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Transitioning from Bimodal to Bilateral Cochlear Implant Listening: Speech Recognition and Localization in Four Individuals

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Abstract

Purpose—The use of bilateral stimulation is becoming common for cochlear implant (CI) recipients, with either a CI in one ear and a hearing aid (HA) in the non-implanted ear (CI&HA - bimodal) or CIs in both ears (CI&CI - bilateral). The objective of this study was to evaluate performance of four individuals who transitioned from bimodal to bilateral stimulation.

Methods—Participants had completed a larger study of bimodal hearing and subsequently received a second CI. Test procedures from the bimodal study, including speech recognition, localization, and a questionnaire (SSQ) were repeated after 6-7 months of experience with bilateral CIs. Speech recognition and localization were measured using words that were presented from unpredictable locations in the room.

Results—Speech recognition and localization were not different between bimodal and unilateral CI. In contrast, performance was significantly better with CI&CI compared with unilateral CI. Speech recognition with CI&CI was significantly better than with CI&HA for 2/4 participants. Localization was significantly better for all participants with CI&CI compared to CI&HA. CI&CI performance was rated as significantly better on the SSQ compared to CI&HA performance for the four participants.

Conclusions—There was a strong subjective preference for CI&CI for all participants. The variability in speech recognition and localization, however, suggests that performance under these stimulus conditions is individualized. Differences in hearing and/or HA history may provide an explanation for performance differences.

Keywords

cochlear implant; hearing aid; speech recognition; localization; bimodal devices; bilateral cochlear implants

Introduction

For years, , unilateral cochlear implants (CI) have been the standard of care in clinical practice; however, in recent years the number of individuals using bimodal devices (CI&HA in opposite ears) or bilateral CIs (CI&CI) has grown substantially. According to a survey by Peters, Wyss, and Manrique (2010) approximately 30% of adult CI recipients have bilateral CIs, with 76% of those receiving the second CI sometime after the first CI (i.e. sequential surgeries). The clinician must now be equipped to answer recipients' questions about the benefits of transitioning from bimodal devices to bilateral CIs. Specifically, what type and how much improvement will a second CI provide compared to performance with bimodal devices.

There has been a notable amount of research focusing on speech recognition, sound localization, and functional abilities with bimodal devices and bilateral CIs (Brown & Balkany, 2007; Ching, van Wanrooy, & Dillon, 2007; Schafer, Amlani, Paiva, Nozari, & Verret, 2011). The majority of studies with bimodally-fitted adults show that there is improvement in speech recognition, localization, and subjective reports with bimodal stimulation compared with monaural CI use (Berrettini, Passetti, Giannarelli, & Forli, 2010; Ching, Incerti, & Hill, 2004; Dunn, Tyler, & Witt, 2005; Firszt, Reeder, & Skinner, 2008; Fitzpatrick, Seguin, Schramm, Chenier, & Armstrong, 2009; Morera et al., 2005; Potts, Skinner, Litovsky, Strube, & Kuk, 2009; Seeber, Baumann, & Fastl, 2004; Tyler et al., 2002).

Similarly, the majority of bilateral CI recipients have improved speech recognition, localization, and subjective reports when both CIs are activated compared to performance with a unilateral CI (e.g., Buss et al., 2008; Litovsky, Parkinson, Arcaroli, & Sammeth, 2006; Noble, Tyler, Dunn, & Bhullar, 2008; Senn, Kompis, Vischer, & Haeusler, 2005; Summerfield et al., 2006; Tyler, Dunn, Witt, & Noble, 2007; van Hoesel, 2004). A criticism of research that compares bilateral and unilateral performance within the same individual is that it may result in poorer unilateral performance as the individual is not routinely listening to only one CI. To address this issue, some studies have matched bilateral CI recipients with unilateral CI recipients on important factors such as hearing loss, age, and duration of deafness. Bilateral CI recipients were found to perform better on localization tasks, as well as speech recognition in quiet and noise compared to unilateral CI recipients (Dunn, Tyler, Oakley, Gantz, & Noble, 2008; Dunn, Tyler, Witt, Ji, & Gantz, 2012). The improvement with binaural stimulation is generally attributable to factors such as (1) redundant or complementary information being received at the two ears, resulting in summation of auditory information; (2) the availability of an ear with audibility regardless of the location of the target speech.

In a meta-analysis study, Schafer et al. (2011) considered the question of which stimulation mode (bimodal or bilateral CI) provides the most benefit. The analysis examined 42 studies of speech recognition in noise and found a slight advantage for the binaural squelch effect with bilateral CIs. There was no statistical difference between bimodal and bilateral CI performance for binaural summation and head shadow effects. This analysis, while helpful in directly comparing bimodal to bilateral CI performance, does not examine the differences

in the two modes of bilateral hearing within the same individual. To address this, Ching et al. (2007) reported on two adults who transitioned from bimodal to bilateral CI use. These individuals showed notable differences in performance across tasks. For example, subject one's performance with CI&CI showed an improvement in localization, but no improvement in consonant perception compared to CI&HA. Subject two's performance, however, showed no improvement with CI&CI in localization or consonant perception compared to CI&HA. Interestingly, both subjects had a reported improvement in functional performance with CI&CI. The authors concluded that the factors that determine CI&CI benefit are unknown.

There are several factors that have been shown to be predictive of unilateral CI performance, including years of deafness, amplification history, and residual hearing (Blamey et al., 1996; Finley et al., 2008; Rubinstein, Gantz, & Parkinson, 1999). In addition to these, there are several factors that could affect bilateral CI performance by creating asymmetric hearing between bilaterally implanted ears. These include differences in electrode placement inside the two cochleae, lack of coordination between speech processors, un-matched sensitivity or automatic-gain control settings, differences in speech processing strategies and/or rate of stimulation (Dawson, Skok, & Clark, 1997; Litovsky, Parkinson, & Arcaroli, 2009; Lu, Litovsky, & Zeng, 2011; van Hoesel, 2004). Research has found improvement with bilateral CIs despite known differences between implanted ears, such as different processing strategies and even different CI manufacturers in each ear (Dorman & Dahlstrom, 2004; Tyler, Dunn, Witt, & Noble, 2007). Bilateral CI recipients can, therefore, utilize bilateral input received despite differences that exist between bilaterally implanted ears. It is unclear, however, how these differences may influence or possibly limit the benefit obtained from bilateral CIs.

Lastly, bimodal recipients also have a complicated integration task as they have an asymmetry in hearing threshold levels and the type of auditory input received in each ear is different (CI - electric and HA - acoustic). There is also notable differences in signal processing between a CI and a HA. Therefore, both bimodal and bilateral stimulation could result in sound being delivered that requires integration of atypical and asymmetric cues.

The purpose of this study was to investigate four participants who had hearing loss from a young age, and who during adulthood transitioned from being bimodal to being bilateral CI users. These participants had previously been in an investigation that included a larger population of bimodal recipients (Potts et al., 2009). The testing approach used in the present study and its predecessor emphasizes listening conditions that simulate an individual's real-life listening situation, where speech recognition was evaluated with words presented from random locations and localization testing which used speech stimuli.

The approach used in this study is to focus on four individual case studies, whereby detailed information is available about hearing history and performance before and after bilateral implantation. Due to the large variability in CI recipient's performance, a within-subject case study approach is intended to provide insight into the transition between bimodal and bilateral CIs with more direct information about the differences between these stimulation modes and aid in estimating bilateral CI performance at the individual level.

Methods

Participants

The four participants in this study, who had been part of a larger study (Potts et al., 2009), received a second CI following their participation in the bimodal study (see Table 1 for demographic information). Participants 1 and 4 were diagnosed with hearing loss at a young age; P1 at age 1 and P4 at age 5. These subjects both received an aural education at a school for the deaf following their diagnosis and have very clear speech and normal language. Participants 2 and 3 acquired severe-profound hearing loss as adults.

The unaided pure-tone thresholds, prior to implantation, show moderately-severe to profound loss in both ears for all participants (see Table 2). All participants had been wearing two HAs at the time of the first CI surgery, and continued full-time HA use in the non-implanted ear in conjunction with their first CI. Table 3 shows the aided speech recognition for sentences prior to activation of the first CI, HA experience, along with number of years of experience with the first CI at the time of bimodal and bilateral testing. All participants had six months experience with the second CI prior to bilateral testing. Table 4 lists the type of implant array, strategy, rate, maxima, as well as the type of speech processor that participants used at the time of testing. All participants were implanted and programmed at Washington University School of Medicine. The advanced combination encoder strategy (ACE) was used by all participants.

Test Environment

Soundfield threshold, speech recognition, and localization testing was completed in a double-walled sound-treated booth (IAC, Model 404-A; $254 \times 272 \times 198$ cm) at a distance of 1.5 meters from the loudspeaker(s). For soundfield threshold testing, a single loudspeaker was positioned at 0° (front). For speech recognition and localization testing, participants were seated in the center of a 15-loudspeaker array; loudspeakers (Cambridge Soundworks MC50) were positioned on a horizontal arc with a radius of 140° (137 cm) and spaced in increments of 10° from $+70^\circ$ (left) to -70° (right) at a height of 117 cm. The loudspeakers were numbered from 1 (-70°) to 15 ($+70^\circ$), and controlled by a computer using Tucker Davis Technologies (TDT) hardware with a dedicated channel for each loudspeaker. Each channel included a digital-to-analog converter (TDT DD3-8), a filter with a cut-off frequency of 20 kHz (TDT FT5), an attenuator (TDT PA4) and a power amplifier (Crown D-150).

Stimuli

Soundfield thresholds were obtained by using frequency-modulated warble tones in which sinusoidal carriers were modulated (rate 10 Hz) with a triangular function over standard bandwidths. For speech recognition and localization testing, newly recorded lists of CNC words were used (Consonant-Vowel Nucleus-Consonant; Skinner et al., 2006; Peterson & Lehiste, 1962). A detailed description of the calibration is given in Potts et al. (2009).

Hearing Aid Fitting and Cochlear Implant Programming

A Widex Senso Vita 38 was fit to all participants as part of the previous study. A detailed description of the hearing aid processing and fitting protocol can be found in Potts et al., (2009). Briefly, In-situ threshold measurements, in four frequency bands (500, 1000, 2000, and 4000 Hz), were used in the initial fitting. Real-ear measurements were employed to adjust the HA output within the subjects dynamic range for soft (55 dB SPL), medium (65 dB SPL) and loud (75 dB SPL) inputs. The hearing aid was programmed to be above threshold for the 55 dB SPL input and below a judgment of loud for the 75 dB SPL input. In addition, soundfield thresholds were utilized to maximize audibility of soft sounds. The programming was fine-tuned to achieve these goals over 6-8 weeks.

The CI programming regime followed in the Adult Cochlear Implant and Aural Rehabilitation Program at Washington University School of Medicine for unilateral CIs has been detailed previously (Skinner, Holden, Holden, & Demorest, 1999; Skinner et al., 2002; Skinner, Binzer, Potts, Holden, & Aaron, 2006). CI recipients are programmed weekly for 6-8 weeks utilizing loudness judgments and counted thresholds on every electrode. Soundfield thresholds, speech recognition, and aural rehabilitation exercises are used to evaluate performance across a variety of strategies, rates, and maxima.

For the bimodal study, the participants' preferred CI program was not modified. The HA was fit to maximize audibility and be balanced in loudness with the CI based on subjective judgments and loudness growth measures. Aided loudness scaling was obtained in the bimodal study and bilateral study (Skinner et al., 1999; Potts et al., 2009). In each listening condition, the aided threshold for four-talker broadband speech babble was measured to determine a beginning input and used to calculate fifteen evenly spaced presentation levels from threshold to 80 dB SPL. These levels were presented in a randomized order. The subject responded to each presentation of speech babble by choosing the appropriate loudness category from very soft to very loud. Individual loudness judgments for each condition are shown in Table 5.

For the second CI, the strategy and rate that the recipient used with the first CI was programmed initially and then variations of rate were tried. For the participants in this study, three (1, 3, and 4) preferred the same rate and maxima as that used with the first CI. The overall T and C levels were programmed in the same manner used in the unilateral CI protocol. The bilateral fitting resulted in modifications to overall stimulation levels to obtain balanced loudness between ears based on subjective input and loudness growth measures (see Table 5). All testing was completed with programs that were worn in everyday life. There were no additional processing features active in any of the participants' preferred programs (i.e. noise suppression, adaptive dynamic range optimization, etc.). The differences in the CI programs between the first and second CIs for the individual participants are discussed below.

For Participant 1, the first and second CIs were programmed with the same strategy, rate and maxima (ACE 1800 pps/ch 8 maxima). Both devices had the two most basal electrodes deactivated. The T and C levels were slightly higher (approximately 12 CLs) for the first CI, but the dynamic ranges (DR) were equivalent. The frequency allocation was different

between processors, with the first CI having an upper boundary of 6063 Hz and the second CI having an upper boundary of 6938 Hz.

Participant 2 had notable differences between the programmed settings, with different rates and maxima (first CI 900 pps/ch 12 maxima; second CI 1800 pps/ch 8 maxima). All electrodes were active in the second CI, but the first CI had three electrodes deactivated (1, 16, and 17). Electrodes 16 and 17 were flagged as shorted at initial hook-up. The T and C levels were higher overall for the first CI (mean difference T=32 CLs; C=18 CLs). In addition, the DR was twice as wide for the second CI (mean DR first CI=25 CLs; second CI=57 CLs). The frequency allocation was different, with the first CI having an upper boundary of 6063 Hz and the second CI having an upper boundary of 6438 Hz.

Participant 3 had the first and second CI programmed with the same strategy, rate, and maxima (ACE 1800 pps/ch 8 maxima). The three most basal electrodes were deactivated in both processors. The mean T and C levels were 12 to 14 CLs lower for the second CI. The DRs were equivalent. The frequency allocation was different, with the first CI having an upper boundary of 6938 Hz and the second CI having an upper boundary of 6063 Hz.

For Participant 4, the first and second CI were programmed with the same strategy, rate, and maxima (ACE 1200 pps/ch 10 maxima). The two most basal electrodes were deactivated in the first CI and all electrodes were active in the second CI. The T and C levels were lower overall for the second CI (mean difference T=16 CLs; C=8 CLs). The DR was wider with the second CI, but both had large DRs (mean DR first CI=45 CLs; second CI=52 CLs). The frequency allocation was the same, with an upper boundary of 6938 Hz.

Soundfield Thresholds

Soundfield thresholds were obtained from 250-6000 Hz in a modified Hughson-Westlake procedure with 2 dB ascents and 4 dB descents (Carhart & Jerger, 1959). Soundfield thresholds were obtained in the bimodal phase of the study with HA, CI, and CI&HA and in the bilateral phase of the study with first CI, second CI, and CI&CI.

Speech Recognition and Sound Localization Measures

The testing methods were identical to those described in Potts et al. (2009). For both the speech recognition and localization tasks, two lists of 50 CNC words were presented randomly from loudspeakers in the array ($\pm 70^\circ$), at 60 dB SPL (± 3 dB SPL rove). The speech recognition task required the participant to repeat each word after its presentation. The localization task required the participants to state the perceived location of the stimulus (i.e. speaker number 1-15). The participants faced front (0° azimuth) prior to initiation of each trial, but were permitted to turn their head (i.e., turn toward the loudspeaker from which the word was perceived) during the trial. An equal number of words were presented from each of 10 selected positions; five of the visible loudspeakers were inactive ($\pm 60^\circ$, $\pm 40^\circ$ and 0°), but participants were not aware of this. The order of conditions was counterbalanced among participants, and lists were randomly assigned for each participant.

Questionnaires

The Speech, Spatial, Sound Qualities (SSQ) questionnaire version 3.1.1 (Gatehouse & Noble, 2004; Noble & Gatehouse, 2004) was completed at the end of each phase of the study (i.e. end of bimodal study and end of bilateral study). The participants did not have answers from their bimodal questionnaire to view when completing the bilateral CI SSQ.

Schedule

Bimodal study testing was completed after 4-6 weeks of optimized HA use. Bilateral testing was completed after 6 months of bilateral CI use. The protocols were approved by the Human Studies Committee at Washington University School of Medicine (#04-110 and #05-1052).

Data Analysis

Speech recognition scores were analyzed using a binomial model (Carney & Schlauch, 2007). The three conditions from the bimodal phase of the study (HA, CI, CI&HA) were compared to each other. The three conditions from the bilateral phase of the study (first CI, second CI, and CI&CI) were compared to each other. Finally comparisons between the bimodal and bilateral phases were compared [HA vs. second CI, first CI (bimodal phase) vs. first CI (bilateral phase), CI&HA vs. CI&CI] for each participant independently. Speech recognition scores were also analyzed with the binomial model based on the side of the loudspeaker array that presented the word (-70 to -10° vs. $+70$ to $+10^\circ$) for each listening condition and participant.

Raw data collected during the localization of speech task were analyzed by calculating root mean square (RMS) error. The RMS error is the mean deviation of the responses from the target locations, irrespective of the direction of the deviation. This analysis was used in the previous study (bimodal phase) and repeated for the current study (bilateral phase). Localization data were analyzed using a mixed random effects model where listening condition, side of presentation, and condition by side interaction were fixed effects. Also in this model, participant, participant by condition interaction, and participant by side interaction were random effects. Variance was not homogeneous among conditions and sources. The model included 12 separate covariance parameters to allow for different variance among combinations of conditions and sides. The SSQ questionnaires were analyzed with a dependent *t*-test matched-paired sample comparing responses from the bimodal phase and bilateral phase of the study for each participant independently.

Results

Aided soundfield thresholds measured during the bimodal and bilateral phases show the difference in audibility provided by the HA compared to the CI (see Figure 1). Unilateral CI soundfield thresholds (average CI thresholds across phases and ears) were notably better than the HA soundfield thresholds, especially above 1000 Hz. This is expected given the unaided thresholds in the HA ear. Soundfield thresholds in the CI&CI condition were better than unilateral CI thresholds at all frequencies tested, which is an indication of frequency-independent binaural summation. In contrast, thresholds in the CI&HA condition were only

better than the unilateral CI condition at the lowest frequencies tested, suggesting that audibility was generally similar in bimodal and unilateral CI listening. Soundfield thresholds for each participant in each condition can be found in Table 6.

Speech recognition scores in percent correct are shown in Figure 2 for each participant. This figure compares data from the bimodal testing phase (reanalyzed from Potts et al., 2009) and bilateral testing phase (current study). Note that at each testing phase, three conditions were included: two unilateral conditions and one condition with both ears stimulated. In the bimodal testing, speech recognition was significantly better in the CI and CI&HA conditions compared to the HA condition ($p<.05$) for all participants. This was not surprising, given the minimal speech recognition with the HA alone ($<6\%$). Although all participants had higher percent correct with CI&HA, this was not significantly better than unilateral CI scores.

In the bilateral testing (data from current study), there was a significant difference between the two unilateral CI conditions (first implanted vs. second implanted ears) for three of the participants. The unilateral ear that resulted in better scores varied such that the first implanted ear was better for Participants 1 and 3, the second implanted ear was better for Participant 4. The bilateral CI condition (CI&CI) was significantly better than at least one of the unilateral CIs for all participants; for Participant 3 bilateral was better than the first CI, while for Participant 4 bilateral was better than the second CI, and for Participants 1 and 2 bilateral was better than both of the unilateral CIs.

Figure 3 shows the difference in speech recognition between the bilateral testing and the previous bimodal testing (from Potts et al., 2009). Speech scores were analyzed with the binomial model as follows: second CI minus HA, CI&CI minus CI&HA; first CI in bilateral phase minus first CI in bimodal phase. All participants had a significant improvement (range 20-69%) when the HA ear transitioned to the second. This was primarily due to the poor speech recognition with the HA. Only one participant (2) had a significant improvement when listening with the first CI between test sessions. This participant had the longest time period (3 years) between bimodal and bilateral testing. Two participants (2 and 4) had a significant improvement with CI&CI compared to CI&HA. Participant 2 had significant improvements in both unilateral CIs, which most likely contributed to his CI&CI improvement. Participant 4's bilateral improvement was due to the second CI becoming the better ear.

Speech recognition data were evaluated with the binomial model based on the side of the loudspeaker array from which stimuli were presented (-70 to -10° vs. $+70$ to $+10^\circ$) to determine if the location and/or the better ear were contributing factors in speech recognition scores. There were no significant differences in speech recognition based on side of presentation for any participant in any condition.

Localization data are shown in Figure 4 for each participant, for the three conditions in the bimodal phase (left column; from Potts et al., 2009) and the three conditions in the bilateral phase (right column; from current study). The graphs show stimulus-response functions, i.e., perceived location as a function of actual source location; a diagonal line would represent perfect localization. For all participants the bilateral condition resulted in the most accurate

localization; a comparison of bimodal with bilateral listening conditions is shown in the bottom panels for each participant. Although the bimodal vs. unilateral performance had been compared in the Potts et al. (2009) study, these comparisons are conducted again here on the subset of 4 patients who participated in the bilateral transition study. Group RMS errors were significantly lower in the bimodal condition than the unilateral HA condition [$t=2.4(37)$; $p<.05$], but did not differ from the unilateral CI condition. The unilateral CI condition resulted in lower RMS errors than the unilateral HA condition [$t=2.2(35)$; $p<.05$]. In the follow-up portion of the study, with bilateral stimulation, RMS errors were significantly smaller when both CIs were used than when subjects used either only the first CI [$t=4.8(12)$; $p<.05$] or second CI [$t=5.0(17)$; $p<.05$]. There was no significant difference between first and second CI conditions.

Figure 5 shows the difference in localization between the bilateral testing and the previous bimodal testing (from Potts et al., 2009). After transitioning from bimodal to bilateral CIs subjects' localization performance improved when two CIs were used; RMS errors were significantly lower in the bilateral vs. bimodal conditions [$t=4.9(8)$; $p<.05$]. There was no significant difference between any unilateral conditions. In addition, performance with the first CI alone did not change between the bimodal and bilateral phases. Performance in the unilateral conditions comparing listening with the ear that transitioned from having a HA to having a second CI did not show a significant improvement on the localization task. This is not surprising because localization abilities are generally poor under unilateral listening conditions regardless of the mode of stimulation (e.g., Litovsky et al., 2006; Nopp, Schleich & D'Haese, 2004; Potts et al., 2009). Finally, localization RMS values were analyzed to determine whether performance differed depending on the side from which the stimuli were presented along the loudspeaker (-70 to -10° vs. $+70$ to $+10^\circ$), revealing no significant effect of direction differences for any condition.

The SSQ was completed at the end of the bimodal study and at the end of the bilateral study. The analysis of overall SSQ scores showed a significant improvement with CI&CI compared to CI&HA for all participants [P1 ($t=-4.97$); P2 ($t=-7.90$); P3 ($t=-10.05$); P4 ($t=-6.31$); ($p<.05$)]. The description of sound with CI&CI contained reports of improved localization, which was not used to portray CI&HA hearing. Participant 4, for example, reported that with CI&CI she can focus on a single voice in a crowd and hear that voice clearly.

Discussion

The purpose of this study was to examine changes in speech recognition, localization, and functional performance in four individuals who had onset of hearing loss at a young age, and who transitioned from bimodal devices (CI&HA) to bilateral CIs (CI&CI) during adulthood. The methods used here are identical to those of Potts et al. (2009) who studied a group of bimodal patients. Here, the case studies which transition from bimodal to bilateral CI allowed a unique opportunity to evaluate functional hearing resulting from stimulation to both ears, within the same individuals. One of the main goals of providing hearing to both ears is to improve performance relative to unilateral listening. Due to poor audibility and speech recognition provided from the HA, it would be reasonable to expect a smaller

improvement with bimodal than bilateral stimulation, however, this was not the case. Improvement in speech recognition was almost the same when a HA or a CI were used in the second ear. In other words, upon transitioning from bimodal to bilateral listening, the improvement from the second device relative to single-ear CI was the same. This finding is consistent with effect sizes reported previously (for review see Ching et al., 2007). Thus, speech recognition alone may not be the most appropriate tool for evaluating the potential benefits of transitioning from bimodal to bilateral listening.

A hallmark of effects that result from having stimulation in both ears is sound localization, which requires processing of information from the two ears in a coordinated fashion (Blauert, 1997; Durlach & Colburn, 1978). The extent to which binaural cues are available with CI&HA is unknown, and is an issue of great importance as the clinician is faced with determining whether patients will gain benefit from stimulation to both ears. One must consider the cues that are available from the HA and the CI. The HA typically provides low-frequency amplification in which fine-structure is preserved, while the CI discards fine-structure cues, rendering the existence of usable low-frequency ITDs non-existent. For bimodal hearing, listeners may receive fine-structure cues in the ear that uses the HA, if the stimulus is audible; in addition they receive envelope cues in the ear that uses the CI. Thus, bimodal listeners are unlikely to take advantage of classic binaural cues such as ITDs at low frequencies. Depending on the frequencies at which the HA is stimulated, it is possible that bimodal users have access to some ILDs at high frequencies; however, these cues would only be usable if the inputs to the CI and HA are temporally coordinated. It is more likely the case that ILDs are small or absent with bimodal hearing because the ear with the HA typically has profound high-frequency loss, thus only the CI ear would be stimulated at high frequencies. This may help explain why Participant 3 had the best bimodal localization, as she was the only participant receiving high-frequency input (through 4kHz) with the HA.

After transitioning from bimodal to bilateral listening, all participants showed improved sound localization. The two CI devices are not coordinated, which reduces or eliminates binaural timing difference cues (van Hoesel, 2004) that may be otherwise available from envelopes of modulated stimuli (e.g., van Hoesel, Jones, & Litovsky, 2009; Bernstein, 2001), but the range of stimulated frequencies is certainly more comparable across the two ears of a bilateral CI recipient than a bimodal recipient. Thus, the improvement is likely due to the increased availability of high-frequency ILD cues (Grantham, Ashmead, Ricketts, Labadie, & Haynes, 2007; Litovsky, Jones, Agrawal, & van Hoesel, 2010; van Hoesel, 2004).

Participants stated a strong preference for listening with two ears (CI&HA or CI&CI) compared to one ear, with the sound being described as clearer and more natural when listening with two ears. However, the improvement seen localization was reflected in higher SSQ ratings for bilateral vs. bimodal listening; this finding is similar to that of Noble et al. (2008). In addition, when participants were asked to describe their hearing with bilateral CIs all mentioned improved localization. Subjects did not provide this subjective feedback regarding bimodal listening.

Hearing and amplification history has been shown to affect unilateral CI performance (Blamey et al., 1996; Rubinstein et al., 1999), and is likely to affect bilateral CI performance. However, bilateral CI use depends on additional factors such as the remaining ability in the auditory system to integrate inputs from both ears. As was recently reported by Litovsky et al. (2010) sensitivity to the binaural cues, specifically ITDs, is significantly better in adults whose onset of deafness occurred during late-childhood or adulthood than for prelingually deafened people. The two participants (2 and 3) whose hearing loss did not become severe-profound until adulthood had better localization, while the two participants (1 and 4) with the earliest diagnosed hearing losses had poorer localization. This is consistent with other studies showing that hearing loss in early childhood may lead to poorer localization outcomes when bilateral CIs are provided during adulthood (Litovsky et al., 2009; Nopp et al., 2004). Clearly, additional research is needed in this area to determine the importance of different factors, including hearing history, electrode placement, and equipment on bilateral performance. In addition, the small number of participants in this present study makes it difficult to draw conclusions regarding effects such as early hearing history on performance. Nonetheless, because participants demonstrated some bilateral benefit when transitioning from bimodal to bilateral CIs, the likelihood is that early stimulation with HAs promotes connections within the auditory system that are important for utilization of spatial cues.

A related issue is that bilateral implantation ensures that the “better-performing” ear is always implanted. Approaches for predicting which ear will be “better” have not been firmly established. Participant 4 is an example of someone whose better ear was implanted second. Performance with the second CI surpassed that with the first CI almost immediately following activation, even though this person had 5 years of experience with the first CI. Prior to the first CI, hearing thresholds and speech recognition were similar between ears, but hearing aid history was notably different (33 years first ear compared to 16 years in the second ear). Therefore, the decision was made to implant the ear with the most HA experience. However for this CI recipient, this may not have been the best predictor for post-implantation outcome.

The variability in performance, across tasks and between participants, suggests a complex set of factors are involved in determining performance. Variability in bilateral CI performance has been noted in most studies (e.g., Ramsden et al., 2005; Senn et al., 2005). Differences in HA and CI history may provide an explanation for some of the performance differences (Müller, Schon, & Helms, 2002; Nopp et al., 2004). Some studies have suggested that a shorter time between the first and second CI may be important in obtaining the greatest benefit after activation of the second CI in adults (Ramsden et al., 2005; Senn et al., 2005) and children (Peters, Litovsky, Parkinson, & Lake, 2007). In the present study, all participants had a relatively short amount of time between the first and second CI (five years or less). However, the participant (P3) with the longest time between the first and second CIs had the best speech recognition, which is inconsistent with suggestions promoted in the aforementioned reports. Other research has shown that benefit from a second CI can extend to recipients with intervals between the two CIs longer than 15 years (e.g., Litovsky et al., 2010; Tyler et al., 2007). The issue of inter-CI interval in bilateral CI recipients is likely to

be impacted by numerous factors, including the integrity of the underlying auditory system and continuous stimulation of the ear prior to implantation.

The time needed for maximum performance to be achieved with bilateral CIs is unknown, but most likely continues to improve over time as seen with unilateral CIs (Finley et al., 2008). Litovsky et al. (2009) showed significant improvement on measures of speech understanding, including benefits arising from the use of spatial cues, when comparing performance in the same listeners at 3- and 6-months following bilateral activation. Grantham et al. (2007) showed improvement in localization after four months of bilateral CI experience, with no additional benefit measured after ten months. These differences suggest that the time required to reach an optimum level of performance with bilateral CIs may vary for speech recognition and sound localization tasks, as well as between individuals. Continued research is needed to provide greater insight into the timeline for expected effects when transitioning from bimodal to bilateral CIs.

The relation between speech recognition and localization has been suggested for many years (Hirsh, 1950) and recently supported for bilateral CI recipients (Ching et al., 2004; Litovsky et al., 2009). It may be the case that similar auditory mechanisms are involved in the two tasks, or that while the mechanisms may not be exactly the same, better-performing patients will generally achieve higher scores on most tasks. One issue that cannot be resolved from the data presented here and in previous studies that looked at speech recognition-localization relations is that comparisons are potentially more accurate when all measures are performed in either quiet or noise (Zurek, 1993). Because localization data to date exist only in quiet, this comparison remains an issue to be resolved in future work.

Finally, the decision regarding transitioning from bimodal to bilateral CI stimulation is best considered on an individual basis taking into account several factors. First, all participants subjectively reported a preference for bilateral CIs. This was despite the often small improvement objectively measured for bilateral CI compared to their bimodal performance. Clinically, an evaluation of speech recognition and localization, as well as patient reports of bimodal performance should be considered prior to implantation of the second ear. Lastly, more research needs to be completed to determine which measures or factors, such as degree of hearing loss and/or speech recognition, would suggest when a second CI should be recommended.

Future work is needed in the areas of improved fitting and/or programming of bimodal and bilateral stimulation devices. Advancements in these areas may change the benefits achieved with these devices (Blamey, Dooley, James, & Parisi, 2000; Ramsden et al., 2005; Tyler, Noble, Dunn, & Witt, 2006; Ullauri, Crofts, Wilson, & Titley, 2007; van Hoesel, 2007). Improvement in performance with either stimulation mode could result in clearer criteria for determining the best type of stimulation for an individual. Finally, evaluation of speech and localization in noise needs to be included using test procedures which mimic everyday listening situations. Performance in background noise may provide additional information for determination of the best stimulation mode for an individual.

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References

- Bernstein LR. Auditory processing of interaural timing information: New insights. *Journal of Neuroscience Research*. 2001; 66:1035–1046. [PubMed: 11746435]
- Berrettini S, Passetti S, Giannarelli M, Forli F. Benefit from bimodal hearing in a group of prelingually deafened adult cochlear implant users. *American Journal of Otolaryngology*. 2010; 31:332–338. [PubMed: 20015774]
- Blamey P, Arndt P, Bergeron F, Bredberg G, Brimacombe J, Facer G, Whitford L. Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants. *Audiology and Neurotology*. 1996; 1:293–306. [PubMed: 9390810]
- Blamey PJ, Dooley GJ, James CJ, Parisi ES. Monaural and binaural loudness measures in cochlear implant users with contralateral residual hearing. *Ear and Hearing*. 2000; 21:6–17. [PubMed: 10708069]
- Blauert, J. *Spatial Hearing*. 2nd. Cambridge, MA: MIT Press; 1997.
- Brown KD, Balkany TJ. Benefits of bilateral cochlear implantation: A review. *Current Opinion in Otolaryngology and Head and Neck Surgery*. 2007; 15:315–318. [PubMed: 17823546]
- Buss E, Pillsbury HC, Buchman CA, Pillsbury CH, Clark MS, Haynes DS, Barco AL. Multicenter U.S. bilateral MED-EL cochlear implantation study: Speech perception over the first year of use. *Ear and Hearing*. 2008; 29:20–32. [PubMed: 18091099]
- Carhart R, Jerger J. Preferred method for clinical determination of pure tone thresholds. *Journal of Speech and Hearing Disorders*. 1959; 24:330–345.
- Carney E, Schlauch RS. Critical difference table for word recognition testing derived using computer simulation. *Journal of Speech Language and Hearing Research*. 2007; 50:1203–1209.
- Ching TY, Incerti P, Hill M. Binaural benefits for adults who use hearing aids and cochlear implants in opposite ears. *Ear and Hearing*. 2004; 25:9–21. [PubMed: 14770014]
- Ching TY, van Wanrooy E, Dillon H. Binaural-bimodal fitting or bilateral implantation for managing severe to profound deafness: A review. *Trends in Amplification*. 2007; 11:161–192. [PubMed: 17709573]
- Dawson PW, Skok M, Clark PM. The effect of loudness imbalance between electrodes in cochlear implant users. *Ear and Hearing*. 1997; 18:156–165. [PubMed: 9099565]
- Dorman MF, Dahlstrom L. Speech understanding by cochlear-implant patients with different left- and right-ear electrode arrays. *Ear and Hearing*. 2004; 25:191–194. [PubMed: 15064664]
- Dunn CC, Tyler RS, Witt SA. Benefit of wearing a hearing aid on the unimplanted ear in adult users of a cochlear implant. *Journal of Speech and Language Hearing Research*. 2005; 48:668–680.
- Dunn CC, Tyler RS, Oakley S, Gantz GJ, Noble W. Comparison of speech recognition and localization performance in bilateral and unilateral cochlear implant users matched on duration of deafness and age at implantation. *Ear and Hearing*. 2008; 29:352–359. [PubMed: 18453885]
- Dunn CC, Noble W, Tyler RS, Kordus M, Gantz BJ, Ji H. Bilateral and unilateral cochlear implant users compared on speech perception in noise. *Ear and Hearing*. 2010; 31:296–298. [PubMed: 19858720]
- Durlach, N.; Colburn, H. *Binaural Phenomena*. New York: Academic Press; 1978.
- Finley CC, Holden TA, Holden LK, Whiting BR, Chole RA, Neely GJ, Skinner MW. Role of electrode placement as a contributor to variability in cochlear implant outcomes. *Otology and Neurotology : Official Publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology*. 2008; 29:920–928.

- Firszt JB, Reeder RM, Skinner MW. Restoring hearing symmetry with two cochlear implants or one cochlear implant and a contralateral hearing aid. *Journal Rehabilitation and Research Development*. 2008; 45:749–767.
- Fitzpatrick EM, Seguin C, Schramm D, Chenier J, Armstrong S. Users' experience of a cochlear implant combined with a hearing aid. *International Journal of Audiology*. 2009; 48:172–182. [PubMed: 19363718]
- Gatehouse S, Noble W. The speech, spatial, and qualities of hearing scale (SSQ). *International Journal of Audiology*. 2004; 43:85–99. [PubMed: 15035561]
- Grantham DW, Ashmead DH, Ricketts TA, Labadie RF, Haynes DS. Horizontal-plane localization of noise and speech signals by postlingually deafened adults fitted with bilateral cochlear implants. *Ear and Hearing*. 2007; 28:524–541. [PubMed: 17609614]
- Hirsh IJ. The relationship between localization and intelligibility. *Journal of the Acoustical Society of America*. 1950; 22:196–200.
- Litovsky R, Parkinson A, Arcaroli J, Sammeth C. Simultaneous bilateral cochlear implantation in adults: A multicenter clinical study. *Ear and Hearing*. 2006; 27:714–731. [PubMed: 17086081]
- Litovsky RY, Jones GL, Agrawal S, van Hoesel R. Effect of age at onset of deafness on binaural sensitivity in electric hearing in humans. *Journal of the Acoustical Society of America*. 2010; 127:400–414. [PubMed: 20058986]
- Litovsky RY, Parkinson A, Arcaroli J. Spatial hearing and speech intelligibility in bilateral cochlear implant users. *Ear and Hearing*. 2009; 30:419–431. [PubMed: 19455039]
- Lu T, Litovsky R, Zeng FG. Binaural unmasking with multiple adjacent masking electrodes in bilateral cochlear implant users. *Journal of the Acoustical Society of America*. 2011; 12:3934–3945. [PubMed: 21682415]
- Morera C, Manrique M, Ramos A, Garcia-Ibanez L, Cavalle L, Huarte A, Estrada E. Advantages of binaural hearing provided through bimodal stimulation via a cochlear implant and a conventional hearing aid: A 6-month comparative study. *Acta Oto-Laryngologica*. 2005; 125:596–606. [PubMed: 16076708]
- Müller J, Schon F, Helms J. Speech understanding in quiet and noise in bilateral users of the MED-EL COMBI 40/40+ cochlear implant system. *Ear and Hearing*. 2002; 23:198–206. [PubMed: 12072612]
- Noble W, Gatehouse S. Interaural asymmetry of hearing loss, speech, spatial, and qualities of hearing scale (SSQ) disabilities, and handicap. *International Journal of Audiology*. 2004; 43:100–114. [PubMed: 15035562]
- Noble W, Tyler R, Dunn C, Bhullar N. Unilateral and bilateral cochlear implants and the implant-plus-hearing-aid profile: Comparing self-assessed and measured abilities. *International Journal of Audiology*. 2008; 47:505–514.10.1080/14992020802070770 [PubMed: 18608531]
- Nopp P, Schleich P, D'Haese P. Sound localization in bilateral users of MED-EL COMBI 40/40+ cochlear implants. *Ear and Hearing*. 2004; 25:205–214. [PubMed: 15179112]
- Peters BR, Litovsky R, Parkinson A, Lake J. Importance of age and postimplantation experience on speech perception measures in children with sequential bilateral cochlear implants. *Otology and Neurotology* : Official Publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2007; 28:649–657.
- Peters BR, Wyss J, Manrique M. Worldwide trends in bilateral cochlear implantation. 2010; 120(Suppl 2):S17–44.
- Peterson GE, Lehiste I. Revised CNC lists for auditory tests. *Journal of Speech and Hearing Disorders*. 1962; 27:62–70. [PubMed: 14485785]
- Potts LG, Skinner MW, Litovsky RA, Strube MJ, Kuk F. 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*. 2009; 20:353–373. [PubMed: 19594084]
- Ramsden R, Greenham P, O'Driscoll M, Mawman D, Proops D, Craddock L, Pickerill M. Evaluation of bilaterally implanted adult subjects with the nucleus 24 cochlear implant system. *Otology and Neurotology*. 2005; 26:988–998. [PubMed: 16151348]

- Rubinstein JT, Gantz BJ, Parkinson WS. Management of cochlear implant infections. *American Journal of Otology*. 1999; 20:46–49. [PubMed: 9918171]
- Schafer EC, Amlani AM, Paiva D, Nozari L, Verret S. A meta-analysis to compare speech recognition in noise with bilateral cochlear implants and bimodal stimulation. *International Journal of Audiology*. 2011; 30:871–880. [PubMed: 22103439]
- Seeber BU, Baumann U, Fastl H. Localization ability with bimodal hearing aids and bilateral cochlear implants. *Journal of the Acoustical Society of America*. 2004; 116:1698–1709. [PubMed: 15478437]
- Senn P, Kompis M, Vischer M, Haeusler R. Minimum audible angle, just noticeable interaural differences and speech intelligibility with bilateral cochlear implants using clinical speech processors. *Audiology and Neurotology*. 2005; 10:342–352. [PubMed: 16103645]
- Skinner, MW.; Binzer, SM.; Potts, LG.; Holden, LK.; Aaron, RJ. Hearing rehabilitation for individuals with severe and profound hearing impairment: Hearing aids, cochlear implants, and counseling. In: Valente, M., editor. *Strategies for selecting and verifying hearing aid fittings*. 2nd. New York: Thieme; 2002.
- Skinner MW, Holden LK, Fourakis MS, Hawks JW, Holden T, Arcaroli J, Hyde M. Evaluation of equivalency in two recordings of monosyllabic words. *Journal of the American Academy of Audiology*. 2006; 17:350–366. [PubMed: 16796301]
- Skinner MW, Holden LK, Holden TA, Demorest ME. Comparison of two methods for selecting minimum stimulation levels used in programming the nucleus 22 cochlear implant. *Journal of Speech and Hearing Research*. 1999; 42:814–828.
- Summerfield A, Barton G, Toner J, McAnallen C, Proops D, Harries C, Pringle M. Self-reported benefits from successive bilateral cochlear implantation in post-lingually deafened adults: Randomized controlled trial. *International Journal of Audiology*. 2006; 45:s99–107. [PubMed: 16938781]
- Tyler RS, Dunn CC, Witt SA, Noble WG. Speech perception and localization with adults with bilateral sequential cochlear implants. *Ear and Hearing*. 2007; 28(2 Suppl):86S–90S. [PubMed: 17496655]
- Tyler RS, Noble W, Dunn C, Witt S. Some benefits and limitations of binaural cochlear implants and our ability to measure them. *International Journal of Audiology*. 2006; 45(Suppl 1):S113–119. [PubMed: 16938783]
- Tyler RS, Parkinson AJ, Wilson BS, Witt S, Preece JP, Noble W. Patients utilizing a hearing aid and a cochlear implant: Speech perception and localization. *Ear and Hearing*. 2002; 23:98–105. [PubMed: 11951854]
- Ullauri A, Crofts H, Wilson K, Titley S. Bimodal benefits of cochlear implant and hearing aid (on the non-implanted ear): A pilot study to develop a protocol and a test battery. *Cochlear Implants International*. 2007; 8:29–37. [PubMed: 17479966]
- van Hoesel RJ. Exploring the benefits of bilateral cochlear implants. *Audiology and Neurotology*. 2004; 9:234–246. [PubMed: 15205551]
- van Hoesel RJ. Sensitivity to binaural timing in bilateral cochlear implant users. *Journal of the Acoustical Society of America*. 2007; 121:2192–2206. [PubMed: 17471733]
- van Hoesel RJ, Jones GL, Litovsky RY. Interaural time-delay sensitivity in bilateral cochlear implant users: Effects of pulse rate, modulation rate, and place of stimulation. *Journal of the Association for Research in Otolaryngology : JARO*. 2009; 10:557–567. [PubMed: 19513792]
- Zurek PM. A note on onset effects in binaural hearing. *Journal of the Acoustical Society of America*. 1993; 93:1200–1201. [PubMed: 8445124]

Abbreviations

ACE	Advanced Combination Encoder
CI	Cochlear Implant
CI&HA	Cochlear Implant and Hearing Aid (bimodal hearing)

CI&CI	Bilateral Cochlear Implants
CNC	Consonant Nucleus Vowel Consonant
HA	Hearing Aid
HINT	Hearing in Noise Test
SII	Speech Intelligibility Index
SSQ	Speech, Spatial, Qualities Questionnaire

Figure 1.
Mean aided soundfield thresholds (dB HL) for the HA, unilateral CI (combined average from bimodal and bilateral phase), CI&HA, and CI&CI conditions.

Figure 2.

CNC word scores (in percent correct) for the three conditions from the bimodal phase of the study (CI, CI&HA, HA) and the three conditions from the bilateral phase of the study (first CI, CI&CI, second CI) for each of the participants in the speech recognition task. The asterisks represent a significant difference between the bimodal phase conditions and between the three bilateral phase conditions ($p < .05$).

Figure 3.

Difference in CNC word scores (in percent correct) between the bimodal and bilateral phases across conditions for each of the participants. The bars represent the difference in speech recognition scores with the second CI minus the speech recognition score with the HA; the speech recognition score with CI&CI minus the speech recognition score with CI&HA; and the speech recognition score with the first CI from the bilateral phase minus the speech recognition score with the first CI from the bimodal phase. The asterisks represent a significant difference between the bimodal phase conditions and the bilateral phase conditions ($p < .05$).

Figure 4.

Speech localization results are shown for the four participants for the bimodal phase conditions (left column) and bilateral phase conditions (right column). Within each plot, the average reported location and $\pm$ SD are shown as a function of the actual source location in degrees azimuth.

Figure 5.

Difference in RMS error (in degrees) between the bimodal and bilateral phases across conditions for each of the participants. The bars represent the differences in the localization error with the second CI minus the localization error with the HA; the localization error with CI&CI minus the localization error with CI&HA; and the localization error with the first CI from the bilateral phase minus the localization error with the first CI from the bimodal phase. Negative bars represent better performance in the bilateral phase.

Table 1

Participant demographic information and hearing loss history. The group means and standard deviations for age hearing impairment (HI) was diagnosed and became severe-profound, and time between first cochlear implant (1st CI) and second cochlear implant (2nd CI) is also included.

Participant	Gender	Age HI Diagnosed	Age HI Severe-Profound	Age 1 st CI	Yrs/Mths between 1 st and 2 nd CI	Etiology
1	M	1	1	43	3y 9m	Unknown
2	M	8	56	58	5y 3m	High Fever/ Autoimmune Disease
3	F	14	42	44	2y 0m	Genetic
4	F	5	5	38	5y 4m	Unknown
Mean		7.1	26.1	45.8		
St Dev		5.6	27.4	8.6		

Table 2

Pure tone thresholds (dB HL) for each participant in the right and left ear prior to implantation. The group means and standard deviations are also included.

Participant	Ear	250	500	750	1000	1500	2000	3000	4000	6000	8000	Hz
1	Left	105	100	105	110	120	120	120	NR	NR	NR	dB HL
	Right	95	105	105	110	120	115	NR	NR	NR	NR	dB HL
2	Left	60	75	70	80	100	115	110	120	NR	NR	dB HL
	Right	55	80	75	80	105	110	110	NR	NR	NR	dB HL
3	Left	85	85	90	95	95	100	105	100	85	90	dB HL
	Right	80	90	90	95	95	100	100	95	90	90	dB HL
4	Left	80	100	106	110	115	NR	NR	NR	NR	NR	dB HL
	Right	95	110	120	NR	NR	115	115	115	NR	NR	dB HL
Mean		81.88	93.13	95.13	97.14	107.14	110.71	110.00	107.50	87.50	90.00	
St Dev		17.31	12.52	16.99	13.50	11.13	7.87	7.07	11.90	3.54	0.00	

Table 3

Pre-operative speech recognition scores in the first (1st) CI ear and the second (2nd) CI ear, years of HA use in the first CI ear and the second CI ear prior to the first implantation, years of CI use at the time of bimodal and bilateral implant testing for the first and second CI. Means and standard deviations are also reported.

Participant	Pre-Op Sentences 1 st CI Ear (%)	Pre-Op Sentences 2 nd CI Ear (%)	Years HA Use 1 st CI Ear	Years HA Use 2 nd CI Ear	Years of CI Use 1 st CI Bimodal Testing	Years of CI Use 1 st CI Bilateral Testing	Years of CI Use 2 nd CI Bilateral Testing
1	3	3	42	42	3.5	4.5	0.5
2	15	45	29	4	2.5	5.5	0.5
3	31	52	25	28	1.5	2.5	0.5
4	DNT	45	33	16	5	5.5	0.5
Mean	20.8	36.3	23.2	25.3	3.1	4.5	0.5
St Dev	18.8	22.4	13.8	15.9	1.5	1.4	0.5

Preoperative aided sentence score at 70 dB SPL with Hearing in Noise Test (Nilsson et al. 1994) or *in italics* Central Institute for the Deaf sentences (Davis & Silverman, 1978).

Table 4

The cochlear implant array, speech processor, and MAP information for the first CI and the second CI are listed for each participant. In the bimodal testing, participants 1, 2, and 4 used the 3G processor and subsequently upgraded to the Freedom processor prior to bilateral testing.

First Cochlear Implant	P1	P2	P3	P4
Internal Array	CI24 Contour	CI24 Contour	CI24 Contour	CI24 Straight
Processor	Sprint/Freedom	3G/Freedom	3G	3G/Freedom
Strategy and Rate	ACE 1800	ACE 900	ACE 1800	ACE 1200
Maxima	8	12	8	10
Electrodes Deactivated	1, 2	1,16,17	1,2,3	1,2
Upper Freq Boundary	6063 Hz	6063 Hz	6938 Hz	6938 Hz
Mean T Current Level	152	172	132	149
Mean C Current Level	194	196	169	194
Mean Dynamic Range	42	24	37	45
Second Cochlear Implant	P1	P2	P3	P4
Internal Array	Freedom Contour	Freedom Contour	Freedom Contour	Freedom Contour
Processor	Freedom	Freedom	Freedom	Freedom
Strategy and Rate (pps/ch)	ACE 1800	ACE 1800	ACE 1800	ACE 1200
Maxima	8	8	8	10
Electrodes Deactivated	1,2	none	1,2,3	none
Upper Freq Boundary	6938 Hz	6438 Hz	6063 Hz	6938 Hz
Mean T Current Level	140	120	121	133
Mean C Current Level	182	177	156	186
Mean Dynamic Range	42	57	35	53