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Research Article

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

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Purpose: The use of bilateral stimulation is becoming common for cochlear implant (CI) recipients with either (a) a CI in one ear and a hearing aid (HA) in the nonimplanted ear (CI&HA—bimodal) or (b) CIs in both ears (CI&CI—bilateral). The objective of this study was to evaluate 4 individuals who transitioned from bimodal to bilateral stimulation.
Method: Participants had completed a larger study of bimodal hearing and subsequently received a second CI. Test procedures from the bimodal study, including roaming speech recognition, localization, and a questionnaire (the Speech, Spatial, and Qualities of Hearing Scale; Gatehouse & Noble, 2004) were repeated after 6–7 months of bilateral CI experience.
Results: Speech recognition and localization were not significantly 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 of 4 participants. Localization was significantly better for all participants with CI&CI compared with CI&HA. CI&CI performance was rated as significantly better on the Speech, Spatial, and Qualities of Hearing Scale compared with CI&HA.
Conclusions: There was a strong 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 explain performance differences.

Key Words: cochlear implant, hearing aid, speech recognition, localization, bimodal devices, bilateral cochlear implants

For years, unilateral cochlear implants (CIs) have been the standard of care in clinical practice; however, in recent years, the number of individuals using bimodal devices (a CI and a hearing aid [HA]; CI&HA; in opposite ears) or bilateral CIs (CI&CI) has grown substantially. According to a survey conducted 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). Clinicians must now be equipped to answer recipients' questions about the benefits of transitioning from bimodal devices to bilateral CIs—specifically, what type of CI and how much improvement a second CI will provide compared 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 (see, e.g., Buss et al., 2008; Litovsky,

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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 because 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 perform better on localization tasks, as well as on speech recognition in quiet and noise, compared with unilateral CI recipients (Dunn, Tyler, Oakley, Gantz, & Noble, 2008; Dunn, Tyler, Witt, Haihong, & Gantz, 2012). The improvement with binaural stimulation is generally attributable to factors such as redundant or complementary information being received at the two ears, resulting in summation of auditory information, and/or the availability of an ear with audibility regardless of the location of the target speech.

In a meta-analysis, 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, although helpful in directly comparing bimodal to bilateral CI performance, did 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, Participant 1's performance with CI&CI showed an improvement in localization but no improvement in consonant perception compared with the participant's performance with CI&HA. Participant 2's performance, however, showed no improvement with CI&CI in localization or consonant perception compared with CI&HA. It is interesting to note that both participants had a reported improvement in functional performance with CI&CI. Ching et al. concluded that the factors that determine CI&CI benefit are unknown.

Several factors have been shown to be predictive of unilateral CI performance, including number of years of deafness, amplification history, and residual hearing (Blamey et al., 1996; Finley et al., 2008; Rubinstein, Gantz, & Parkinson, 1999). In addition to these, several factors 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, unmatched 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 CIs from different manufacturers in each ear (Dorman & Dahlstrom, 2004; Tyler et al., 2007). Bilateral CI recipients can, therefore, use 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.

Last, bimodal recipients also have a complicated integration task because they have an asymmetry in hearing threshold levels, and the type of auditory input received in each ear is different (electric for CI, and acoustic for HA). There also are notable differences in signal processing between a CI and an 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 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 emphasize listening conditions that simulate an individual's real-life listening situation, in which speech recognition was evaluated with words presented from random locations and localization testing that used speech stimuli.

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

Method

Participants

The four participants in this study, who had been part of a larger study (Potts et al., 2009), received a second CI after 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: 1 year and 5 years, respectively. Both participants received an aural education at a school for the Deaf following their diagnosis and had very clear speech and normal language. Participants 2 and 3 acquired severe-to-profound hearing loss as adults.

The unaided pure-tone thresholds, prior to implantation, showed moderately severe-to-profound hearing 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 nonimplanted ear in conjunction with their first CI. The aided speech recognition for sentences prior to activation of the first CI, HA experience, and number of years of experience with the first CI at the

Table 1. Participant demographic information and hearing loss history.

Participant	Gender	Age when HI diagnosed	Age when HI severe-profound	Age at 1st CI	Time between 1st and 2nd CI (years;months)	Etiology
1	M	1	1	43	3;9	Unknown
2	M	8	56	58	5;3	High fever/autoimmune disease
3	F	14	42	44	2;0	Genetic
4	F	5	5	38	5;4	Unknown
M		7.1	26.1	45.8		
SD		5.6	27.4	8.6		

Note. HI = hearing impairment; CI = cochlear implant.

time of bimodal and bilateral testing are shown in Table 3. All participants had 6 months' experience with the second CI prior to bilateral testing. The type of implant array, strategy, rate, and maxima, as well as the type of speech processor that participants used at the time of testing, are listed in Table 4. All participants were implanted and programmed at the Washington University School of Medicine in St. Louis, Missouri. The advanced combination encoder (ACE) strategy was used by all participants.

Test Environment

Sound-field threshold, speech recognition, and localization testing was completed in a double-walled, sound-treated booth (IAC, Model 404-A, 254 × 272 × 198 cm) at a distance of 1.5 m from the loudspeaker(s). For sound-field threshold testing, a single loudspeaker was positioned at 0° azimuth (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 were spaced in increments of 10° from +70° (left) to –70° (right) at a height of 117 cm. The loudspeakers were numbered 1 (–70°) to 15 (+70°) and were 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 cutoff frequency of 20 kHz (TDT FT5), an attenuator (TDT PA4), and a power amplifier (Crown D-150).

Stimuli

Sound-field thresholds were obtained through the use of 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 consonant–vowel nucleus–consonant (CNC) words were used (Peterson & Lehiste, 1962; Skinner et al., 2006). A detailed description of the calibration is given in Potts et al.'s (2009) article.

HA Fitting and CI Programming

A Widex Senso Vita 38 was fit to all participants as part of the previous study. A detailed description of the HA processing and fitting protocol can be found in Potts et al.'s (2009) article. In brief, *in situ* threshold measurements, in four frequency bands (500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz), were used in the initial fitting. Real-ear measurements were

Table 2. Pure-tone thresholds (in dB HL) for each participant in the right and left ear prior to implantation.

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

Note. NR = no response.

Table 3. Preoperative (preop) speech recognition scores in the first CI ear and the second CI ear, years of HA use in the first CI ear and the second CI ear prior to the first implantation, and years of CI use at the time of bimodal and bilateral implant testing for the first and second CI.

Participant	Preop sentences 1st CI ear (%)	Preop sentences 2nd CI ear (%)	Years HA use 1st CI ear	Years HA use 2nd CI ear	Years of CI use 1st CI bimodal testing	Years of CI use 1st CI bilateral testing	Years of CI use 2nd 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
M	20.8	36.3	23.2	25.3	3.1	4.5	0.5
SD	18.8	22.4	13.8	15.9	1.5	1.4	0.5

Note. Table values are preoperative aided sentence scores at 70 dB SPL from Hearing in Noise Test (Nilsson, Soli, & Sullivan, 1994) or (in boldface type) Central Institute for the Deaf sentences (Davis & Silverman, 1978). DNT = did not test.

used to adjust the HA output within the participants' dynamic range for soft (55 dB SPL), medium (65 dB SPL), and loud (75 dB SPL) inputs. The HA 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, sound-field thresholds were used to maximize the audibility of soft sounds. The programming was fine-tuned to achieve these goals over 6–8 weeks.

The CI programming regimen followed in the Adult Cochlear Implant and Aural Rehabilitation Program at the Washington University School of Medicine for unilateral CIs has been detailed previously (Skinner et al., 2006; Skinner, Binzer, Potts, Holden, & Aaron, 2002; Skinner, Holden, Holden, & Demorest, 1999). CI recipients are programmed weekly for 6–8 weeks using loudness judgments and counted thresholds on every electrode. Sound-field thresholds, speech recognition, and aural rehabilitation exercises were 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 (Potts et al., 2009; Skinner et al., 1999). In each listening condition, the aided threshold for four-talker broadband speech babble was measured to determine a beginning input and was used to calculate 15 evenly spaced presentation levels from threshold to 80 dB SPL. These levels were presented in a randomized order. The participants 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.

Table 4. The CI array, speech processor, and map information for the first CI and the second CI are listed for each participant (P).

CI	P1	P2	P3	P4
First				
Internal array	CI24 contour	CI24 contour	CI24 contour	CI24 straight
Processor	Sprint/Freedom	3G/Freedom	3G	3G/Freedom
Strategy and rate (pps/ch)	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 (Hz)	6063	6063	6938	6938
Mean T current level	152	172	132	149
Mean C current level	194	196	169	194
Mean dynamic range	42	24	37	45
Second				
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 (Hz)	6938	6438	6063	6938
Mean T current level	140	120	121	133
Mean C current level	182	177	156	186
Mean dynamic range	42	57	35	53

Note. In the bimodal testing, Participants 1, 2, and 4 used the 3G processor and subsequently upgraded to the Freedom processor prior to bilateral testing. ACE = advanced combination encoder; freq. = frequency.

Table 5. Loudness judgments (in dB SPL) measured with four-talker babble for each listening condition for the bimodal device testing (top panel) and bilateral device testing (bottom panel).

Participant	Threshold	Very soft	Soft	Medium soft	Medium	Medium loud	Loud	Very loud
Bimodal device testing								
1								
HA condition	44	49	60	62	74	74		
CI condition	30	34	42	51	57	66	74	
CI&HA condition	30	35	51	51		68	71	
2								
HA condition	32	37	49	59		69	71	
CI condition	34	37	47	55	62	73	73	
CI&HA condition	32	34	42	54	70	66	77	77
3								
HA condition	32	40	53	65	73	80		
CI condition	34	37	49	64	72			
CI&HA condition	34	36	45	53	64	75		
4								
HA condition	38	40	44	52	54	67	77	
CI condition	32	34	45	47	58	68	78	
CI&HA condition	30	35	46		53	66		72
Bilateral device testing								
1								
CI2 condition	30	34	42	51	57	66	74	
CI1 condition	34	39	46	59	65	73	78	
CI&CI condition	30	35	45	53	59	68	75	
2								
CI2 condition	32	37	49	59		69	71	
CI1 condition	30	37	44	54	66	69	74	
CI&CI condition	34	38	48	55	59	67	71	76
3								
CI2 condition	36	39	48	52	58	64	68	74
CI1 condition	34	38	45	57	65	73	78	
CI&CI condition	34	36	45	53	64	75		
4								
CI2 condition	26	30	45	45	61	57	71	76
CI1 condition	30	35	48	55	62	66	76	76
CI&CI condition	26	26	34	45	55	61	67	76

For the second CI, the strategy and the rate that the recipient used with the first CI were programmed initially, and then variations of rate were tried. For the participants in this study, three (Participants 1, 3, and 4) preferred the same rate and maxima as those used with the first CI. The overall T and C levels were programmed in the same manner as that 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 1,800 pps/ch 8 maxima). Both devices had the two most basal electrodes deactivated. The T and C levels were slightly higher (approximately 12 current levels [CLs]) for the first CI, but the dynamic ranges (DRs) 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 = 1,800 pps/ch 8 maxima). All electrodes were active in the second CI, but the first CI had three electrodes deactivated (Electrodes 1, 16, and 17). Electrodes 16 and 17 were flagged as shorted at the initial hookup. The T and C levels were higher overall for the first CI ($M_{\text{difference}}$: T = 32 CLs, C = 18 CLs). In addition, the DR was twice as wide for the second CI (M_{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 1,800 pps/ch 8 maxima). The three most basal electrodes were deactivated in both processors. The mean T and C levels were 12–14 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 1,200 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 ($M_{\text{difference}}$: T = 16 CLs, C = 8 CLs). The DR was wider with the second CI, but both had large DRs (M_{DR}: first CI = 45 CLs, second CI = 52 CLs). The frequency allocation was the same, with an upper boundary of 6938 Hz.

Sound-Field Thresholds

Sound-field thresholds were obtained from 250 to 6000 Hz in a modified Hughson–Westlake procedure with 2-dB ascents and 4-dB descents (Carhart & Jerger, 1959). Sound-field 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 by 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 (± 70°) at 60 dB SPL (± 3dB SPL rove). The speech recognition task required the participants to repeat each word after its presentation. The localization task required the participants to state the perceived location of the stimulus (i.e., Loudspeaker Nos. 1–15). The participants faced front (0° azimuth) prior to initiation of each trial but were permitted to turn their heads (i.e., turn toward the loudspeaker from which the word was perceived) during the trial. An equal number of words was presented from each of 10 selected positions; five of the visible loudspeakers were inactive (± 60°, ± 40°, and 0°), but participants were not aware of this fact. The order of conditions was counterbalanced among participants, and lists were randomly assigned for each participant.

Questionnaires

The Speech, Spatial, and Qualities of Hearing Scale (SSQ), 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 the Washington University School of Medicine (Nos. 04-110 and 05-1052).

Data Analysis

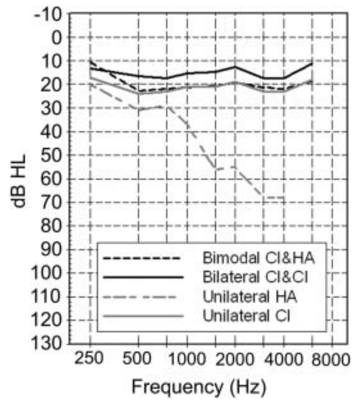
Speech recognition scores were analyzed using a binomial model (Carney & Schlauch, 2007). The three conditions from the bimodal phase of the study (HA, CI, CI&HA) were compared to each other. The three conditions from the bilateral phase of the study (first CI, second CI, and CI&CI) were compared to 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°) for each listening condition and participant.

We analyzed raw data collected during the localization of speech task by calculating the root-mean-square (RMS) error, which is the mean deviation of the responses from the target locations, irrespective of the direction of the deviation. This analysis was used in Potts et al.'s (2009) study (bimodal phase) and was repeated for the present study (bilateral phase). We analyzed localization data using a mixed random-effects model in which listening condition, side of presentation, and Condition × Side interaction were fixed effects. Also in this model, participant, the Participant × Condition interaction, and the Participant × 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. We analyzed the SSQs with a dependent t test matched-pair sample that compared responses from the bimodal phase and bilateral phase of the study for each participant independently.

Results

Aided sound-field thresholds measured during the bimodal and bilateral phases showed the difference in

Figure 1. Mean aided sound-field thresholds (dB HL) for the hearing aid (HA), unilateral cochlear implant (CI; combined average from bimodal and bilateral phase), CI&HA, and CI&CI conditions.



audibility provided by the HA compared to the CI (see Figure 1). Unilateral CI sound-field thresholds (average CI thresholds across phases and ears) were notably better than the HA sound-field thresholds, especially above 1000 Hz. This was expected, given the unaided thresholds in the HA ear. Sound-field 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 better than those in the unilateral CI condition only at the lowest frequencies tested, suggesting that audibility was generally similar in bimodal and unilateral CI listening. Sound-field thresholds for each participant in each condition can be found in Table 6.

Speech recognition scores, in the form of percentage correct, are shown in Figure 2 for each participant. In this figure, data from the bimodal testing phase (reanalyzed from Potts et al., 2009) and bilateral testing phase (the current study) are compared. Note that at each testing phase, three conditions were included: two unilateral conditions and one condition with both ears stimulated. In the bimodal testing phase, speech recognition was significantly better in the CI and CI&HA conditions than in 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 percentage-correct scores with CI&HA, this was not significantly better than unilateral CI scores.

In the bilateral testing phase (data from current study), there was a significant difference between the two unilateral CI conditions (first-implanted ear vs. second-implanted ear) 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, and 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, whereas 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.

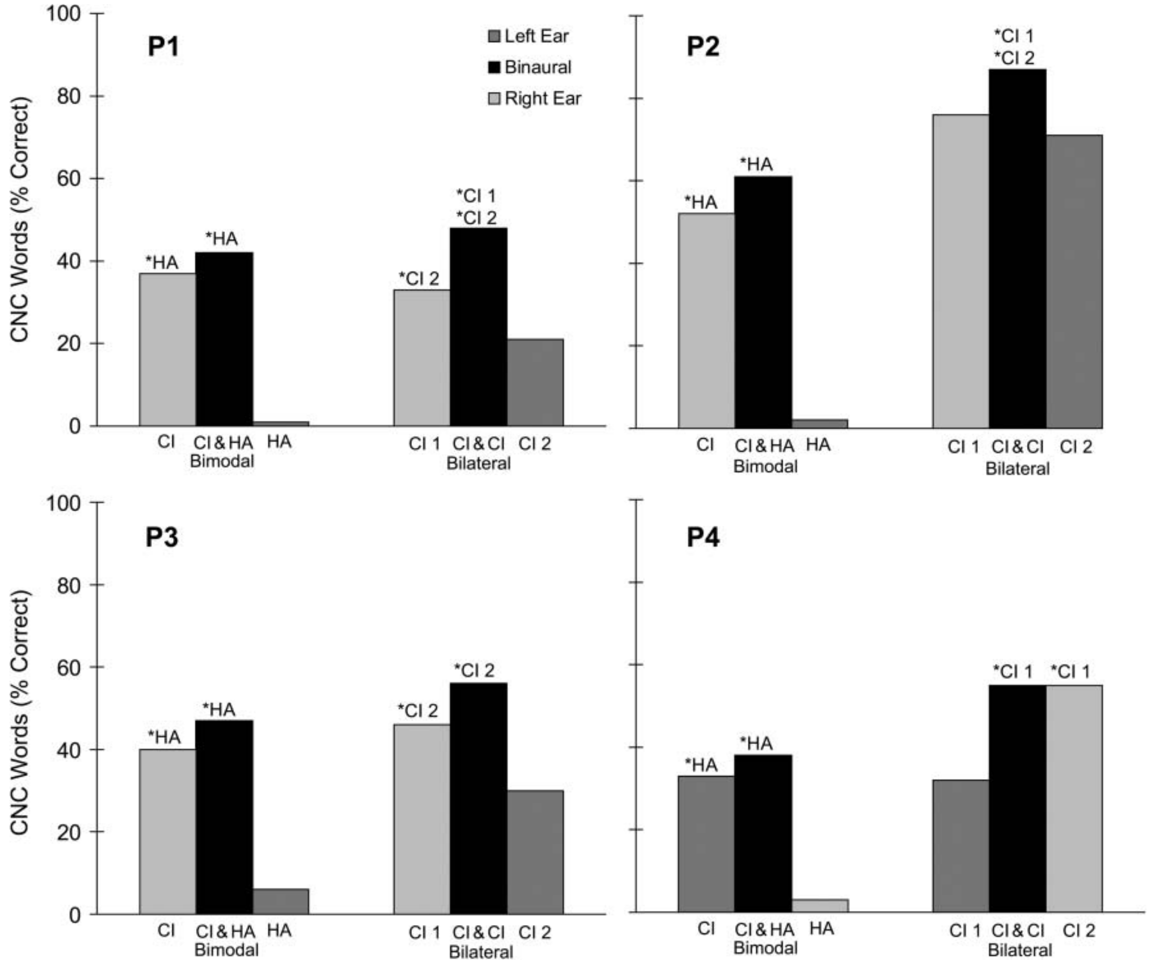
The difference in speech recognition between the bilateral testing and the previous bimodal testing (from Potts et al., 2009) is shown in Figure 3. We analyzed speech scores with the binomial model as follows: second CI minus HA,

Table 6. Sound-field thresholds (in dB HL) for each participant in each listening condition for the bimodal device testing (top panel) and bilateral device testing (bottom panel).

Participant	250	500	750	1000	1500	2000	3000	4000	6000
				Bimodal device testing					
1									
HA condition	46	38	36	40	66	66	NR	NR	NR
CI condition	16	22	24	22	22	20	22	24	14
CI&HA condition	16	22	24	22	20	20	22	24	16
2									
HA condition	8	18	16	18	70	70	NR	NR	NR
CI condition	22	26	22	26	22	22	30	26	22
CI&HA condition	10	18	14	16	22	22	28	24	22
3									
HA condition	4	26	22	34	46	44	62	68	NR
CI condition	20	26	24	22	22	18	22	22	24
CI&HA condition	6	24	22	22	22	18	20	20	22
4									
HA condition	10	28	30	36	56	54	70	NR	NR
CI condition	14	24	20	20	18	18	24	22	16
CI&HA condition	10	22	20	20	20	20	22	22	18
				Bilateral device testing					
1									
CI2 condition	14	16	18	14	18	16	18	20	16
CI1 condition	18	22	24	20	22	22	22	24	16
CI&CI condition	16	16	20	16	16	16	18	18	10
2									
CI2 condition	16	16	16	10	14	18	20	22	20
CI1 condition	18	22	22	18	16	18	18	18	12
CI&CI condition	16	16	18	12	14	18	20	18	14
3									
CI2 condition	12	18	20	18	18	16	14	22	18
CI1 condition	18	26	24	22	14	14	20	20	30
CI&CI condition	14	20	20	18	12	10	12	22	16
4									
CI2 condition	10	16	10	14	16	14	20	14	12
CI1 condition	18	18	14	14	22	20	26	18	18
CI&CI condition	10	14	12	12	16	12	22	12	8

Note. NR = not reported.

Figure 2. Consonant–vowel nucleus–consonant (CNC) word scores (in percentage 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 ($p < .05$).



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 (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 (Participants 2 and 4) had a significant improvement with CI&CI compared with 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.

We evaluated speech recognition data with the binomial model based on the side of the loudspeaker array from which stimuli were presented (–70° to –10° vs. +70° to +10°) to determine whether 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 for the three conditions in the bilateral phase (right column; from the current study). The graphs show stimulus–response functions—that is, 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 of Figure 4 for each participant. Although the bimodal-versus-unilateral performance had been compared in Potts et al.'s (2009) study, we conducted these comparisons again on the subset of four individuals who participated in the bilateral transition study. Group RMS errors were significantly lower

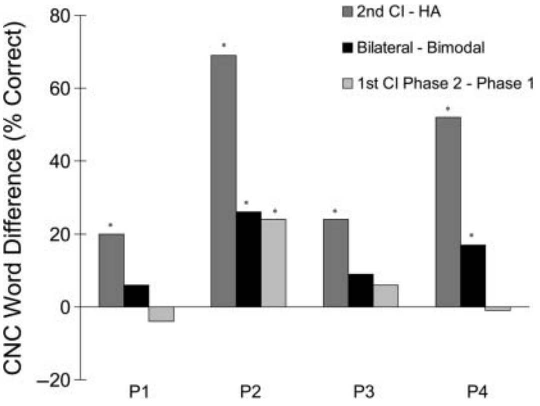


Figure 3. Difference in CNC word scores (in percentage correct) between the bimodal and bilateral phases across conditions for each of the four participants (Ps). The bars represent the difference in speech recognition scores with the second CI minus the speech recognition score with the HA ("2nd CI–HA"), the speech recognition score with CI&CI minus the speech recognition score with CI&HA ("1st CI Phase 2–Phase 1"), 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 ("Bilateral–Bimodal"). The asterisks represent a significant difference between the bimodal phase conditions and the bilateral phase conditions ($p < .05$).

in the bimodal condition than in the unilateral HA condition, $t(37) = 2.4$, $p < .05$, but did not differ from those in the unilateral CI condition. The unilateral CI condition resulted in lower RMS errors than the unilateral HA condition, $t(35) = 2.2$, $p < .05$. In the follow-up portion of the study, with bilateral stimulation, RMS errors were significantly smaller when both CIs were used than when participants used either only the first CI, $t(12) = 4.8$, $p < .05$, or the second CI, $t(17) = 5.0$, $p < .05$. 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, participants' localization performance improved when two CIs were used; RMS errors were significantly lower in the bilateral versus bimodal conditions, $t(8) = 4.9$, $p < .05$. 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, in which we compared listening with the ear that transitioned from having an 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, we analyzed localization RMS values 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°) but observed 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 with CI&HA for all participants: Participant 1, $t = –4.97$; Participant 2, $t = –7.90$; Participant 3, $t = –10.05$; Participant 4, $t = –6.31$; $p < .05$. The description of sound with CI&CI contained reports of improved localization, which was not used to portray CI&HA hearing. For example, Participant 4 reported that with CI&CI, she could 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 we used in this study are identical to those used by Potts et al. (2009), who studied a group of patients who used bimodal devices. Here, the participants who transitioned from a bimodal to a 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. Because of poor audibility and speech recognition provided from the HA, it would be reasonable to expect a smaller improvement with bimodal than with bilateral stimulation; however, this was not the case. Improvement in speech recognition was almost the same when an HA or a CI was 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 a 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 because clinicians are faced with having to determine whether patients will benefit from stimulation to both ears. One must consider the cues that are available from the HA and from the CI. The HA typically provides low-frequency amplification in which fine structure is preserved, whereas the CI discards fine-structure cues, rendering usable, low-frequency, interaural time differences (ITDs) nonexistent. 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

Figure 4. Speech localization results 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 ± *SD* are shown as a function of the actual source location in degrees azimuth. LE = left ear; RE = right ear.

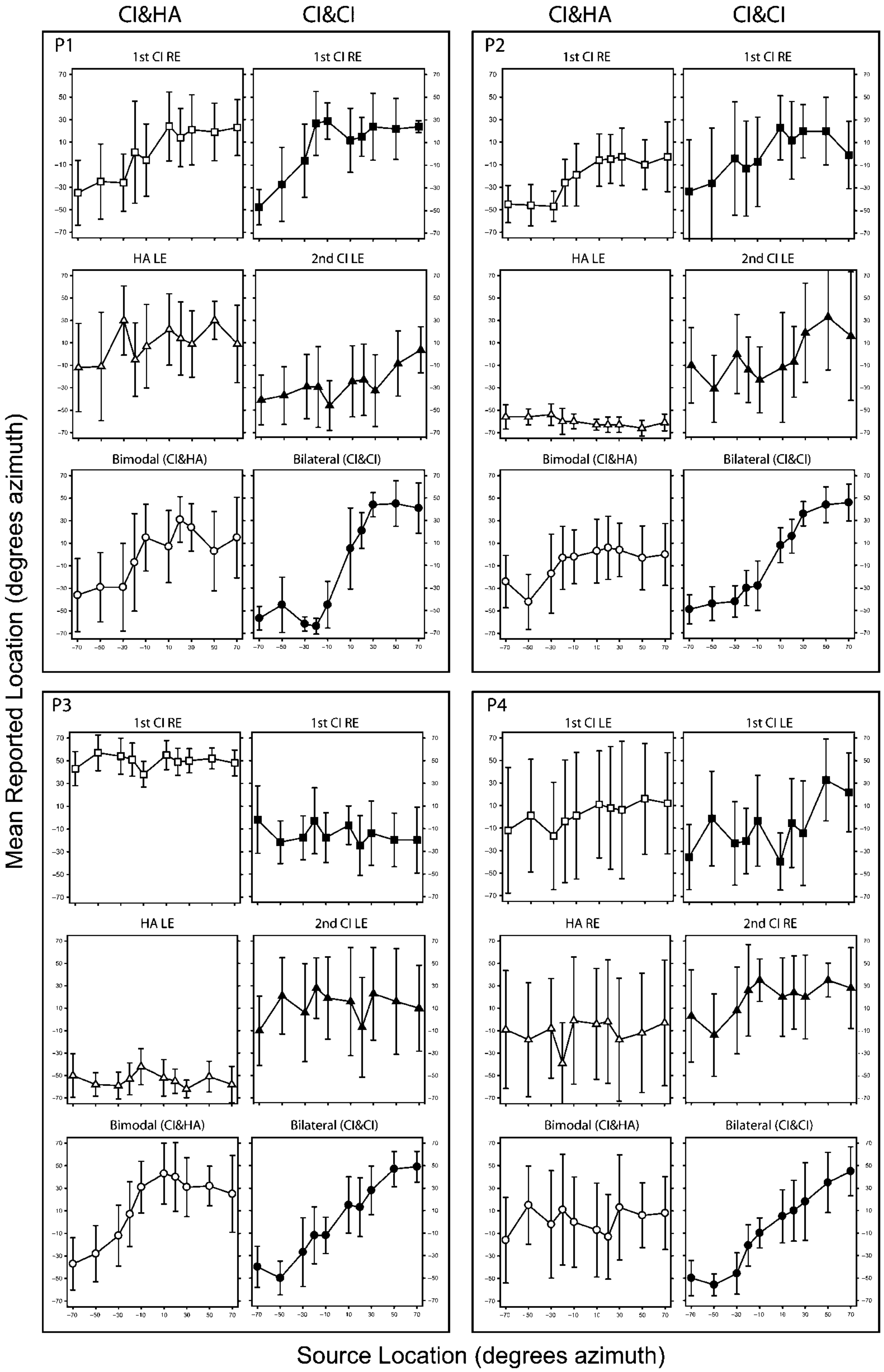
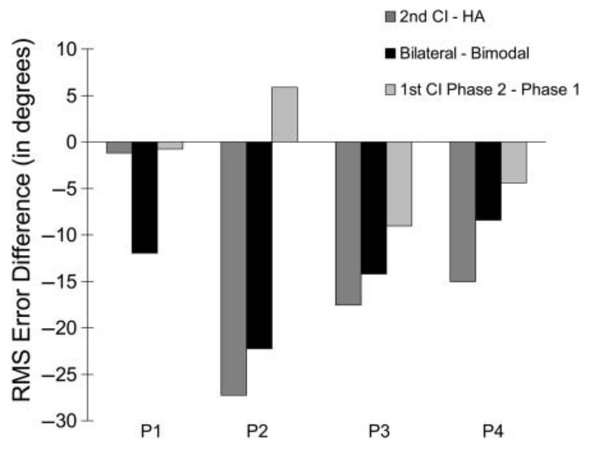


Figure 5. Difference in root-mean-square (RMS) error (in degrees) between the bimodal and bilateral phases across conditions for each of the participants. The bars represent the differences in the localization error with the second CI minus the localization error with the HA, the localization error with 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.



that bimodal users have access to some interaural level differences (ILDs) at high frequencies; however, these cues would be usable only if the inputs to the CI and HA were 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 hearing loss and, thus, only the CI ear would be stimulated at high frequencies. This may help explain why Participant 3 had the best bimodal localization because she was the only participant receiving high-frequency input (through 4 kHz) 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., Bernstein, 2001; van Hoesel, Jones, & Litovsky, 2009), but the range of stimulated frequencies is certainly more comparable across the two ears of a bilateral CI recipient than of 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 with one ear, with the sound being described as clearer and more natural when listening with two ears. However, the improvement seen in localization was reflected in higher SSQ ratings for bilateral versus 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 of them mentioned improved localization. They did not provide this subjective feedback regarding bimodal listening.

Hearing and amplification history have been shown to affect unilateral CI performance (Blamey et al., 1996; Rubinstein et al., 1999) and are 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 Litovsky et al. (2010) recently reported, sensitivity to the binaural cues—specifically, ITDs—is significantly better in adults whose onset of deafness occurred during late childhood or adulthood than for people with prelingual deafness. The two participants (Participants 2 and 3) whose hearing loss did not become severe to profound until adulthood had better localization, whereas the two participants (Participants 1 and 4) with the earliest diagnosed hearing losses had poorer localization. This finding is consistent with those of 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). Additional research is clearly 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 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, it is likely 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 HA history was notably different (33 years in the first ear compared with 16 years in the second ear). Therefore, the decision was made to implant the device into the ear that had the most HA experience; however, for this CI recipient, this may not have been the best predictor for postimplantation outcome.

The variability in performance, across tasks and between participants, suggests that a complex set of factors is involved in determining performance. Variability in bilateral CI performance has been noted in most studies (see, 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 in 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 (5 years or fewer). However, the participant (Participant 3) 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 that is longer than 15 years (see, e.g., Litovsky et al., 2010; Tyler et al., 2007). The issue of inter-CI interval in bilateral CI recipients is likely to be influenced 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 performance 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 they compared performance in the same listeners at 3 months and 6 months after bilateral activation. Grantham et al. (2007) showed improvement in localization after 4 months of bilateral CI experience, with no additional benefit measured after 10 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 has been recently supported for bilateral CI recipients (Ching et al., 2004; Litovsky et al., 2009). It may be that similar auditory mechanisms are involved in the two tasks or that, although the mechanisms may not be exactly the same, better performing individuals will generally achieve higher scores on most tasks. One issue that cannot be resolved from the data presented here and in previous studies that have 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 with their bimodal performance. In clinical milieux, an evaluation of speech recognition and localization, as well as persons' reports of bimodal performance, should be considered prior to implantation of the second ear. Last, more research is needed 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 that 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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