitude compression in bilateral CI users (Ricketts, Grantham, D'Haese, Edwards, & Barco, 2006). It has also been argued that binaural hearing in patients with a unilateral CI and contralateral acoustic hearing is limited by the asymmetry between ears, particularly with respect to the mapping of frequency to place of excitation in the cochlea (Wess, Brungart, & Bernstein, 2017). These asymmetries could interfere with binaural fusion, which is thought to be a prerequisite for the optimal use of binaural spatial cues (Kan, Stoelb, Litovsky, & Goupell, 2013; Ma, Morris, & Kitterick, 2016; Suneel, Staisloff, Shayman, Stelmach, & Aronoff, 2017).

There are a growing number of recent studies evaluating the use of CIs to restore spatial hearing in patients with highly asymmetric hearing loss, including patients with moderate-to-profound UHL who have one ear with normal or near-normal thresholds; this patient population is sometimes described as having single-sided deafness. Results of CI use in this population have been generally positive, although the details differ widely across studies. Most datasets have demonstrated better localization with than without the CI (Arndt et al., 2010; Grossmann et al., 2016; Hoth, Rosli-Khabas, Herisanu, Plinkert, & Praetorius, 2016; Mertens, De Bodt, & Van de Heyning, 2017; Tavora-Vieira, De Ceulaer, Govaerts, & Rajan, 2015), although this benefit is not always observed (Friedmann et al., 2016). Data are mixed regarding the importance of prior listening experience with the CI for localization ability; a preliminary report of 6-month data on the cohort followed in the present study showed asymptotic performance after 3 months of CI experience (Dillon, Buss, Anderson, et al., 2017), while other studies indicate marked variability across individuals and acclimatization over a period of a year or more (Hansen, Gantz, & Dunn, 2013).

Providing a CI in cases of moderate-to-profound UHL has also been shown to benefit speech perception in multisource environments under some conditions. The benefit of binaural hearing for masked speech perception, and the mechanism responsible for that benefit, differs depending on the positions of target and masker sources in space. These benefits fall into three main categories: head shadow, true binaural hearing, and summation. When the target and masker are spatially separated on the horizontal plane, the target-to-masker ratio (TMR) differs between ears; this occurs because the head attenuates low-frequency energy at the ear contralateral to a sound source. If the TMR is poorest on the side of the acoustic-hearing ear, a CI may benefit performance by providing information at a more advantageous TMR than available acoustically. This benefit is described as *head shadow effect* or *better-ear glimpsing*. A CI tends to improve performance under these conditions for patients with UHL (Grossmann et al., 2016; Hoth et al., 2016; Mertens et al., 2017). In contrast, when the target and masker are spatially separated, and the TMR is better on the side of the acoustic-hearing ear, the signal provided by the CI is dominated by the masker. A benefit under these conditions is described as *true binaural benefit* or *squelch*. This benefit has been reported in CI recipients with UHL (Grossmann et al., 2016), but it is more frequently not observed (Arndt et al., 2010; Mertens et al., 2017). The final category of binaural benefit occurs when the target and masker are colocated in space, such that the TMR is equal on the two sides. A binaural benefit under these conditions is attributed to the availability of two samples of the stimulus in the auditory system, an effect that is described as *summation*. Summation is sometimes observed in CI recipients with UHL, particularly in cases of hearing loss contralateral to the CI (Mertens et al., 2017), but this effect is more often not observed (Arndt et al., 2010; Grossmann et al., 2016). Asymmetry in the place of stimulation across ears has been argued to be more disruptive for squelch and summation than for head shadow (Yoon, Shin, & Fu, 2013).

The published outcome data on spatial hearing in CI patients with UHL indicate benefits under some listening conditions, but there is substantial variability in the degree of benefit (Zeitler et al., 2015) and the duration of listening experience required to see that benefit. Some data indicate that even the head shadow benefit requires 12 months or more of listening experience (Gartrell et al., 2014; Mertens et al., 2017). Whereas some data indicate improved localization in all patients and asymptotic benefit by 3 months after CI activation (Dillon, Buss, Anderson, et al., 2017), other studies report inconsistent benefit across study subjects (Tavora-Vieira et al., 2015) and evidence of improved performance with increasing listening experience of up to a year or more (Hansen et al., 2013). One challenge for understanding the factors responsible for individual differences in the spatial hearing benefit and the time course over which it emerges is the fact that some of the study samples are quite small and heterogeneous with respect to variables known to impact CI performance, such as duration of deafness prior to implantation (Kitterick & Lucas, 2016). Variability in test materials and procedures across studies further complicates interpretation.

Although published data indicate that most patients with moderate-to-profound UHL receive some benefit from a CI, speech recognition with the CI alone tends to be poorer than that observed in conventional CI patients (Finke, Strauss-Schier, Kludt, Büchner, & Illg, 2017; Plant, McDermott, van Hoesel, Dawson, & Cowan, 2016; Sladen et al., 2016), with a negative correlation between CI-alone performance and contralateral hearing sensitivity (Plant et al., 2016). This result has been attributed to dominance of the better-hearing ear. Unilateral auditory deprivation degrades binaural processing (Clopton & Silverman, 1977; Moore & Irvine, 1981; Silverman & Clopton, 1977), a result attributed to cortical reorganization that optimizes response to sound from the better-hearing ear (Keating & King, 2013). These effects are particularly pronounced when moderate-to-profound UHL is congenital or begins early in development (Kral, Heid, Hubka, & Tillein, 2013; Kral, Hubka, Heid, & Tillein, 2013; Tillein, Hubka, & Kral, 2016), but asymmetries and degraded binaural processing are also observed when UHL is acquired in adulthood (Maslin, Munro, & El-Deredy, 2013; Ponton et al., 2001; Pross et al., 2015). Better ear dominance is one reason why clinicians and researchers often recommend postoperative rehabilitation with the CI alone for patients with UHL (Finke, Strauss-Schier, et al., 2017; Kral, Hubka, & Tillein, 2015; Nawaz, McNeill, & Greenberg, 2014; Plant et al., 2016; Tavora-Vieira, Marino, Krishnaswamy, Kuthbutheen, & Rajan, 2013). Similarly, traditional CI recipients are sometimes counseled to temporarily discontinue contralateral hearing aid use (if any) during the early postoperative period (Scherf & Arnold, 2014).

The present study prospectively evaluated a population of CI recipients with moderate-to-profound sensorineural UHL and normal or near-normal hearing in the other ear, using methods designed to maximize the likelihood of observing a spatial hearing benefit. Subjects were adults with acquired hearing loss and a short duration of UHL ($\leqslant 10$ years), and they were followed at defined intervals for 1 year. Speech maskers were used to assess masked speech perception, based on the finding that binaural hearing benefits performance most in a CI simulation with normal-hearing listeners when the target and masker are perceptually similar (e.g., both voices; Bernstein, Iyer, & Brungart, 2015). Of particular interest was the time course over which localization and spatial release from masking emerge with listening experience. Preliminary data on localization in this cohort indicate consistent benefit across subjects and relatively rapid gains in localization in the first few months after device activation (Dillon, Buss, Anderson, et al., 2017). Based on those data, we expected to observe binaural benefit for both masked speech recognition and localization in the first few months of listening experience with the CI in all or nearly all subjects.

Methods

The procedures described here were carried out as part of a clinical trial for the Food and Drug Administration. Data on control subjects with normal or near-normal hearing bilaterally were collected after study completion, to provide a fuller context for interpreting the magnitude of the CI benefits observed. In addition to the data in the present report, the clinical trial also included testing with a BCHA at the preoperative and 12-month test intervals. Two subjects were BCHA users prior to enrollment in the study, and the remaining 18 subjects were fitted acutely for this assessment. Performance with the BCHA was comparable to or worse than that obtained in the unaided condition for both localization and masked sentence recognition. In addition to the speech measures reported below, data were also obtained with the BKB-SIN (Auditec, Inc.). Due to the number of lists available for this instrument, lists were repeated between sequential test sessions. While many of the effects reported below were also evident in the BKB-SIN data, improvements in the unaided condition make interpretation of those results difficult. They are therefore omitted from the present report. In addition to speech perception and localization, subjects in the CI group provided data on subjective benefit and pitch perception; results from those protocols are described in separate reports (e.g., Dillon, Buss, Rooth, et al., 2017).

Subjects

The study population was 20 CI recipients. All had one ear with normal or near-normal audiometric thresholds (referred to as NH ear) and one ear that met criterion for cochlear implantation (referred to as CI ear). These subjects met the following criteria: (a) moderate-to-profound hearing loss in the CI ear, with aided word recognition of $\leqslant 60\%$ and a duration of loss $\leqslant 10$ years, (b) thresholds of $\leqslant 35$ dB HL 125 to 8000 Hz in the NH ear, (c) 1 month or more prior experience wearing a BCHA, conventional hearing aid, or CROS hearing aid without substantial benefit, (d) no evidence of conductive hearing loss, compromised auditory nerve, or cochlear ossification, (e) no history of Meniere's disease with intractable vertigo or tinnitus reported to be severe or catastrophic, (f) ability and willingness to return for follow-up testing associated with the study protocol, (g) absence of known cognitive deficits, (h) English as the native language, and (i) no medical condition to contraindicate surgery. Age at implantation ranged from 23 to 66 years, with a mean of 50 years. Duration of deafness prior to implantation ranged from 0.6 to 6.6 years, with a mean of 2.6 years. The etiology of hearing loss was either unknown ($n = 16$), Meniere's disease ($n = 3$), or trauma ($n = 1$; Dillon, Buss, Anderson, et al., 2017).

All subjects in the study population received a MED-EL standard electrode array, with a full insertion based on surgeon report. They were fitted with an OPUS 2 speech processor, an ear-level processor with a single, omnidirectional microphone oriented toward the front. Subjects were programmed with the FS4 coding strategy, which presents timing cues on the four most apical channels. The majority of subjects ($n = 17$) listened with frequency filter assignments of 100 to 8500 Hz and all electrodes active throughout the study period, and the compression ratio was kept at the default value of 3:1 for all subjects. Threshold levels for each electrode were estimated at 10% of the comfort levels (represented in charge units) at initial activation and were measured behaviorally at all follow-up intervals, with the contralateral ear plugged to avoid distraction from external noise. Comfort levels were measured as "loud but comfortable" on all active electrodes. Those levels were then adjusted based on loudness comparisons between sequential pairs of electrodes, starting with a mid-frequency electrode (routinely E6), and based on the loudness of stimulation on E6 compared with all other electrodes (Throckmorton & Collins, 2001). Finally, subjects compared the loudness of live speech and environmental sounds between the CI and the NH ear. Subjects were counseled to use CI settings that resulted in equal loudness with their NH-ear. Outcome data at each postoperative interval were obtained prior to modifying the CI map.

The normal-hearing control group was composed of 20 adults between the ages of 23 and 74 years, with a mean of 53 years. All had pure-tone thresholds of 35 dB HL or less at 125 to 8000 Hz in both ears, and all were native English speakers. Ten out of 20 NH control subjects had at least one threshold above 20 dB HL. The decision to enroll listeners with minimal or mild hearing loss in the control group was based on two considerations. First, age-matching the CI recipients and NH control subjects was of high priority, and thresholds of 20 dB HL or less become increasingly rare with increasing age (Lin, Niparko, & Ferrucci, 2011). Second, a primary goal of comparing performance across groups was to understand the contribution of the CI to binaural hearing. Roughly matching the two groups on acoustic sensitivity increases the validity of this comparison, as we know that even subclinical differences in hearing sensitivity can affect performance on binaural tasks (Bernstein & Trahiotis, 2016).

Audiometric thresholds for the two groups of subjects at the time of enrollment in the study are shown in Figure 1. The left panel shows thresholds for CI recipients, plotted separately for the ear with UHL and the ear with NH. A value of 120 dB HL indicates no response at the 115-dB-HL output limit of the audiometer. The right panel shows thresholds for the NH control group.

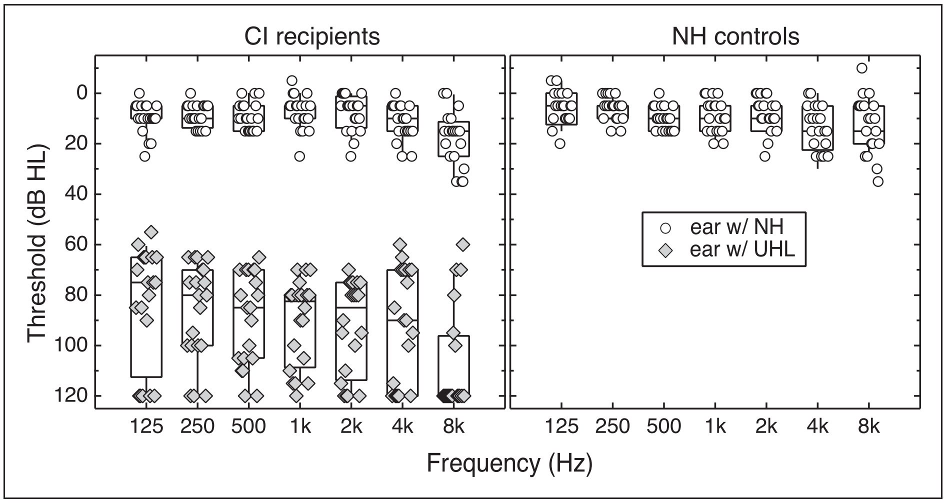

Figure 1. Unaided thresholds at the time of study enrollment. Pure-tone thresholds are plotted in dB HL as a function of frequency for individual CI recipients (left panel) and the NH controls (right panel). Symbols indicate thresholds for individual subjects. Circles show data for the normal or near-normal hearing ear, and diamonds show data for the ear with UHL. Thresholds shown for the NH control listeners were based on the ear with the higher mean threshold. Boxplots show the distribution of points: horizontal lines indicate the median, boxes span the 25th to 75th percentiles, and vertical lines span the 10th to 90th percentiles.
CI = cochlear implant; UHL = unilateral hearing loss; NH = normal hearing.

Thresholds for the poorer of the two ears are shown for each NH control subject, based on mean thresholds across frequency. Individual subjects' thresholds are shown with symbols, and the order of symbols at each frequency reflects listener age (younger on the left). For the NH control subjects and the NH ear of the CI recipients, there was a trend for higher thresholds in older subjects, particularly at higher frequencies. There was a significant positive correlation between thresholds and subject age at 8000 Hz (NH, $r_s = .61$, $p = .005$; CI, $r_s = .56$, $p = .010$), but not at 125 Hz (NH, $r_s = .22$, $p = .363$; CI, $r_s = .30$, $p = .205$). This is consistent with the observation that age-related hearing loss tends to emerge at high frequencies before low frequencies.

Word Recognition in Quiet

Word recognition in quiet with the CI alone was evaluated using CNC words (Peterson & Lehiste, 1962) presented at 60 dB SPL. The CI recipients were tested in the ear with UHL, with a hearing aid in the preoperative period and with the CI in the postoperative intervals. A 50-dB-HL speech-shaped masking noise was presented to the NH ear via an insert earphone, and a circumaural earphone was placed over the NH ear to provide additional attenuation of the speech target. This procedure was compared with direct-audio input to the CI at the 3-month test interval for 19 of the 20 CI recipients. There was a nonsignificant trend for better performance with direct-audio input, $t(19) = 0.97$, $p = .345$. This result confirms that the NH ear likely did not contribute to performance to CNC word scores measured in the sound field. CNC word testing was not performed for the NH ear due to ceiling effects. Similarly, CNC word recognition was not routinely completed for NH control subjects. For reference, the mean score for a subset of 10 subjects in the NH control group who completed CNC testing was 96.2%. Each assessment was based on a 50-word list.

Masked Sentence Recognition

Masked sentence recognition was evaluated using the AzBio sentences (Spahr et al., 2012) at a presentation level of 60 dB SPL, played at 0 dB TMR in a 10-talker masker. The target was presented from a loudspeaker 1 m in front of the subject. The masker was presented either from the same speaker as the target (0°, colocated), a speaker at −90° (to the left), or a speaker at 90° (to the right). The CI recipients were tested with and without their CI at each postoperative test interval; preoperative testing was performed unaided. One list was used for each assessment, and performance was quantified as percent of words correct (0–100%). The order of sentence lists was randomized for each subject. Most test sessions used 6 of the 23 AzBio sentence lists; the 12-month interval used nine lists due to BCHA testing. This protocol ensured that no subject heard a previously presented sentence before the 6-month test interval.

Localization

Localization testing was performed in an 11-speaker arc, with 18° separations between neighboring speakers spanning −90° to 90°. The arc had a radius of approximately 1 m. Subjects sat in the center of the arc, facing the center speaker, positioned at 0°. Speakers were mounted at ear level, and a mark on the ceiling of the sound booth was used to confirm that the subject maintained an appropriate head position. Each speaker was labeled with a number, 1 to 11, and subjects used these numbers to identify the speaker location. Localization performance was evaluated by playing a 200-ms speech-shaped noise sample and asking the subject to identify the source location. Stimulus level was randomly varied to prevent listeners from correctly identifying source location based solely on level; levels were 52, 62, and 72 dB SPL, interleaved randomly across trials. Each assessment included four repetitions at each of 11 locations and each of three levels, for a total of 132 trials. The CI recipients were tested with and without their CI at each postoperative test interval; preoperative testing was performed unaided. These methods are identical to those described by Dillon, Buss, Anderson, et al. (2017), who reported data for CI recipients out to the 6-month test interval.

Study Timeline and General Procedures

The CI recipients provided baseline data in both speech perception and localization protocols prior to implantation. Initial CI activation occurred 2 to 4 weeks after surgery. A 1-hr session of aural rehabilitation was provided immediately following activation and at the 1-month follow-up. During these sessions, subjects learned how to use direct-audio input to their CI, practiced listening to recorded speech materials, and were counseled regarding the potential training benefits of using this input mode. Speech perception and localization data were collected with the CI on and with the CI off at 1, 3, 6, 9, and 12 months following activation of the CI. Data collection at each test interval took 3 to 4 hr for subjects in the CI group. Subjects in the NH control group provided speech perception and localization data in a single 1-hr test session.

Testing was carried out by a licensed audiologist and took place in a double-walled booth. The test protocol was approved by the institutional review board associated with the University of North Carolina at Chapel Hill. All subjects provided written informed consent. The CI recipients received their implant, surgery, two external speech processors, and batteries to power the device over the study period. Subjects in the NH control group were paid an hourly rate of $15/hr.

Data Analysis

Data analysis was guided by three main questions: (a) how does the CI affect performance in subjects with UHL, (b) how does performance of subjects with UHL change over time with CI experience, and (c) how does performance of CI recipients with UHL compared to that of NH control subjects. A significance criterion of $\alpha = .05$ was adopted for all analyses, and significance was evaluated two-tailed. Scores for CNC words and AzBio sentences are reported in percent correct, but analyzed in rationalized arcsine units (Studebaker, 1985) to normalize error variance. Trends in performance over time were evaluated using linear mixed models that were implemented in R (Pinheiro et al., 2016; R Core Team, 2016), with subject as a random factor and test interval represented in months. Associations between variables were assessed using Pearson correlation or Spearman correlation, when appropriate.

Localization performance was quantified in two ways: root-mean-squared error (RMS_{err}) and side bias. The RMS_{err} was defined as follows:

$$RMS_{err} = \sqrt{A^2 \frac{1}{k} \sum_{l=1}^{k} \frac{1}{m} \sum_{i=1}^{m} (r_{l,i} - 1)^2}$$

where A is the angular separation of sources in degrees ($A = 18°$), l is the index of the stimulus location (1–11), r is the index of the subject's response (1–11), M is the number of trials associated with a source location ($M = 12$), and K is the number of source locations ($K = 11$).

Side bias was defined as:

$$\text{Bias} = xA \frac{1}{k} \sum_{l=1}^{k} \frac{1}{M} \sum\nolimits_{i=1}^{M} r_{l,i} - l$$

$$x = \begin{cases} 1, & \text{UHL left} \\ -1 & \text{UHL right} \end{cases}$$

The scalar x normalizes the estimate of Bias, such that positive values reflect a tendency to localize sound on the side of the NH ear, and negative values reflect a tendency to localize sound on the side of the UHL.

Results and Discussion

Whereas the majority of CI recipients had at least one threshold $\leqslant$ 80 dB HL in the impaired ear prior to implantation, only three subjects had thresholds $\leqslant$ 80 dB HL after surgery. In all three cases, that preserved hearing (60–75 dB HL) was limited to 125 Hz, and thresholds were stable through the 12-month follow-up. No attempt was made to mask this residual hearing in the CI ear.

Word Recognition in Quiet for the CI Ear

For the CI recipients, scores on CNC words in quiet in the impaired ear rose from an average of 4% (0–24%)

with a hearing aid at the preoperative test interval to a mean of 55% correct (10%–84%) with the CI alone at the 12-month test interval. There was also evidence of performance improvement in the postoperative period. Those results are shown in Figure 2. There was a significant effect of test interval for linear mixed models including all postoperative data ($\beta = 1.53$, $SE = 0.25$, $p < .001$) or just the 3- to 12-month data ($\beta = 0.87$, $SE = 0.28$, $p = .003$). The effect of test interval was not significant when evaluating just the 6- to 12-month data ($p = .264$). These results are consistent with asymptotic CNC scores by the 6-month test interval.

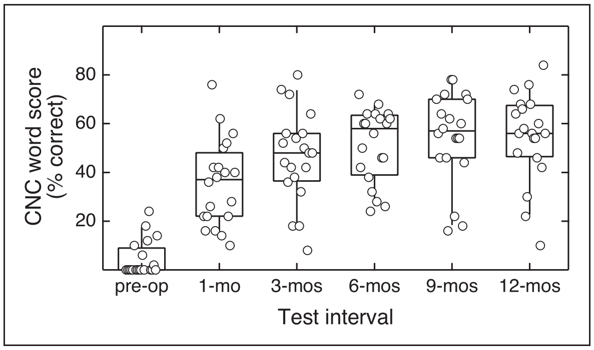

Figure 2. CNC word scores across test intervals for CI recipients. Preoperative testing was performed with a hearing aid, and subsequent assessments were performed with the CI alone. The NH ear was masked at all intervals. Results are plotted in percent correct, and plotting conventions follow those of Figure 1.
CNC = consonant-nucleus-consonant.

These CNC results are broadly similar to those observed by Buchman et al. (2014) in a group of conventional CI candidates with bilateral moderate-to-profound hearing loss. In that study, mean scores rose from 45% at the 1-month interval to 60% at the 3- and 12-month intervals. The similarity between CI-alone word recognition for subjects with UHL and traditional CI recipients indicates that normal or near-normal hearing contralateral to the CI did not impair performance. This is interesting in light of published data indicating that CI recipients with UHL tend to perform more poorly in the CI-alone condition (Finke, Strauss-Schier, et al., 2017; Plant et al., 2016; Sladen et al., 2016).

Masked Sentence Recognition

The distributions of data for masked sentence recognition are plotted in Figure 3 as a function of the masker position relative to the ear with UHL for CI recipients. The largest benefit of introducing a CI occurred when the masker was presented on the side of the subject's NH ear (contralateral to the UHL); benefits in this condition are often described as reflecting head shadow. Comparing performance in the preoperative unaided condition and the 12-month CI listening condition, the

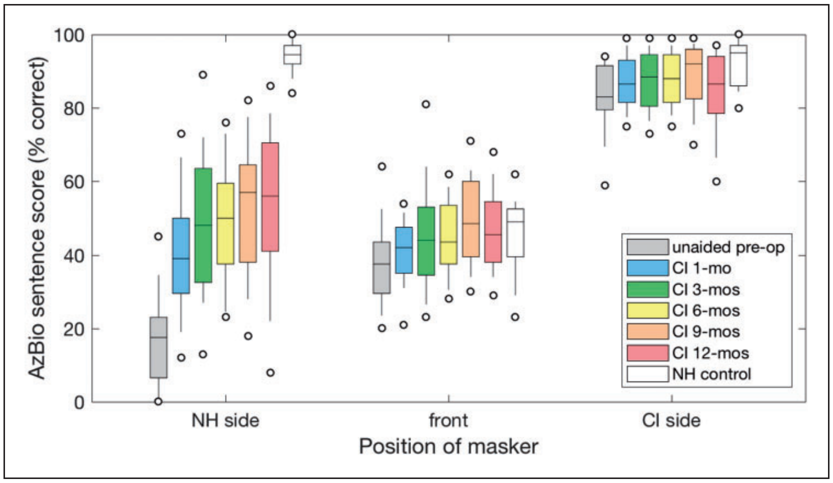

Figure 3. Distribution of AzBio sentence recognition scores as a function of masker position in units of percent correct. The abscissa indicates the position of the masker; data obtained for the masker at −90° and 90° for the NH control group were randomly assigned as control data for the NH side and the CI side. Horizontal lines indicate the median, boxes span the 25th to 75th percentiles, vertical lines span the 10th to 90th percentiles, and circles indicate the minimum and maximum values. Box shading reflects the subject group and follow-up interval (for the CI recipients). Within each condition, boxes are ordered by the time point of data collection (preoperative on the left, 12-month on the right), with NH control data on the far right of each cluster. For the CI recipients, preoperative data were collected unaided, and postoperative data were collected with the CI.
CI = cochlear implant; NH = normal hearing.

CI significantly improved performance by an average of 36 percentage points, $t(19) = 9.30$, $p < .001$. Despite these strong gains, performance with the CI at the 12-month test interval remained poorer than that observed in the NH control group, with an average difference of 42 percentage points, $t(38) = 9.36$, $p < .001$. Previous data are consistent with a CI benefit when the masker is presented contralateral to the CI (Grossmann et al., 2016; Plant & Babic, 2016; Tavora-Vieira, Marino, et al., 2013), although it may take up to 12 months to emerge (Mertens et al., 2017).

One question of interest is whether the benefits associated with the CI when the masker is on the subject's NH side emerged immediately after CI activation or took time to develop. There was an effect of postoperative test interval ($\beta = 0.96$, $SE = 0.27$, $p < .001$); performance at the 1-month interval was significantly poorer than performance at the 12-month interval (13 percentage points; $p = .002$), but removing the 1-month data from the model resulted in a nonsignificant effect of test interval ($p = .183$). These results indicate some improvement between the 1- and 3-month intervals when the masker is on the subject's NH side.

There was modest evidence that the CI improved performance when the masker was presented from the front, colocated with the target; benefits in this condition are often described as reflecting summation. Comparing performance in the preoperative unaided condition and the 12-month CI listening condition, the CI improved performance by a mean of 9.7 percentage points, $t(19) = 4.62$, $p < .001$. Performance also improved in the postoperative interval ($\beta = 0.55$, $SE = 0.22$, $p = .014$), and this effect became nonsignificant when just the 3- to 12-month data were evaluated ($p = .252$). At the 12-month interval, performance for CI recipients was comparable to that of NH control subjects, with nonsignificant differences of -1.8 percentage points, $t(38) = 0.56$, $p = .577$. Previous studies provide mixed evidence of a CI benefit when the target and masker are colocated: Some studies report no significant benefit (Arndt et al., 2010; Grossmann et al., 2016), and others report a clear benefit after 36 months of listening experience in listeners with some hearing loss in the better-hearing ear (Mertens, Punte, De Bodt, & Van de Heyning, 2015).

There was no evidence that the CI improved performance when the masker was presented on the side of the subject's CI; benefits in this condition are described as reflecting true binaural hearing. Under these listening conditions, mean performance worsened by a nonsignificant 1.6 percentage points, $t(19) = 1.59$, $p = .128$. While the CI did not significantly affect performance, having normal or near-normal hearing bilaterally does support better performance than unilateral acoustic hearing. Comparing results for the CI group at the 12-month interval with results for the NH control group indicates a difference of 7.6 percentage points, $t(38) = 2.84$, $p = .007$. Some studies report evidence of true binaural hearing in CI users with UHL (Grossmann et al., 2016), but it is more frequently not observed (Arndt et al., 2010; Mertens et al., 2017). One caveat when considering data obtained with the masker on the side of the CI is the fact that performance approached the limit of the test (i.e., 100% correct) in some subjects.

Group data indicate a significant benefit of the CI when the masker was from the side of the subject's NH ear or from the front, but the consistency of this benefit across subjects is also of interest. Benefit was quantified by comparing scores at the preoperative interval with mean scores at the 3- to 12-month test intervals, the time points associated with asymptotic performance. When the masker was on the side of the subject's NH ear, there was a benefit for 20 of the 20 subjects, and when the masker was from the front, there was a benefit for 15 of the 20 subjects.

Whereas performance improved over test intervals in some conditions with the CI, performance in the unaided condition was stable over time. This was quantified by comparing the unaided data from across all test intervals for colocated target and masker (1- to 12-month unaided data not shown). Data for the masker front condition were chosen for this analysis because they are the least likely to be limited by floor or ceiling effects. Between these intervals, performance improved by 1 percentage point ($\beta = 0.34$, $SE = 0.21$, $p = .105$), although this trend failed to reach significance. The 1-point change in unaided AzBio sentence scores over time is modest compared with the benefits of a CI associated with head shadow and summation (36 and 9.7 percentage points, respectively).

Localization

Localization was generally poor in the preoperative period for the CI recipients, but it improved markedly after device activation. As described by Dillon, Buss, Anderson, et al. (2017), the pattern of localization responses at the preoperative test interval fell into four general categories: (a) responses at or near 0° regardless of source location ("midline", $n = 9$), (b) responses to the side of the subject's NH ear ("NH side," $n = 5$), (c) responses that were correlated with the source location ("location-based," $n = 2$), and (d) responses that were distributed across the range of speaker locations, but unrelated to source location ("random," $n = 3$). Two subjects whose data were categorized as "random" appeared to be responding based on stimulus level; stimuli presented at 52 dB SPL tended to be localized on the subject's CI side, and stimuli presented at 72 dB SPL tended to be localized on the NH side. In contrast to these preoperative data, responses obtained with the CI at the postoperative test intervals were uniformly associated with source location. Data from the 12-month test interval fell into four categories: (a) localization approaching the accuracy of the NH control group ("normal-like"), (b) responses that were correlated with source location, but with some error ("variable"), (c) responses that were associated with source location but did not span the full range of speakers ("compressed"), and (d) responses that were clearly correlated with the source but did not include the speaker at 90° on the CI side. ("NH bias"). Most subjects' data fell on a continuum between "normal-like" and "variable" responses ($n = 15$); the compressed and NH bias response patterns were less common ($n = 3$ and $n = 2$, respectively).

Figure 4(a) shows RMS error plotted as a function of test interval for CI recipients, with values for the NH control group shown at the far right. Localization error dropped with the introduction of a CI for all 20 listeners. There was also clear evidence of improvement within the postoperative period. A linear mixed model including just the postoperative data indicates an effect of test interval ($\beta = -0.79$, $SE = 0.21$, $p < .001$). Restricting the analysis to just 3- to 12-month data resulted in a nonsignificant effect of test interval ($p < .189$). Performance at the 12-month interval for the CI recipients was significantly poorer than performance in the NH control group, $t(38) = 11.10$, $p < .001$. Although not shown in the figure, there was no evidence that localization error changed significantly over test intervals in the unaided condition ($p = .797$).

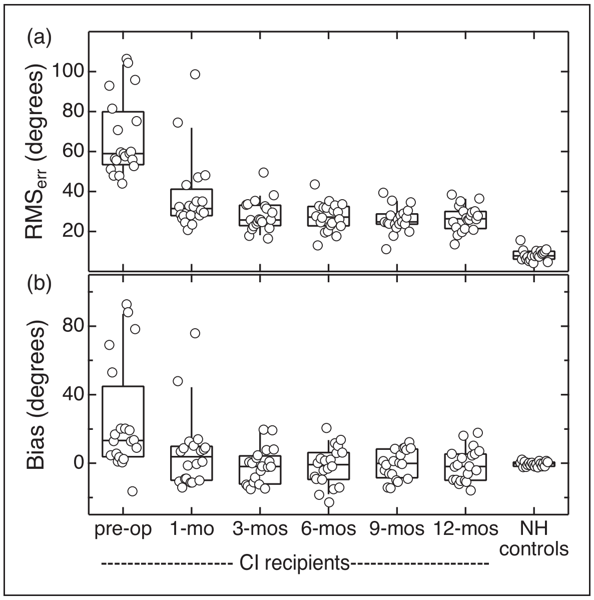

Figure 4. Derived statistics characterizing localization performance as a function of test interval, with unaided performance indicated at the preoperative interval and performance with the CI indicated for postoperative intervals. Values for the NH control group are shown at the far right of each panel. (a) Overall RMS error, with points representing values for individual subjects. (b) The distribution of side bias, with positive values indicating a bias to localize sound on the side of the NH ear, and negative numbers reflecting a bias to localize sound on the CI side. The side representing the NH ear was randomly selected for the NH control group. CI = cochlear implant; NH = normal hearing.

One consideration when evaluating performance at the preoperative test interval is whether listeners were performing above chance. Normal-hearing subjects tested with input to just one ear are sometimes able to perform above chance based on monaural spectral shape cues (Shub, Carr, Kong, & Colburn, 2008; Slattery & Middlebrooks, 1994). Residual hearing in the implanted ear could have supported above-chance performance. However, a role for residual hearing in the present data set is undermined by the observation that RMS error was not significantly lower for stimuli presented at 72 dB SPL than 52 dB SPL, $t(19) = 0.74$, $p = .470$.

Three strategies that a listener might use in the absence of valid cues to stimulus location were evaluated with Monte Carlo simulation ($n = 1e5$). Those strategies were: (a) always select the speaker on the midline, (b) always select the speaker at 90° (as if selecting the side of the NH ear), and (c) randomly select a speaker. Selecting the midline (0°) speaker for all trials results in $RMS_{err} = 56.9°$, and selecting the speaker at 90° results in $RMS_{err} = 106.5°$. Randomly selecting from among the 11 speaker positions with equal likelihood results in $RMS_{err} = 80°$ (95% CI = 72.8–87.8). For 8 of the 20 CI recipients, RMS error for the unaided condition at the preoperative interval was less than 56.9°, the most stringent estimate of chance performance. However, the Spearman correlation between signal and response location was significant for 14 of the 20 subjects. This result highlights the fact that RMS error does not fully capture a listener's localization ability and demonstrates that more than half of the CI recipients likely had some ability to localize sound preoperatively.

Side bias quantifies the extent to which subjects tended to localize sound on the side of the NH ear. Whereas the response category "NH bias" was determined based on the absence of responses corresponding to the speaker at 90° on the CI side, this measure of side bias incorporates responses from across the speaker array. Figure 4(b) shows the distribution of Bias. Bias was most pronounced at the preoperative interval and fell with introduction of the CI. Bias was larger for CI recipients at the 12-month interval than for NH control subjects. Although Bias in the postoperative test intervals had a group mean near zero, individual subjects tended to maintain a consistent side bias across test intervals, with some tending to localize sounds on the NH side, and others on the CI side. This consistency is reflected in the correlation between bias in sequential postoperative test intervals, which ranges from $r = .24$ ($p = .314$) to $r = .53$ ($p = .017$).

Association Between Outcome Measures

Performance was compared across outcome measures in an attempt to better understand the relationship between abilities tapped by each measure. Due to the large number of comparisons conducted, these results should be viewed as preliminary. Performance scores were averaged between 3- and 12-month intervals to obtain an estimate of asymptotic performance. Masked sentence scores with the CI were positively correlated with each other ($r = .46$ to $.87$, $p \leqslant 0.43$) and with scores obtained in the unaided condition ($r = .47$ to $.84$, $p \leqslant 0.38$). One interpretation of this data pattern is that there are individual differences in subjects' ability to recognize degraded speech irrespective of masker location or information provided by the CI. CNC word scores with the CI alone were correlated with masked sentence recognition scores for the masker on the NH side ($r = .47$, $p = .036$), but not for the other two masker positions ($p \geqslant .185$). This result is consistent with the idea that performance in the head shadow condition relies on the same abilities as speech recognition in quiet with the CI alone. Localization error, quantified as RMS error, tended to be negatively associated with speech performance in the three masked sentence recognition tasks, with values ranging from $r = -.32$ ($p = .165$) to $-.59$ ($p = .006$). Interestingly, the largest correlation was observed for the condition in which the target and masker were colocated in front of the subject, the only masked speech condition in which no spatial cues are available. This observation highlights the fact that binaural benefit for masked speech recognition does not necessarily reflect spatial hearing abilities.

For CI recipients, there was an association between performance on tasks reflecting binaural benefit and subject age, but not between performance and duration of deafness. There was a correlation between subject age and RMS error ($r_s = .42$, $p = .033$ one-tailed), between age and sentence recognition for a target and masker from the front ($r_s = -.38$, $p = .049$ one-tailed), and between age and sentence recognition for a target from the front and masker on the NH side ($r_s = -.61$, $p = .002$ one-tailed). Only the correlation between age and sentence recognition with the masker on the NH side remains significant after controlling for 8-kHz threshold in the NH ear ($r = -.46$, $p = .023$ one-tailed). There was a nonsignificant trend for a correlation between duration of deafness and RMS error ($r_s = -.33$, $p = .079$ one-tailed), and no evidence of a correlation between duration of deafness and masked sentence recognition ($p \geqslant .264$).

Conclusions

Results of the present study showed that adults with acquired moderate-to-profound UHL benefit from receiving a CI, with improved ability to localize sound on the horizontal plane and modest benefits for masked sentence recognition in a subset of conditions. While performance of the CI recipients was poorer than that observed in the NH control group, there was no evidence that CI use degraded performance in any condition. A growing body of literature has found comparable binaural benefit in CI users with UHL (Arndt et al., 2010; Grossmann et al., 2016; Mertens et al., 2017), consistent with reports of subjective benefit (Arndt et al., 2010; Dillon, Buss, Rooth, et al., 2017; Vannson et al., 2015). In contrast to previous reports, word recognition in quiet with the CI alone in this cohort was comparable to that obtained with traditional CI users (e.g., Buchman et al., 2014), and binaural benefits were observed earlier in the postoperative period than previously observed for CI users with moderate-to-profound UHL.

The benefits conferred by a CI for localization and masked sentence recognition appeared to reach their 12-month asymptote by the 3-month test interval. This is somewhat surprising given previous reports in the literature that the benefits of binaural hearing may take years to fully develop. For example, Mertens et al. (2017) evaluated masked speech recognition over time for 23 CI recipients with varying degrees of hearing sensitivity on the contralateral side. That study showed that the CI did not confer a head shadow benefit at the 6-month interval; benefit was not observed until the 12-month interval. Some data indicate that localization may actually get worse before improvements are eventually seen (Hansen et al., 2013), with continued improvement out to a year or more in some subjects. In contrast, the benefit of a CI in the present cohort was evident at the 1-month interval and reached the 12-month asymptote by the 3-month test interval. These data are consistent with the preliminary localization outcome data reported by Dillon et al. (2017a). Whereas previous reports have noted marked individual differences in the benefit conferred by the CI (Hansen et al., 2013; Zeitler et al., 2015), binaural benefits were observed for all subjects in the present dataset.

While masked speech recognition and localization emerged in parallel, the relationship between these abilities is unclear. Localization error, quantified as RMS error, was negatively related to sentence recognition scores across individual subjects. This association has been observed in some previous studies (Vannson et al., 2015), but not others (Firszt et al., 2017; Rothpletz, Wightman, & Kistler, 2012). Although a correlation between localization and speech recognition could reflect a close correspondence between cues to sound source location and the ability to perceptually segregate target speech from a spatially separated masker, it could also reflect the general quality of cues provided by the CI. This latter interpretation is supported by the observation that the correlation between RMS error and masked speech scores was largest when the target and masker were colocated, a condition for which no binaural difference cues are present. Further, the CI did not improve performance above the preoperative baseline for masked sentence recognition when the target was presented from the front and the masker was on the CI side. Benefit in this condition is thought to reflect true binaural processing, which is dominated by low-frequency ITD cues. One caveat is that benefit in this condition develops over years of bilateral CI use (Eapen, Buss, Adunka, Pillsbury, & Buchman, 2009); it is therefore possible that true binaural hearing could be observed in CI users with UHL after the 12-month interval.

In addition to early and consistent binaural benefit, subjects in the present study performed comparably to traditional CI candidates when tested on word recognition in quiet with their CI alone. In contrast, a number of studies have observed a negative association between performance with the CI and contralateral acoustic hearing, with relatively poor performance in patients with normal or near-normal hearing contralateral to the CI (Finke, Strauss-Schier, et al., 2017; Plant et al., 2016; Sladen et al., 2016). Interestingly, CI-alone performance was correlated with masked speech recognition when the masker was presented on the side of the subject's NH ear, the condition associated with the head shadow effect. This association is consistent with the idea that better utilization of cues provided by the CI supports speech recognition, either alone or in combination with acoustic cues. The magnitude of binaural benefit could therefore be causally linked to good performance with the CI alone, and the time course with which the binaural benefit emerges could be affected by the emergence of good performance with the CI alone.

It is unclear what accounts for the good performance in the CI-alone and spatial hearing tasks early in the postoperative period in the present cohort. While listener age is negatively correlated with CI performance, both in the literature (Sladen & Zappler, 2015) and in the current data set, the mean age at the time of implantation for the study cohort (50 years) is not atypical of the populations evaluated in previous studies (e.g., Mertens et al., 2015; Vermeire & Van de Heyning, 2009). Another factor could be the relative short duration of deafness in the study cohort, which was 2.6 years on average. Auditory deprivation associated with postlingual single-sided deafness has been shown to result in cortical reorganization (Maslin et al., 2013; Ponton et al., 2001; Pross et al., 2015), favoring representation of sound from the NH side. Implantation shortly after the onset of moderate-to-profound hearing loss could maximize outcomes by providing stimulation to the affected side before the potential deterioration of binaural hearing. This explanation is undermined somewhat by the fact that individual differences in previous data were not explained by duration of deafness (Zeitler et al., 2015), and modest differences in duration of deafness did not have an appreciable effect on binaural benefit in the present study. Further, binaural benefit can be obtained in patients with longstanding UHL of more than 25 years (Tavora-Vieira, Boisvert, McMahon, Maric, & Rajan, 2013), and some studies have reported inconsistent benefit in patients with less than 5 years duration of deafness (Arndt et al., 2010; Grossmann et al., 2016).

Another factor that may contribute to the early and consistent benefit observed for CI recipients in the present study is the relatively deep insertion of the MED-EL standard electrode array. Monaural speech perception and binaural processing can be degraded by a shift in the mapping of place to frequency (Suneel et al., 2017; Svirsky, Talavage, Sinha, Neuburger, & Azadpour, 2015; Wess et al., 2017). For example, studies of dichotic vocoded speech recognition with normal-hearing listeners suggest that performance is detrimentally affected by a mismatch in place to frequency mapping across ears (Wess et al., 2017; Zhou, Li, Yuan, Galvin, & Fu, 2017). There is some evidence that CI users can learn to accommodate mismatches with respect to pitch perception (Reiss, Turner, Karsten, & Gantz, 2014), and it is possible that a similar process occurs for spatial hearing. The MED-EL standard electrode array is inserted 31 mm into the cochlea, such that low-frequency stimulation applied to the apical electrodes closely approximates the natural pitch to place association (Landsberger, Svrakic, Roland, & Svirsky, 2015; Vermeire et al., 2015). It is possible that this correspondence between place and frequency confers a benefit with respect to the experience needed to achieve asymptotic performance. It is also possible that the use of FS4, a coding strategy designed to introduce temporal fine-structure cues on low-frequency channels, could have played a role in performance. Further research is needed to evaluate the role of electrode length and coding strategy for CI users with good contralateral hearing sensitivity. However, these factors are unlikely to fully account for the results observed here, in light of the fact that some previous datasets showing variable outcomes have included patients implanted with a 31-mm array (e.g., Mertens et al., 2015), and preliminary results indicate no binaural benefit of FS4 for speech recognition (Zirn, Arndt, Aschendorff, Laszig, & Wesarg, 2016).

The mapping procedure utilized with this cohort may also have contributed to early and relatively consistent binaural benefit. CI recipients with normal to near-normal hearing in the contralateral ear may be resistant to optimal electric stimulation levels due to the novelty and quality of the sound compared with their NH hearing ear. Audiologists may respond by scaling back in the initial map and gradually increasing stimulation levels over time. If comfort levels are set below "loud, but comfortable" sensation, then early performance may be degraded due to limited access to auditory input via the CI. The cohort followed in the present study was instructed during initial activation and subsequent follow-up intervals to match the loudness of the CI to that of the normal to near-normal hearing ear. The use of appropriate loudness settings was then reinforced during aural rehabilitation at initial activation and at the 1-month test interval. During those sessions, subjects listened to recorded materials through direct-audio input, which encouraged them to adjust the CI volume to achieve audibility. Several subjects reported using direct-audio input to listen to music, and one even used this mode to listen to foreign language instruction materials. It is possible that listening with the CI alone may be responsible for the beneficial effects of aural rehabilitation reported in the literature for this population (Finke, Strauss-Schier, et al., 2017; Nawaz et al., 2014; Tavora-Vieira, Marino, et al., 2013), although the present data would suggest that two sessions may be sufficient to support good outcomes.

A final factor to consider when evaluating the early and consistent benefit of a CI in this cohort is the number of hours of device use per day. Consistency of CI use could play a role in the rate of acclimatization. While this variable is often not specified, one recent study (Finke, Bonitz, Lyxell, & Illg, 2017) found that a group of 19 adult CI users with normal or near-normal hearing in the contralateral ear reported an average CI use of 5 hr/day. In contrast, most subjects in the present cohort reported wearing their CI between 10 and 12 hr per day throughout the 12-month follow-up period. Anecdotally, two subjects in the present study initially used their CI somewhat unreliably (4 hr/day), and those were the two poorest performers at the 1- and 3-month test intervals. Those subjects were encouraged to listen with the CI more consistently, which they reported doing at subsequent intervals, and their scores were in line with those of other subjects by the 6-month interval. While the present study was not designed explicitly to evaluate this parameter, it is possible that consistent device use played a role in the positive outcomes observed in this cohort.

Acknowledgments

The authors gratefully acknowledge the helpful comments of Dr. Ning Zhou and two anonymous reviewers. Aural rehabilitation was provided by Hannah Eskridge and Dr. Maegan Evans. The contribution of research assistants Margaret Richter and Katharina Boyce is also acknowledged.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

References

Arndt, S., Aschendorff, A., Laszig, R., Beck, R., Schild, C., Kroeger, S., . . . Wesarg, T. (2010). Comparison of pseudobinaural hearing to real binaural hearing rehabilitation after cochlear implantation in patients wtih unilateral deafness adn tinnitus. *Otology & Neurotology*, *32*, 39–47. doi:10.1097/MAO.0b013e3181fcf271.

Bernstein, J. G., Iyer, N., & Brungart, D. S. (2015). Release from informational masking in a monaural competing-speech task with vocoded copies of the maskers presented contralaterally. *The Journal of Acoustical Society of America*, *137*, 702–713. doi:10.1121/1.4906167.

Bernstein, L. R., & Trahiotis, C. (2016). Behavioral manifestations of audiometrically-defined "slight" or "hidden" hearing loss revealed by measures of binaural detection. *The Journal of Acoustical Society of America*, *140*, 3540–3548. doi:10.1121/1.4966113.

Bronkhorst, A. W. (2015). The cocktail-party problem revisited: Early processing and selection of multi-talker speech. *Attenion, Perception, & Psychophysics*, *77*, 1465–1487. doi:10.3758/s13414-015-0882-9.

Buchman, C. A., Dillon, M. T., King, E. R., Adunka, M. C., Adunka, O. F., & Pillsbury, H. C. (2014). Influence of cochlear implant insertion depth on performance: A prospective randomized trial. *Otology & Neurotology*, *35*, 1773–1779. doi:10.1097/MAO.0000000000000541.

Buss, E., Pillsbury, H. C., Buchman, C. A., Pillsbury, C. H., Clark, M. S., Haynes, D. S., . . . Barco, A. L. (2008). Multicenter U.S. bilateral MED-EL cochlear implantation study: Speech perception over the first year of use. *Ear and Hearing*, *29*, 20–32. doi:10.1097/AUD.0b013e31815d7467.

Clopton, B. M., & Silverman, M. S. (1977). Plasticity of binaural interaction. II. Critical period and changes in midline response. *Journal of Neurophysiology*, *40*, 1275–1280. doi:10.1152/jn.1977.40.6.1275.

Desmet, J. B., Wouters, K., De Bodt, M., & Van de Heyning, P. (2012). Comparison of 2 implantable bone conduction devices in patients with single-sided deafness using a daily alternating method. *Otology & Neurotology*, *33*, 1018–1026. doi:10.1097/MAO.0b013e31825e79ba.

Dillon, M. T., Buss, E., Anderson, M. L., King, E. R., Deres, E. J., Buchman, C. A., . . . Pillsbury, H. C. (2017a). Cochlear implantation in cases of unilateral hearing loss: Initial localization abilities. *Ear and Hearing*, *38*, 611–619. doi:10.1097/AUD.0000000000000430.

Dillon, M. T., Buss, E., Rooth, M. A., King, E. R., Deres, E. J., Buchman, C. A., . . . Brown, K. D. (2017b). Effects of cochlear implantation on quality of life in patients with unilateral hearing loss. *Audiology and Neurootology*, *22*, 259–271. doi:10.1159/000484079.

Dorman, M. F., Loiselle, L., Stohl, J., Yost, W. A., Spahr, A., Brown, C., & Cook, S. (2014). Interaural level differences and sound source localization for bilateral cochlear implant patients. *Ear and Hearing*, *35*, 633–640. doi:10.1097/AUD.0000000000000057.

Dunn, C. C., Tyler, R. S., & Witt, S. A. (2005). Benefit of wearing a hearing aid on the unimplanted ear in adult users of a cochlear implant. *Journal of Speech, Language, and Hearing Research*, *48*, 668–680. doi:10.1044/1092-4388(2005/046).

Dwyer, N. Y., Firszt, J. B., & Reeder, R. M. (2014). Effects of unilateral input and mode of hearing in the better ear: Self-reported performance using the speech, spatial and qualities of hearing scale. *Ear and Hearing*, *35*, 126–136. doi:10.1097/AUD.0b013e3182a3648b.

Eapen, R. J., Buss, E., Adunka, M. C., Pillsbury, H. C., & Buchman, C. A. (2009). Hearing-in-noise benefits after bilateral simultaneous cochlear implantation continue to improve 4 years after implantation. *Otology & Neurotology*, *30*, 153–159. doi:10.1097/MAO.0b013e3181925025.

Finke, M., Bonitz, H., Lyxell, B., & Illg, A. (2017a). Cochlear implant effectiveness in postlingual single-sided deaf individuals: What's the point? *International Journal of Audiology*, *56*, 417–423. doi:10.1080/14992027.2017.1296595.

Finke, M., Strauss-Schier, A., Kludt, E., Büchner, A., & Illg, A. (2017b). Speech intelligibility and subjective benefit in single-sided deaf adults after cochlear implantation. *Hearing Research*, *348*, 112–119. doi:10.1016/j.heares.2017.03.002.

Firszt, J. B., Reeder, R. M., & Holden, L. K. (2017). Unilateral hearing loss: Understanding speech recognition and localization variability-implications for cochlear implant candidacy. *Ear and Hearing*, *38*, 159–173. doi:10.1097/AUD.0000000000000380.

Friedmann, D. R., Ahmed, O. H., McMenomey, S. O., Shapiro, W. H., Waltzman, S. B., & Roland, J. T. (2016). Single-sided deafness cochlear implantation: Candidacy, evaluation, and outcomes in children and adults. *Otology & Neurotology*, *37*, e154–e160. doi:10.1097/MAO.0000000000000951.

Gartrell, B. C., Jones, H. G., Kan, A., Buhr-Lawler, M., Gubbels, S. P., & Litovsky, R. Y. (2014). Investigating long-term effects of cochlear implantation in single-sided deafness: A best practice model for longitudinal assessment of spatial hearing abilities and tinnitus handicap. *Otology & Neurotology*, *35*, 1525–1532. doi:10.1097/MAO.0000000000000437.

Gifford, R. H., Grantham, D. W., Sheffield, S. W., Davis, T. J., Dwyer, R., & Dorman, M. F. (2014). Localization and interaural time difference (ITD) thresholds for cochlear implant recipients with preserved acoustic hearing in the implanted ear. *Hearing Research*, *312*, 28–37. doi:10.1016/j.heares.2014.02.007.

Grantham, D. W., Ashmead, D. H., Haynes, D. S., Hornsby, B. W., Labadie, R. F., & Ricketts, T. A. (2012). Horizontal plane localization in single-sided deaf adults fitted with a bone-anchored hearing aid (BAHA). *Ear and Hearing*, *33*, 595–603. doi:10.1097/AUD.0b013e3182503e5e.

Grantham, D. W., Ashmead, D. H., Ricketts, T. A., Labadie, R. F., & Haynes, D. S. (2007). Horizontal-plane localization of noise and speech signals by postlingually deafened adults fitted with bilateral cochlear implants. *Ear and Hearing*, *28*, 524–541. doi:10.1097/AUD.0b013e31806dc21a.

Grossmann, W., Brill, S., Moeltner, A., Mlynski, R., Hagen, R., & Radeloff, A. (2016). Cochlear implantation improves spatial release from masking and restores localization abilities in single-sided deaf patients. *Otology & Neurotology*, *37*, 658–664. doi:10.1097/MAO.0000000000001043.

Hansen, M. R., Gantz, B. J., & Dunn, C. (2013). Outcomes after cochlear implantation for patients with single-sided deafness, including those with recalcitrant Meniere's disease. *Otology & Neurotology*, *34*, 1681–1687. doi:10.1097/MAO.0000000000000102.

Hoth, S., Rosli-Khabas, M., Herisanu, I., Plinkert, P. K., & Praetorius, M. (2016). Cochlear implantation in recipients with single-sided deafness: Audiological performance. *Cochlear Implants International*, *17*, 190–199. doi:10.1080/14670100.2016.1176778.

Ihlefeld, A., & Litovsky, R. Y. (2012). Interaural level differences do not suffice for restoring spatial release from masking in simulated cochlear implant listening. *PLoS One*, *7*, 1–9. doi:10.1371/journal.pone.0045296.

Jones, H., Kan, A., & Litovsky, R. Y. (2014). Comparing sound localization deficits in bilateral cochlear-implant users and vocoder simulations with normal-hearing listeners. *Trends in Hearing*, *18*, pii:2331216514554574. doi:10.1177/2331216514554574.

Kan, A., Stoelb, C., Litovsky, R. Y., & Goupell, M. J. (2013). Effect of mismatched place-of-stimulation on binaural fusion and lateralization in bilateral cochlear-implant users. *The Journal of Acoustical Society of America*, *134*, 2923–2936. doi:10.1121/1.4820889.

Keating, P., & King, A. J. (2013). Developmental plasticity of spatial hearing following asymmetric hearing loss: Context-dependent cue integration and its clinical implications. *Frontiers in Systems Neuroscience*, *7*, 1–20. doi:10.3389/fnsys.2013.00123.

Kitterick, P. T., & Lucas, L. (2016). Predicting speech perception outcomes following cochlear implantation in adults with unilateral deafness or highly asymmetric hearing loss. *Cochlear Implants International*, *17*(Suppl 1): 51–54. doi:10.1080/14670100.2016.1155806.

Kitterick, P. T., Smith, S. N., & Lucas, L. (2016). Hearing instruments for unilateral severe-to-profound sensorineural hearing loss in adults: A systematic review and meta-analysis. *Ear and Hearing*, *37*, 495–507. doi:10.1097/AUD.0000000000000313.

Kral, A., Heid, S., Hubka, P., & Tillein, J. (2013a). Unilateral hearing during development: Hemispheric specificity in plastic reorganizations. *Frontiers in Systems Neuroscience*, *7*, 93. doi:10.3389/fnsys.2013.00093.

Kral, A., Hubka, P., Heid, S., & Tillein, J. (2013b). Single-sided deafness leads to unilateral aural preference within an early sensitive period. *Brain*, *136*, 180–193. doi:10.1093/brain/aws305.

Kral, A., Hubka, P., & Tillein, J. (2015). Strengthening of hearing ear representation reduces binaural sensitivity in early single-sided deafness. *Audiology and Neurotology*, *20*(Suppl 1): 7–12. doi:10.1159/000380742.

Landsberger, D. M., Svrakic, M., Roland, J. T. Jr, & Svirsky, M. (2015). The relationship between insertion angles, default frequency allocations, and spiral ganglion place pitch in cochlear implants. *Ear and Hearing*, *36*, e207–e213. doi:10.1097/AUD.0000000000000163.

Lin, F. R., Niparko, J. K., & Ferrucci, L. (2011). Hearing loss prevalence in the United States. *Archives of Internal Medicine*, *171*, 1851–1852. doi:10.1001/archinternmed.2011.506.

Linstrom, C. J., Silverman, C. A., & Yu, G. P. (2009). Efficacy of the bone-anchored hearing aid for single-sided deafness. *Laryngoscope*, *119*, 713–720. doi:10.1002/lary.20164.

Litovsky, R. Y., Parkinson, A., & Arcaroli, J. (2009). Spatial hearing and speech intelligibility in bilateral cochlear implant users. *Ear and Hearing*, *30*, 419–431. doi:10.1097/AUD.0b013e3181a165be.

Ma, N., Morris, S., & Kitterick, P. T. (2016). Benefits to speech perception in noise from the binaural integration of electric and acoustic signals in simulated unilateral deafness. *Ear and Hearing*, *37*, 248–259. doi:10.1097/AUD.0000000000000252.

Maslin, M. R., Munro, K. J., & El-Deredy, W. (2013). Source analysis reveals plasticity in the auditory cortex: Evidence for reduced hemispheric asymmetries following unilateral deafness. *Clinical Neurophysiology*, *124*, 391–399. doi:10.1016/j.clinph.2012.07.016.

Mertens, G., De Bodt, M., & Van de Heyning, P. (2017). Evaluation of long-term cochlear implant use in subjects with acquired unilateral profound hearing loss: Focus on binaural auditory outcomes. *Ear and Hearing*, *38*, 117–125. doi:10.1097/AUD.0000000000000359.

Mertens, G., Punte, A. K., De Bodt, M., & Van de Heyning, P. (2015). Binaural auditory outcomes in patients with postlingual profound unilateral hearing loss: 3 years after cochlear implantation. *Audiology and Neuro-Otology*, *20*, 67–72. doi:10.1159/000380751.

Moore, D. R., & Irvine, D. R. (1981). Plasticity of binaural interaction in the cat inferior colliculus. *Brain Research*, *208*, 198–202. doi:10.1016/0006-8993(81)90632-6.

Morera, C., Cavalle, L., Manrique, M., Huarte, A., Angel, R., Osorio, A., . . . Morera-Ballester, C. (2012). Contralateral hearing aid use in cochlear implanted patients: Multicenter study of bimodal benefit. *Acta Otolaryngologica*, *132*, 1084–1094. doi:10.3109/00016489.2012.677546.

Nawaz, S., McNeill, C., & Greenberg, S. L. (2014). Improving sound localization after cochlear implantation and auditory training for the management of single-sided deafness. *Otology & Neurotology*, *35*, 271–276. doi:10.1097/MAO.0000000000000257.

Peters, J. P., Smit, A. L., Stegeman, I., & Grolman, W. (2015). Review: Bone conduction devices and contralateral routing of sound systems in single-sided deafness. *Laryngoscope*, *125*, 218–226. doi:10.1002/lary.24865.

Peterson, G. E., & Lehiste, I. (1962). Revised CNC lists for auditory tests. *The Journal of Speech and Hearing Disorders*, *27*, 62–70. doi:10.1044/jshd.2701.62.

Pinheiro, J., Bates, D., & DebRoy, S., et al. (2016). *nlme: Linear and Nonlinear Mixed Effects Models*. R package version 3.1–125, http://CRAN.R project.org/package = nlme.

Plant, K., & Babic, L. (2016). Utility of bilateral acoustic hearing in combination with electrical stimulation provided by the cochlear implant. *International Journal of Audiology*, *55*(Suppl 2): S31–S38. doi:10.3109/14992027.2016.1150609.

Plant, K., McDermott, H., van Hoesel, R., Dawson, P., & Cowan, R. (2016). Factors predicting postoperative unilateral and bilateral speech recognition in adult cochlear implant recipients with acoustic hearing. *Ear and Hearing*, *37*, 153–163. doi:10.1097/AUD.0000000000000233.

Ponton, C. W., Vasama, J. P., Tremblay, K., Khosla, D., Kwong, B., & Don, M. (2001). Plasticity in the adult human central auditory system: Evidence from late-onset profound unilateral deafness. *Hearing Research*, *154*, 32–44. doi:10.1016/S0378-595501)00214-3.

Potts, L. G., Skinner, M. W., Litovsky, R. A., Strube, M. J., & Kuk, F. (2009). Recognition and localization of speech by adult cochlear implant recipients wearing a digital hearing aid in the nonimplanted ear (bimodal hearing). *Journal of the American Academy of Audiology*, *20*, 353–373. doi:10.3766/jaaa.20.6.4.

Pross, S. E., Chang, J. L., Mizuiri, D., Findlay, A. M., Nagarajan, S. S., & Cheung, S. W. (2015). Temporal cortical plasticity in single-sided deafness: A functional imaging study. *Otology & Neurotology*, *36*, 1443–1449. doi:10.1097/MAO.0000000000000821.

R Core Team. (2016). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Rana, B., Buchholz, J. M., Morgan, C., Sharma, M., Weller, T., Konganda, S. A., . . . Kawano, A. (2017). Bilateral versus unilateral cochlear implantation in adult listeners: Speech-on-speech masking and multitalker localization. *Trends in Hearing*, *21*, pii:2331216517722106. doi:10.1177/2331216517722106.

Reiss, L. A., Turner, C. W., Karsten, S. A., & Gantz, B. J. (2014). Plasticity in human pitch perception induced by tonotopically mismatched electro-acoustic stimulation. *Neuroscience*, *256*, 43–52. doi:10.1016/j.neuroscience.2013.10.024.

Ricketts, T., Grantham, D. W., D'Haese, P., Edwards, J., & Barco, A. (2006). Cochlear implant speech processor placement and compression effects on sound sensitivity and interaural level difference. *Journal of the American Academy of Audiology*, *17*, 133–140. doi:10.3766/jaaa.17.2.5.

Rothpletz, A. M., Wightman, F. L., & Kistler, D. J. (2012). Informational masking and spatial hearing in listeners with and without unilateral hearing loss. *Journal of Speech, Language, and Hearing Research*, *55*, 511–531. doi:10.1044/1092-4388(2011/10-0205).

Saroul, N., Akkari, M., Pavier, Y., Gilain, L., & Mom, T. (2013). Long-term benefit and sound localization in patients with single-sided deafness rehabilitated with an osseointegrated bone-conduction device. *Otology & Neurotology*, *34*, 111–114. doi:10.1097/MAO.0b013e31827a2020.

Scherf, F. W., & Arnold, L. P. (2014). Exploring the clinical approach to the bimodal fitting of hearing aids and cochlear implants: Results of an international survey. *Acta*

Otolaryngologica, *134*, 1151–1157. doi:10.3109/00016489.2014.914244.

Schoof, T., Green, T., Faulkner, A., & Rosen, S. (2013). Advantages from bilateral hearing in speech perception in noise with simulated cochlear implants and residual acoustic hearing. *The Journal of Acoustical Society of America*, *133*, 1017–1030. doi:10.1121/1.4773274.

Shub, D. E., Carr, S. P., Kong, Y., & Colburn, H. S. (2008). Discrimination and identification of azimuth using spectral shape. *The Journal of Acoustical Society of America*, *124*, 3132–3141. doi:10.1121/1.2981634.

Silverman, M. S., & Clopton, B. M. (1977). Plasticity of binaural interaction. *I. Effect of early auditory deprivation*. Journal of Neurophysiology, *40*, 1266–1274. doi:10.1152/jn.1977.40.6.1266.

Sladen, D. P., Frisch, C. D., Carlson, M. L., Driscoll, C. L., Torres, J. H., & Zeitler, D. M. (2016). Cochlear implantation for single-sided deafness: A multicenter study. *Laryngoscope*, *127*, 223–228. doi:10.1002/lary.26102.

Sladen, D. P., & Zappler, A. (2015). Older and younger adult cochlear implant users: Speech recognition in quiet and noise, quality of life, and music perception. *American Journal of Audiology*, *24*, 31–39. doi:10.1044/2014_AJA-13-0066.

Slattery, W. H. 3rd, & Middlebrooks, J. C. (1994). Monaural sound localization: Acute versus chronic unilateral impairment. *Hearing Research*, *75*, 38–46. doi:10.1016/0378-595594)90053-1.

Smulders, Y. E., van Zon, A., Stegeman, I., Rinia, A. B., Van Zanten, G. A., Stokroos, R. J., ... Grolman, W. (2016). Comparison of bilateral and unilateral cochlear implantation in adults: A randomized clinical trial. *JAMA Otolaryngology: Head & Neck Surgery*, *142*, 249–256. doi:10.1001/jamaoto.2015.3305.

Spahr, A. J., Dorman, M. F., Litvak, L. M., Van Wie, S., Gifford, R. H., Loizou, P. C., ... Cook, S. (2012). Development and validation of the AzBio sentence lists. *Ear and Hearing*, *33*, 112–117. doi:10.1097/AUD.0b013e31822c2549.

Studebaker, G. A. (1985). A "rationalized" arcsine transform. *Journal of Speech and Hearing Research*, *28*, 455–462. doi:10.1044/jshr.2803.455.

Suneel, D., Staisloff, H., Shayman, C. S., Stelmach, J., & Aronoff, J. M. (2017). Localization performance correlates with binaural fusion for interaurally mismatched vocoded speech. *The Journal of Acoustical Society of America*, *142*, EL276. doi:10.1121/1.5001903.

Svirsky, M. A., Talavage, T. M., Sinha, S., Neuburger, H., & Azadpour, M. (2015). Gradual adaptation to auditory frequency mismatch. *Hearing Research*, *322*, 163–170. doi:10.1016/j.heares.2014.10.008.

Tavora-Vieira, D., Boisvert, I., McMahon, C. M., Maric, V., & Rajan, G. P. (2013a). Successful outcomes of cochlear implantation in long-term unilateral deafness: Brain plasticity? *Neuroreport*, *24*, 724–729. doi:10.1097/WNR.0b013e3283642a93.

Tavora-Vieira, D., De Ceulaer, G., Govaerts, P. J., & Rajan, G. P. (2015). Cochlear implantation improves localization ability in patients with unilateral deafness. *Ear and Hearing*, *36*, e93–e98. doi:10.1097/AUD.0000000000000130.

Tavora-Vieira, D., Marino, R., Krishnaswamy, J., Kuthbutheen, J., & Rajan, G. P. (2013b). Cochlear implantation for unilateral deafness with and without tinnitus: A case series. *Laryngoscope*, *123*, 1251–1255. doi:10.1002/lary.23764.

Throckmorton, C. S., & Collins, L. M. (2001). A comparison of two loudness balancing tasks in cochlear implant subjects using bipolar stimulation. *Ear and Hearing*, *22*, 439–448. doi:10.1097/00003446-200110000-00008.

Tillein, J., Hubka, P., & Kral, A. (2016). Monaural congenital deafness affects aural dominance and degrades binaural processing. *Cerebral Cortex*, *26*, 1762–1777. doi:10.1093/cercor/bhv351.

Vannson, N., James, C., Fraysse, B., Strelnikov, K., Barone, P., Deguine, O., & Marx, M. (2015). Quality of life and auditory performance in adults with asymmetric hearing loss. *Audiology & Neurootology*, *20*(Suppl 1): 38–43. doi:10.1159/000380746.

Vermeire, K., Landsberger, D. M., Van de Heyning, P. H., Voormolen, M., Kleine Punte, A., Schatzer, R., & Zierhofer, C. (2015). Frequency-place map for electrical stimulation in cochlear implants: Change over time. *Hearing Research*, *326*, 8–14. doi:10.1016/j.heares.2015.03.011.

Vermeire, K., & Van de Heyning, P. (2009). Binaural hearing after cochlear implantation in subjects with unilateral sensorineural deafness and tinnitus. *Audiology & Neurootology*, *14*, 163–171. doi:10.1159/000171478.

Wess, J. M., Brungart, D. S., & Bernstein, J. G. W. (2017). The effect of interaural mismatches on contralateral unmasking with single-sided vocoders. *Ear and Hearing*, *38*, 374–386. doi:10.1097/AUD.0000000000000374.

Wightman, F. L., & Kistler, D. J. (1992). The dominant role of low-frequency interaural time differences in sound localization. *The Journal of Acoustical Society of America*, *91*, 1648–1661. doi:10.1121/1.402445.

Yoon, Y. S., Shin, Y. R., & Fu, Q. J. (2013). Binaural benefit with and without a bilateral spectral mismatch in acoustic simulations of cochlear implant processing. *Ear and Hearing*, *34*, 273–279. doi:10.1097/AUD.0b013e31826709e8.

Zeitler, D. M., Dorman, M. F., Natale, S. J., Loiselle, L., Yost, W. A., & Gifford, R. H. (2015). Sound source localization and speech understanding in complex listening environments by single-sided deaf listeners after cochlear implantation. *Otology & Neurotology*, *36*, 1467–1471. doi:10.1097/MAO.0000000000000841.

Zhou, X., Li, H., Yuan, W., Galvin, J. J. 3rd, & Fu, Q.-J. (2017). Effects of insertion depth on spatial speech perception in noise for simulations of cochlear implants and single-sided deafness. *International Journal of Audiology*, *56*, S41–S48. doi:10.1080/14992027.2016.1197426.

Zirn, S., Arndt, S., Aschendorff, A., Laszig, R., & Wesarg, T. (2016). Perception of interaural phase differences with envelope and fine structure coding strategies in bilateral cochlear implant users. *Trends in Hearing*, *20*, pii:2331216516665608. doi:10.1177/2331216516665608.