Spatial Hearing and Speech Intelligibility in Bilateral Cochlear Implant Users

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Objective: The abilities to localize sounds and segregate speech from interfering sounds in a complex auditory environment were studied in a group of adults who use bilateral cochlear implants. The first aim of the study was to investigate the change in speech intelligibility under bilateral and unilateral listening modes as a function of bilateral experience during the first 6 mo of activation. The second aim was to look at whether localization and speech intelligibility in the presence of interfering speech are correlated and if the relationship is specific to the bilateral listening mode. The third aim was to examine whether sound lateralization (right versus left) emerges before sound localization within a hemifield.

Design: Participants were 17 native English speaking adults with postlingual deafness. All subjects received the Nucleus 24 Contour implant in both ears, either during the same surgery or during two separate surgeries that were no more than 1 mo apart. Both devices for each subject were activated at the same time, regardless of surgical approach. Speech intelligibility was measured at 3 and 6 mo after activation. Target speech was presented at 0° in front. Testing was conducted in quiet and in the presence of four-talker babble. The babble was located on the right, on the left, or in front (colocated with the target). Sound localization abilities were measured at the 3 mo interval. All testing was conducted under three listening modes: left ear alone, right ear alone, or bilateral.

Results: On the speech-in-babble task, benefit of listening with two ears compared with one was greater when going from 3 to 6 mo of experience. This was evident when the target speech and interfering speech were spatially separated, but not when they were presented from the same location. At 3 mo postactivation of bilateral hearing, 82% of subjects demonstrated bilateral benefit when right/left discrimination was evaluated. In contrast, 47% of subjects showed a bilateral benefit when sound localization was evaluated, suggesting that directional hearing might emerge in a two-step process beginning with discrimination and converging on more fine-grained localization. The bilateral speech intelligibility scores were positively correlated with sound localization abilities, so that listeners who were better able to hear speech in babble were generally better able to identify source locations.

Conclusions: During the early stages of bilateral hearing through cochlear implants in postlingually deafened adults, there is an early emergence of spatial hearing skills. Although nearly all subjects can discriminate source locations to the right versus left, less than half are able to perform the more difficult task of identifying source locations in a multispeaker array. Benefits for speech intelligibility with one versus two implants improve with time, in particular when spatial cues are used to segregate speech and competing noise. Localization and speech-in-noise abilities in this group of patients are somewhat correlated.

INTRODUCTION

Humans spend most of their listening hours in auditory environments that are reverberant and contain multiple sound sources. The auditory system is faced with the important task of segregating target signals from competing sounds and identifying the location of sound sources. It is believed that, in normal-hearing listeners, the binaural system is highly important for providing cues that enable this to occur with fidelity (Blauert 1997). Binaural hearing results from a process by which inputs from the two ears are integrated in the auditory pathways and encoded in such a way that listeners perceive an externalized (outside the head) perceptual space. In addition, sounds are segregated into distinct images that can carry information about location and content. When listening with only one ear, sound localization becomes very difficult to achieve (Searle et al. 1976; Middlebrooks & Green 1991; Blauert 1997; Hawley et al. 1999). Binaural benefits can be large when listeners are tested on their ability to understand speech in the presence of competing sounds, particularly when the speech and interfering sounds can be perceptually separated using interaural or spatial cues (Dirks & Wilson 1969; Mac-Keith & Coles 1971; Bronkhorst & Plomp 1988; Peissig & Kollmeier 1997; Hawley et al. 1999, 2004; Culling et al. 2004). The binaural benefit is enhanced in the presence of linguistically meaningful competing sounds, suggesting a role of centrally mediated processes involved in informational masking (Freyman et al. 2001; Durlach et al. 2003; Hawley et al. 2004; Johnstone & Litovsky 2006). The role of binaural benefit in clinical populations has been a topic of considerable interest, in particular in cochlear implant (CI) users. Although CIs have clearly been successful at providing auditory inputs to deaf persons, limitations in the information they are able to provide remain, many of which arise from constraints that exist in the hardware and software of the device. When a single CI is used, one of the limitations is the ability to perceptually segregate multiple inputs associated with independent sources. This translates to difficulties in hearing speech in the presence of competing signals. Another functional limitation arises when unilateral CI users attempt to identify the location of sound sources in the environment.

In an effort to ameliorate some of these functional difficulties, several thousand patients to date (Peters 2007a) have received bilateral CIs. With regard to sound localization, a number of studies have reported improved performance resulting from the use of a second CI compared with single-CI use. Improvement occurs in discrimination of sounds located in the right versus left hemifield (Gantz et al. 2002; Tyler et al. 2002). Identifying the location of sounds emanating from within a multispeaker array generally results in smaller errors when bilateral CIs are used compared with either ear alone. However, variance within groups is high (van Hoesel & Tyler 2003; Litovsky et al. 2004; Nopp et al. 2004; Schleich et al. 2004; Verschuur et al. 2005; Grantham et al. 2007; Neuman et al. 2007). Given that the neural mechanisms coding for spatial cues require a more fine-grained analysis and differentiation between signals when sound localization versus location dis-

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crimination is to be achieved (Hancock & Delgutte 2004), it is likely that the former of these abilities would emerge before the latter. Here, we examined this issue by comparing the discrimination and localization in the same listeners.

The ability of bilateral CI users to hear speech in the presence of competing stimuli and to take advantage of spatial separation between target and competing speech has also been studied. In conditions of spatially separated speech and interferers, bilateral CI users generally score better when using both implants than when using either implant alone (van Hoesel & Clark 1997; Gantz et al. 2002; Müller et al. 2002; Tyler et al. 2002; van Hoesel et al. 2002; van Hoesel & Tyler 2003; Litovsky et al. 2006c). The magnitude and type of advantage seen across patients is not universal. Three primary advantages can be measured when comparing performance under bilateral versus unilateral listening conditions. With target speech in front and babble on the side, benefits from listening with two ears can be attained in at least two ways. First, a benefit can be measured when an ear with a better signal to noise ratio (SNR) is added, which is attributable primarily to "head shadow." Second, a benefit can arise when the ear with the poorer SNR is added, an effect that is attributable to the "binaural squelch" effect. A third effect of "binaural summation" or "redundancy" can be obtained when the target speech and the babble occur from the same direction, that is, when there are no directional cues to segregate them. In this case, redundant information at the two ears becomes helpful and can result in improved speech intelligibility.

Although most patients studied previously have demonstrated benefit from the head shadow effect, the size of effect varies from 1 to 2 dB in some subjects to over 10 dB in others (Litovsky et al. 2006c). In addition, a relatively small number of bilateral CI users show benefits that require binaural processing, such as the "squelch effect" and the binaural summation (Nopp et al. 2004; Schleich et al. 2004; van Hoesel 2004). In this study, we focused on a topic that has not been directly addressed previously: the change in performance over time seen for the three potential measures of bilateral benefit.

Change in performance with increased listening experience in persons who use CIs has been a topic of interest for many years. In children with bilateral CIs, the effect of experience on performance has been recently addressed by Litovsky et al. Experience with bilateral CIs seems to be related to improvements in sound localization acuity (Litovsky et al. 2006a) and speech understanding (Peters et al. 2007b). In a recent study with adults (Ricketts et al. 2006), the effect of experience on speech understanding in noise was evaluated at a fixed SNR in 10 bilateral CI users of the MED-EL C40+ cochlear device. Performance improved by 11 to 20% between two testing intervals: at 4 to 7 mo and at 12 to 17 mo after bilateral activation. The improvement in performance occurred for both bilateral and unilateral listening conditions, but performance under bilateral listening conditions did not seem to be better than that under unilateral listening conditions. This study focused on change in performance over time in a group of patients whose preliminary data at 3 mo after bilateral activation were briefly presented by Litovsky et al. (2004). At that time, results were not yet available from testing conducted at 6 mo postactivation. Here, we present analyses that focus on the changes that occur in speech intelligibility with additional bilateral experience and on the advantages that can be derived from using bilateral CIs. In addition, the brief nature of the study by Litovsky et al. (2004) did not permit in-depth analyses of the localization results, so only group average root mean square (RMS) error values were reported. Here, the results are more finely analyzed to enable differentiation between rudimentary localization abilities that emerge soon after bilateral activation and abilities that might require additional listening experience.

Finally, in this study, we explored the possible relationship between performance on the sound localization and speech intelligibility tasks. These spatial hearing tasks are intended to capture two functional abilities that are known to depend on, and be augmented by, auditory stimulation in both ears. Thus, one might propose that listeners who are good performers on one spatial hearing task will also be the better performers on the other task. Alternatively, it is reasonable to propose that the intersubject variability inherent to CI users will be reflected in these data so that listeners who are generally successful users of CIs will be the best performers on the tasks that are used here, whether conducted under bilateral or unilateral listening modes. These alternative views were tested by determining whether sound localization RMS errors correlated with speech intelligibility only in the binaural condition or in unilateral conditions as well.

SUBJECTS AND METHODS

Subjects

The subjects were 17 native English speaking adults with postlingual deafness who received minimal or no benefit from hearing aids preoperatively. All subjects received the Nucleus 24 Contour implant in both ears, either during the same surgery or during two separate surgeries that were no more than 1 mo apart. However, activation of both CIs took place on the same day under both surgical scenarios. The subjects were fitted bilaterally with either body-worn SPrint speech processors or ear-level ESPrit speech processors. The two speech processors were programmed bilaterally with Spectral PEAK, Advanced Combination Encoder, or Continuous Interleaved Sampling speech-processing strategies. All subjects used their bilateral CIs routinely. Table 1 includes details related to the subjects' type of processor used, reason for onset of deafness in each ear, years of amplification in each ear before implantation, sex, age, and duration of severe/profound hearing loss in each ear. The average age at implantation (shown in the summary at the bottom) was 52.7 yr. Average duration of deafness was 6.5 and 9.7 yr in the right and left ears, respectively. Etiologies include 53% unknown, 23.5% familial, and 23.5% "other." Testing was conducted for each subject while using their clinically fitted processors.

The results presented here represent data collected in the following CI centers under a multicenter clinical trial: California Ear Institute (Palo Alto, CA), Dallas Otolaryngology Associates (Dallas, TX), Ear Medical Group (San Antonio, TX), Houston Ear Research Foundation (Houston, TX), University of Texas Southwestern Medical Center (Dallas, TX), and the Listen for Life Center at Virginia Mason (Seattle, WA). Before participants were enrolled institutional review board approval was obtained at each center. Prior to initial testing, informed consent was obtained from all participants by the respective investigators located at each study center.

TABLE 1. Subject etiology

Processor	Strategy	Onset; severe to profound (left)	Onset; severe to profound (right)	Yrs. Amp (left)	Yrs. Amp (right)	Sex	Age (yr)	Duration; severe to profound (left)	Duration; severe to profound (right)
Sprint	ACE	Sudden	Progressive	None	8	M	68.4	64.00	4.00
3G	ACE	Progressive	Progressive	20	20	F	46.1	2.00	2.00
3G	SPEAK	Progressive	Progressive	20	20	F	78.7	10.00	10.00
3G	ACE	Progressive	Progressive	10	10	M	41.7	6.00	6.00
ESPrit	SPEAK	Progressive	Progressive	33	33	M	40.7	6.00	6.00
3G	ACE	Progressive	Progressive	10	10	F	33.7	10.00	10.00
SPrint	CIS	Sudden	Sudden	None	None	M	32.9	0.17	3.00
SPrint	CIS	Sudden	Sudden	7	8	F	63.9	5.00	5.00
SPrint	ACE	Sudden	Sudden	0.5	0.5	F	41.9	0.75	0.75
SPrint	ACE	Progressive	Progressive	15	15	F	32.8	15.00	15.00
3G	ACE	Progressive	Progressive	10	10	F	71.4	6.00	6.00
3G	SPEAK	Progressive	Progressive	10	10	M	32.7	7.00	7.00
ESPrit 24	SPEAK	Progressive	Progressive	15	15	F	46.2	5.00	5.00
3G	ACE	Progressive	Progressive	10	10	M	59.5	13.00	13.00
3G	ACE	Progressive	Progressive	10	10	M	71.5	8.00	8.00
3G	ACE	Progressive	Progressive	10	4	M	56.5	5.00	3.00
3G	ACE	Progressive	Progressive	10	10	F	34.2	2.00	7.00

Age at implant: 50.2 yr (15.9).
Duration of severe to profound SNHL: right ear, 6.5 yr (3.8); left ear, 9.7 yr (14.6).
Etiology: unknown, 53.0%; familial, 23.5%; all other, 23.5%.

Loudness Level Adjustment

It is well known that perceived loudness of sounds is likely to increase when listening bilaterally compared with unilaterally because of binaural summation effects. For example, van Hoesel (2004) and van Hoesel and Clark (1997) concluded that, for broadband and for single-electrode stimuli, sounds are approximately two times as loud when presented via CIs bilaterally compared with unilaterally. In typical clinical fittings, loudness settings are motivated by the need to provide each patient with comfortable listening levels, but there is a range of sound levels that could produce "comfortable" loudness reports. In an attempt to reduce substantial differences in loudness between the bilateral and unilateral conditions, for each subject, levels were selected that (1) achieved comfortable loudness in all three listening conditions and (2) produced approximately equal perceived loudness for the three conditions. This procedure has also been described by Litovsky et al. (2006c). Before testing at each interval, volume settings were adjusted to comfortable loudness for conversational speech stimuli presented from a loudspeaker in front. Participants were also asked to verbally identify whether environmental sounds, such as a door slamming or a person in the room shouting, produced any discomfort. To set the volume settings, both speech processors were initially activated together with the volume settings initially set to zero for each processor, with incremental increases until a comfortable level was reached when listening with both implants. In addition, the subject verified that sounds presented from the loudspeaker in front seemed to be spatially centered. Finally, comparisons were made by alternating stimulation between each of the unilateral programs and the bilateral stimulation, whereas further adjustments were made as needed to ensure that all three listening modes produced approximately similar loudness perception for conversational speech from the front, along with a centered percept when listening with bilateral implants.

Sound Localization

All 17 subjects participated in this set of measures, and all were tested at 3 mo (± 1 week) after bilateral CI activation. A portable testing apparatus was used to conduct testing at the various clinic sites. At each site, testing was conducted in a soundproof booth (minimum dimensions, 1.5 m $\times$ 1.5 m) with approximate reverberation times of 250 msec. The apparatus had a semicircular shape with a radius of 1 m, spanning $-70°$ azimuth (left) to $+70°$ azimuth (right). An array of eight matched loudspeakers (RCA XTS-50AV; flat frequency response between 150 and 18,000 Hz) was positioned on the apparatus. Loudspeakers were separated by $20°$ and numbered consecutively from left to right (1 to 8). In this setup, which is akin to that used by several other investigators (van Hoesel & Tyler 2003), chance performance is approximately $60°$ (calculated by assessing random localization performance on six normal-hearing listeners); this is within the range of chance performance in other studies using similar approaches ($85°$, van Hoesel 2004; $65°$, Verschuur et al. 2005; $50.5°$, Grantham et al. 2007).

Testing was performed for each subject on three listening modes: right ear alone, left ear alone, and bilateral. The order of testing with these listening modes was randomized for each subject. Stimuli were four bursts of 170 msec pink noise with 10 msec rise/fall times and interstimulus intervals of 50 msec. These stimuli have been used previously with a similar setup to test sound localization abilities in bilaterally implanted adults (van Hoesel & Tyler 2003). Stimulus presentation levels were randomly roved within a 12 dB window spanning 54 to 66 dB SPL; on each trial, the level of the four bursts was constant, and the rove occurred across trials. During each listening mode, stimuli were presented from every loudspeaker 20 times, with the order of presentation randomized. On each trial, subjects were instructed to keep their head centered by looking straight ahead and to minimize head movement. Head movement was

also visually monitored by the tester. Testing consisted of an eight-alternative forced-choice paradigm, whereby following each stimulus presentation subjects were asked to verbally identify a number corresponding to the loudspeaker emitting the signal. For this reason, the task is referred to as sound location identification, differentiating it from tasks on which subjects might report the perceived location of a sound source without being restricted to a specific set of response options. No feedback was provided.

Speech Intelligibility

Of the 17 patients, 15 participated in both the 3 and 6 mo interval testing. Because the speech data are compared for the two intervals, results are restricted to the 15 subjects with dual measures.

Speech understanding in babble noise was assessed using the Bamford-Kowal-Bench-speech in noise (BKB-SIN) test (Etymotic Research Inc. 2005). The BKB-SIN test is based on the QuickSIN test described by Killion et al. (2004). The BKB-SIN uses the BKB sentences and consists of 36 lists, paired to form 18 list pairs equated for difficulty (BKB-SIN User Manual, Etymotic Research Inc. 2005). Each list is made up of nine sentences with three to four key words per sentence presented in four-talker babble noise. The sentences are calibrated to the babble at SNRs that decrease progressively during a list of sentences in 3 dB steps from $+21$ (very easy) to -6 (extremely difficult). The SNRs used were $+21, +18, +15, +12, +9, +6, +3, +0, -3,$ and -6. Testing with each list produces a speech reception threshold (SRT) expressed in dB SNR, defined as the SNR at which performance is at 50%. For each key word that is repeated correctly, one point is given. The total number of correct words for each list is subtracted from the value 23.5 to obtain the SNR-50 (Killion et al. 2004). For each subject, performance on different conditions was deemed significantly different if the difference score was greater than 3.1 dB, the critical difference value derived from testing of the BKB-SIN test in adult CI users (BKB-SIN User Manual, Etymotic Research Inc. 2005, pp. 14–15). This critical value has been previously defined by the creators of the test as the difference between SRTs (SNR-50) estimated for two list pairs (four lists) in each condition with a 95% confidence interval.

Each participant was tested on nine conditions. There were three listening modes (right ear alone, left ear alone, and bilateral). The order of listening mode was randomized for each subject. Within each listening mode, testing was conducted with the babble coming from 1 of 3 spatial locations: 0° azimuth (babble-front), $+90°$ azimuth to the right (babble-right), or $-90°$ azimuth to the left (babble-left); the order of babble locations was quasirandomized. Target speech was presented at 65 dB SPL and was fixed at 0° azimuth. To derive SRTs for each of the nine test conditions, two list pairs (i.e., four lists) were administered without repetitions (i.e., subjects were not exposed to the same list pair more than once on the same day). As noted earlier, each subject was tested at 3 mo and at 6 mo postoperatively with the same materials repeated. The duration of time between testing was long enough to avoid improved performance resulting from subjects' memory of particular sentences.

RESULTS

Sound Localization

Figure 1 shows 3 mo localization data for all 17 subjects with the average ($\pm$SD) of the reported positions plotted as a function of actual source positions along the azimuth. Data from S1 indicate no bilateral benefit for source location identification.

Other subjects (e.g., S3 and S13) have a clear, observable improvement in response distribution under the bilateral listening mode compared with either ear alone. Also apparent from this figure is the tendency for some subjects to distribute their responses across the entire range of response options (e.g., S3, S15, S16), whereas other subjects have a tendency to compress the responses toward the more central loudspeaker locations (e.g., S6, S8, S10).

Individual listeners' data were initially analyzed to determine whether ability to lateralize sources to the correct hemifield varied with listening mode. Data were subjected to three tests whose significance values are shown in Table 2. The Kruskal-Wallis test (essentially a nonparametric one-way ANOVA) was used to estimate the significance of proportion of correct hemifield identification for each of the three listening modes (right ear, left ear, and bilateral). All subjects showed an effect of listening mode. The effects were significant at the level of $p < 0.00001$ (***) for 14 subjects, $p < 0.001$ (**) for one subject, and $p < 0.01$ (*) for two subjects. Next, performance on the two unilateral conditions was considered, and data were subjected to Barnard's unconditional exact test of superiority, which is appropriate for testing the identity of two binomials derived from categorizing two continuous distributions. Values in the middle column suggest that all but four subjects performed similarly in the left-ear and right-ear unilateral listening modes. Values in the right column show whether hemifield discrimination was better in the bilateral listening mode compared with whichever was the better of the two unilateral listening modes. These results suggest that the bilateral listening mode yielded significantly better laterality performance for 14 of 17 subjects.

Although many bilateral CI users show improved performance on right/left discrimination, the ability to identify sound location within a hemifield can be more informative and detailed regarding spatial hearing. The location identification data were further analyzed in two ways. First, for each listening mode (right ear, left ear, and bilateral) results were evaluated separately within each hemifield (stimulus from $-70°$ to $-10°$ on the left side versus $+10°$ to $+70°$ on the right side) to determine whether the responses were uniformly distributed or correlated with the stimulus locations. Spearman coefficient values and significance levels are listed in Table 2. The unilateral left-ear or right-ear listening modes yielded very few cases in which the correlation was significant. In contrast, in the bilateral listening mode, 10 of 17 and 11 of 17 subjects had significant correlation values for stimuli in the left hemifield and right hemifield, respectively. Of these, 8 of 17 had significant correlations for both hemifields, and 5 of 17 showed significant correlations for stimuli in one hemifield but not the other. These findings suggest that, at 3 mo postactivation of bilateral hearing, 82% of subjects demonstrate bilateral benefit on a simple right/left discrimination task, but only 47% have a bilateral benefit on location identification within hemifields.
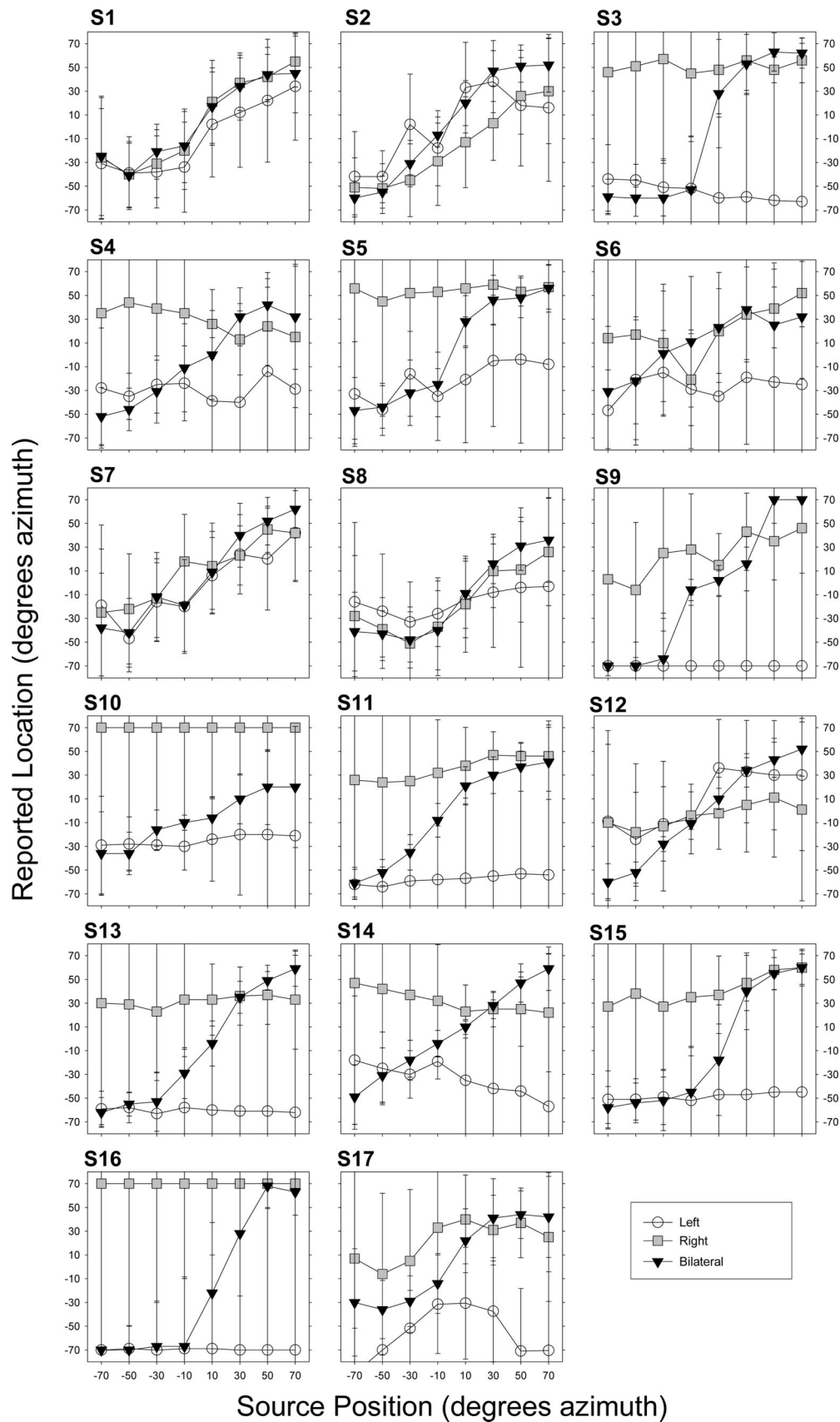
Fig. 1. Sound localization results are shown for 17 individual subjects. Data are compared for three listening modes: left ear alone, right ear alone, and bilateral. Within each plot, the average (±SD) reported location is shown as a function of the actual source position.

TABLE 2. Results from analyses conducted on the sound localization data

Left implant only		Right implant only		Bilateral implants		Summary of RMS data		
L stim	R stim	L stim	R stim	L stim	R stim			
71, −0.07	51, −0.05	68, 0.01	77, 0.39**	67, 0.13	70, .17	42	31	32
62, 0.40	61, −0.09	75, 0.01	56, 0.47***	74, 0.79***	79, 0.53***	41	33	18
80, −0.25	0, n/a	0, n/a	80, 0.14	79, 0.18	75, 0.40**	77	69	27
74, 0.15	15, 0.32	3, n/a	71, −0.16	70, 0.31*	69, 0.16	59	62	60
72, −0.05	25, 0.15	0, n/a	80, −0.06	77, 0.37**	80, 0.55***	55	71	23
62, 0.02	17, 0.46	34, −0.31	68, 0.28*	50, 0.20	64, −0.07	63	54	51
59, 0.22	62, 0.30*	43, −0.00	66, 0.32*	63, 0.23	70, 0.51***	41	38	32
59, 0.24	38, 0.70***	73, −0.19	56, 0.27	80, −0.03	69, 0.74***	55	40	27
80, n/a	0, n/a	19, 0.06	78, 0.23	76, 0.73***	72, 0.86***	84	51	20
80, −0.10	0, n/a	0, n/a	80, n/a	79, 0.76***	63, 0.41**	50	84	28
80, 0.23	0, n/a	9, n/a	78, 0.21	76, 0.83***	78, 0.52***	72	54	18
54, 0.03	62, 0.14	52, 0.30	39, 0.05	80, 0.91***	78, 0.76***	47	54	13
80, −0.02	0, n/a	2, n/a	80, 0.01	80, 0.72***	66, 0.78***	77	58	16
80, −0.08	0, n/a	0, n/a	80, 0.00	74, 0.77***	79, 0.83***	70	66	18
80, −0.01	0, n/a	2, n/a	80, 0.49***	80, 0.31*	59, 0.23	67	57	28
80, 0.07	0, n/a	0, n/a	80, n/a	80, 0.15.	59, 0.23	84	84	39
73, 0.01	53, −0.24	31, 0.27	73, −0.12	72, 0.10	78, 0.25	45	56	30

For each subject, the results from the Kruskal-Wallis and Barnard tests (nonparametric) are shown in the six left-most columns, grouped by stimulation mode (left implant only, right implant only, or bilateral), and hemifield in which stimulation was presented (left or right). Within each cell, the percent of trials with correct hemifield identification is shown alongside the coefficient value (n/a denotes cases in which there are fewer than 10 responses, because the confidence intervals on the Spearman are too wide in that case). In the three right-most columns, the RMS error values for the three listening conditions are shown for the entire array of stimulation spanning both hemifields. RMS, root mean square.
p < 0.00001 (***) for 14 subjects, p < 0.001 (**) for one subject, and p < 0.01 (*).

Second, RMS error was computed. This is a standard measure for evaluating sound localization precision across the entire array of locations including both hemifields. RMS values for each subject, in the left ear, right ear, or bilateral listening modes, are also listed in Table 2 along with the nonparametric results. RMS error was smaller in the bilateral listening mode than either of the two unilateral conditions for 13 of 17 listeners. Of the four listeners (S1, S4, S6, and S7) who did not exhibit bilateral benefit on sound localization, three had also shown no difference in the right-left hemifield discrimination; however, one subject (S4) showed a bilateral benefit in the right-left task but not in sound localization. Group average (±SD) RMS errors were 56.6° (±15.4), 60.4° (±14.9), and 28.4° (±12.5) in the right ear, left ear, and bilateral listening modes, respectively. Groupwise within-subject t tests suggest that RMS errors were significantly smaller in the bilateral mode than either of the unilateral modes ($p < 0.01$). These average values suggest that, overall, an advantage was observed for listening in the bilateral condition compared with either of the two unilateral listening conditions.

Speech Intelligibility

One of the least-studied aspects of the ability of bilateral CI users to hear speech in the presence of interferers is the effect of postimplant experience. In this investigation, each subject was tested at 3 and 6 mo after activation of the CIs; hence, this section is aimed at comparing data from the two time intervals. For each subject, bilateral benefit was deemed present if average thresholds on the bilateral condition were smaller than either ear alone by more than 3.1 dB. Figure 2 shows, for each condition tested, the number of subjects demonstrating the >3.1 dB advantage. Data are compared for the 3 and 6 mo intervals. In the babble-front condition (top panel), both target speech and babble were colocated at 0°; hence, spatial cues to differentiate the speech and babble were absent. The total

number of subjects who received a bilateral benefit on this condition (i.e., who performed better in the bilateral versus either ear alone) was 9 (60%) at 3 mo and 8 (53%) at 6 mo postbilateral activation. The number of remaining subjects who showed no benefit (none) was 6 (40%) at 3 mo and 7 (47%) at 6 mo.

Bilateral benefits emerge more clearly when results are inspected for the conditions with babble-right or babble-left (Fig. 2, middle and bottom panels, respectively). The total number of subjects with bilateral benefit was greater at 6 mo (12 to 13; 80 to 86%) compared with 3 mo (7 to 9; 46 to 60%). In contrast, the number of subjects with no benefit (none) was greater at 3 mo (6 to 8; 40 to 54%) than 6 mo (2 to 3; 14 to 20%).

In addition to the number of participants showing advantages, the magnitude of bilateral advantage across participants is shown in Figure 3, comparing bilateral and left-ear (top) or right-ear (bottom) listening conditions. Bilateral advantage for effects known as "head shadow," "summation," and "squelch" were computed for each subject on a number of conditions by subtracting SRTs obtained in the bilateral listening mode from unilateral SRTs under selected conditions (Hawley et al. 2004; Loizou et al. 2009), as is shown in Table 3. To determine whether there were effects resulting from experience, each data set was subjected to paired t tests, and the p values are indicated above each data set. The head shadow effect was significantly higher at 6 mo than at 3 mo for both right- and left-ear comparisons. The squelch effect was significantly higher at 6 mo versus 3 mo for the left-ear comparison. In contrast, the summation effect was reduced significantly at 6 mo compared with 3 mo for the right-ear comparison (no difference was found for the left-ear comparison). These data suggest that the additional listening experience may have been particularly effective for improvement on advantages that are driven by spatial information. Change in performance with
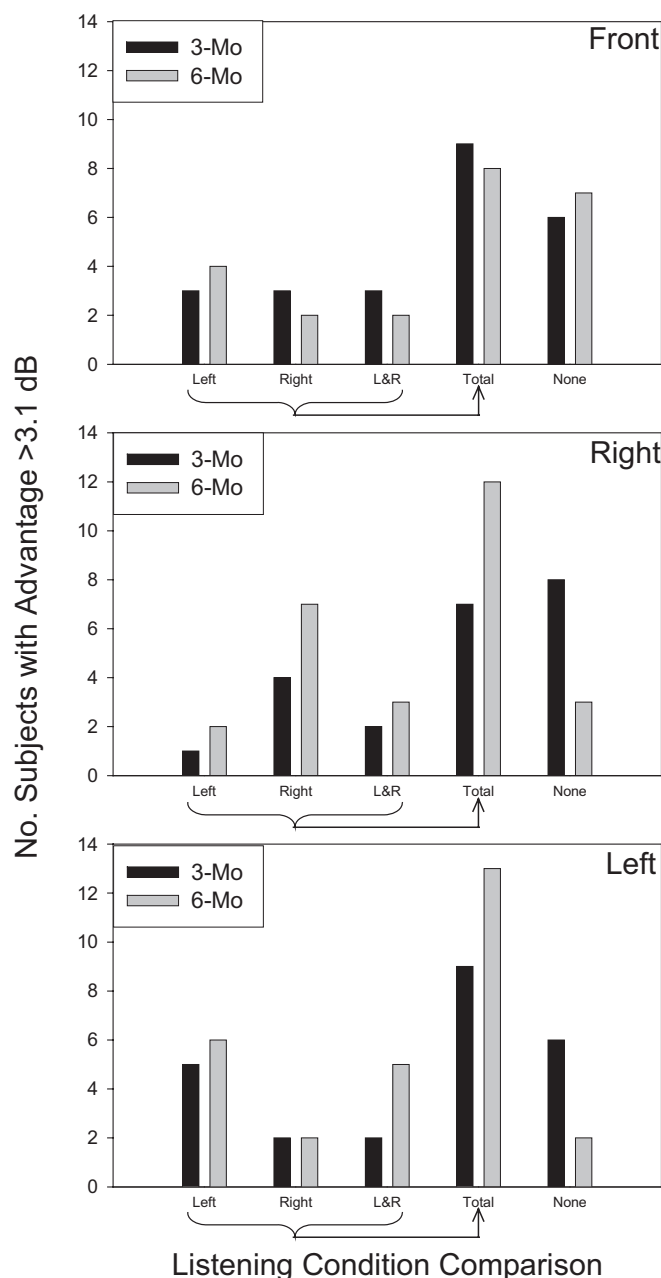
Fig. 2. Effect of listening to target speech presented from 0° in the presence of babble whose location was varied (front, left, and right) is shown for three listening conditions (bilateral, left ear, and right ear) and compared for 3 and 6 mo. Because the criterion of >3.1 was applied to all differences as a measure of significance, here the vertical bars represent the total number of subjects showing each type of benefit, as described in the text.

Fig. 3. The magnitude of bilateral advantage (mean ± SD) is compared for the 3 and 6 mo intervals. The data are categorized into the types of benefits that might occur under conditions in which listeners used both devices compared with either ear alone, including binaural summation, binaural squelch, and head shadow effects. Top and bottom panels show results for cases in which subjects used the left or right ear alone, respectively. Data for the babble locations on the right or left are collapsed for the squelch and summation effects.

time for individual participants is shown in Figure 4, where the 3 and 6 mo data are directly compared. Changes in SRTs between the two intervals are displayed so that positive values denote improvement (decreased SRT) with additional listening experience and negative values denote a decline in performance with additional listening experience. Within each panel, individuals are rank-ordered to facilitate viewing of the overall group effects for each listening condition. The dashed vertical bars within each panel demarcate between subjects for whom a measurable improvement (>3.1 dB criterion) in performance
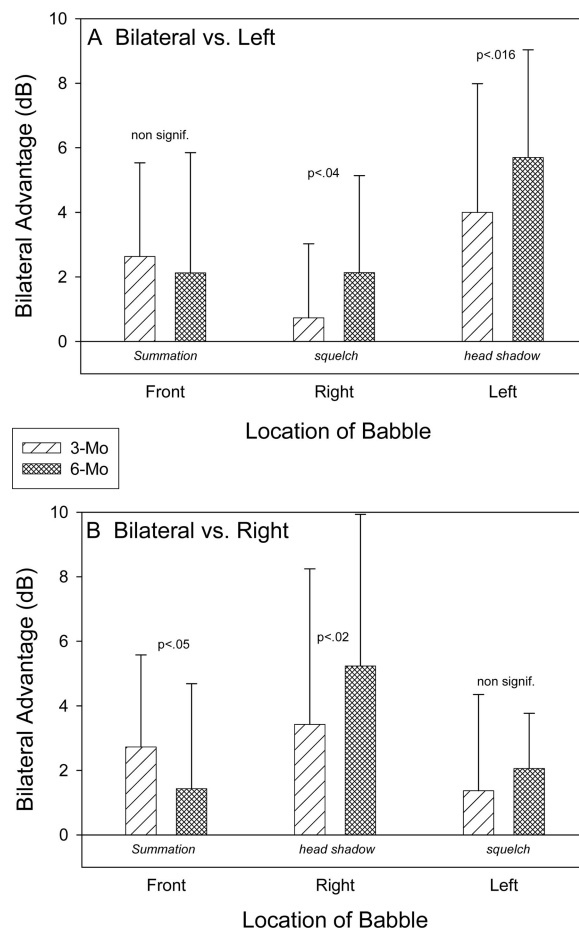
was present and subjects in whom there was no improvement after 3 additional mo of listening experience. The results shown here support the clinically relevant conventional view that additional experience using CIs leads to improved performance. An interesting issue is that performance did not improve only in the bilateral mode (right-most panels in Fig. 4). Rather, there are also substantial improvements in the unilateral (right or left) listening modes as well. A summary of

TABLE 3. Calculations made to estimate bilateral advantages based on conditions tested in this study

|		
Bilateral vs. left ear		
Summation	T, front; babble, front	Left minus bilateral
Squelch	T, front; babble, right	Left minus bilateral
Head shadow	T, front; babble, left	Left minus bilateral
Bilateral vs. right ear		
Summation	T, front; babble, front	Right minus bilateral
Squelch	T, front; babble, left	Right minus bilateral
Head shadow	T, front; babble, right	Right minus bilateral

T, Target.
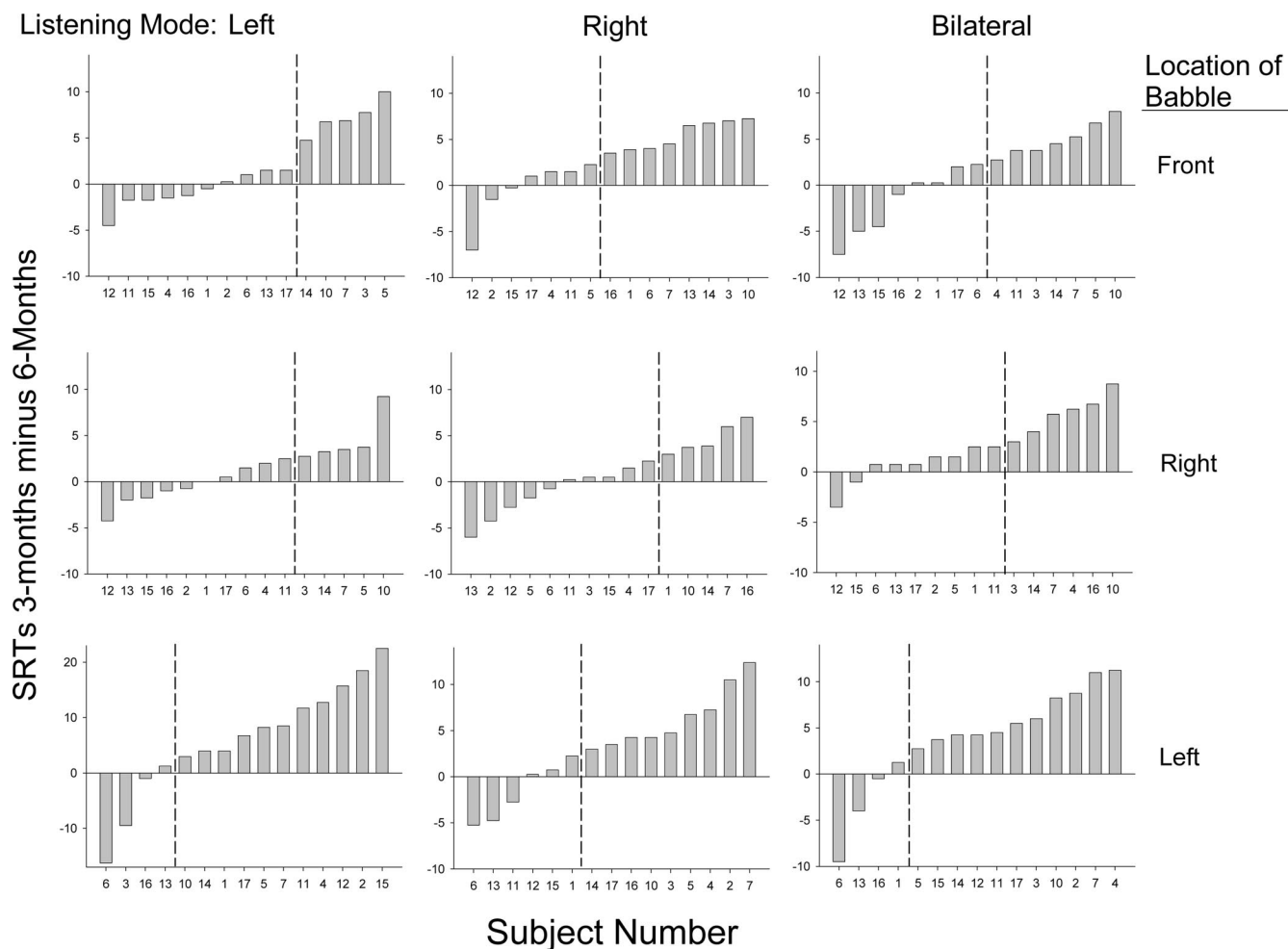
Fig. 4. Change in the SRTs for individual subjects as they transition from 3 to 6 mo of bilateral experience is plotted. The nine plots show data for the three listening modes (left ear, right ear, and bilateral) and the three spatial configurations of the babble (front, right, left). Within each panel, the absolute difference in SRT between the two time intervals is shown, with zero being unity, positive values indicating decreased SRTs over time, and negative values indicating increased SRTs over time. Bars falling to the right of the vertical dashed line in each plot indicate that the difference is greater than the 3.1 dB critical difference for statistically meaningful improved performance. In one case (bottom-left panel), the axes were altered to reflect a different range of performance.

these data is shown in Figure 5; across the nine conditions, average SRTs are higher in the 3 mo testing interval than at the 6 mo interval, indicating overall improved performance with additional listening experience. Finally, data from the location identification and speech intelligibility measures were evalu-

ated for predictive relationships using data from the 15 listeners who were tested on both tasks at the 3 mo interval. A positive correlation would suggest that listeners with poorer localization abilities (large RMS errors) had required higher SNR to reach the threshold criterion of 50% intelligibility and that listeners

Fig. 5. Data from Figure 4 are summarized to show the overall change in SRTs from the 3 mo interval to the 6 mo interval for the nine combinations of listening mode and spatial configuration of the babble. These box plots show the medians (horizontal lines), 25th and 75th interquartile ranges (gray boxes), and SDs.
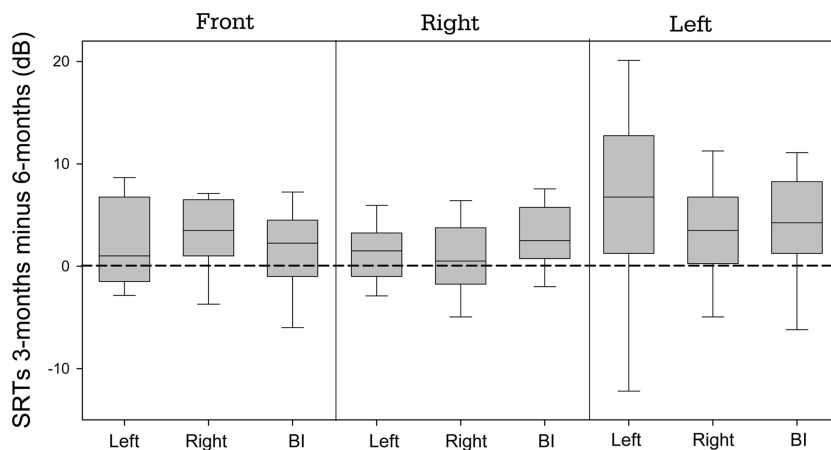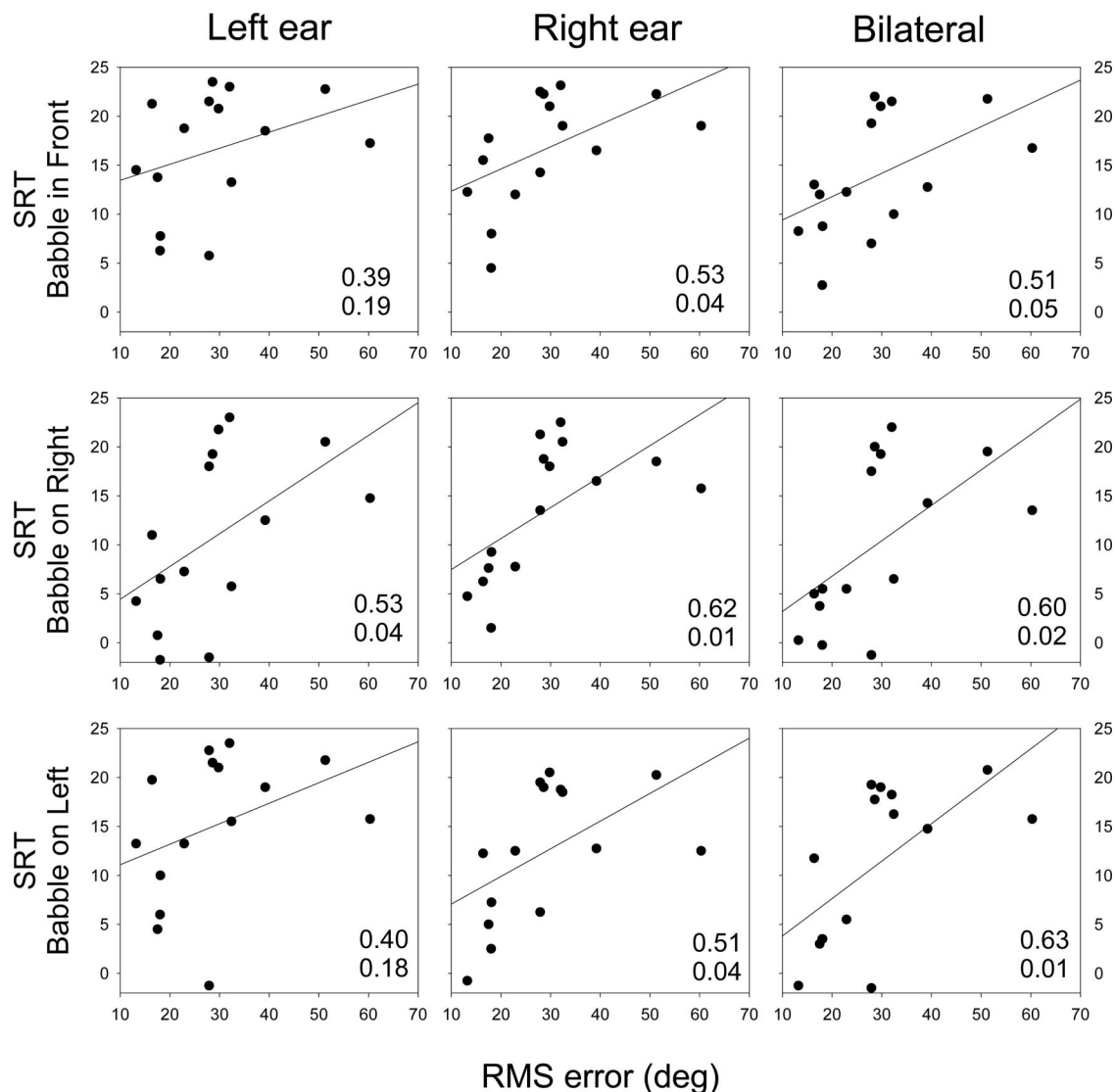
Fig. 6. Correlations between sound localization RMS data obtained when listeners used both devices (abscissa) and SRT values (ordinate). The SRT data in each panel were obtained in one of the nine conditions; left to right are the three listening modes (left ear, right ear, and bilateral) and from top to bottom are the three spatial configurations for the babble (front, right, left). Within each panel, the r (top) and p (bottom) values are shown.

whose RMS errors were lower performed better on the speech intelligibility task. Correlations were computed for RMS errors obtained in each of the three listening modes (right ear, left ear, bilateral; data in Table 2) with each of the nine conditions on which SRT data were obtained (three babble locations [babble right, babble front, or babble left] × three listening modes [right ear, left ear, and bilateral]). There were no significant correlations between SRT values and localization error when using RMS data obtained with either the left or the right unilateral listening modes; therefore, only correlations obtained with RMS data collected in the bilateral mode are reported. Figure 6 shows scatter plots from the nine conditions involving bilateral RMS data; the r and p values are indicated at the bottom-right corner of each plot. Correlations of SRTs with RMS in the bilateral listening mode yielded seven cases in which there was a statistically significant ($p < 0.05$) positive finding. Positive significant correlation values were seen not only in the three bilateral SRT conditions (panels on the right side of the graph), but also in the three right-ear SRT

conditions and one of the left-ear SRT conditions. These findings suggest that there is a relationship between localization performance and overall speech intelligibility performance but that the relationship may not be restricted strictly to bilateral speech intelligibility performance.

DISCUSSION

This study investigated outcomes from bilateral implantation in 17 adults who became deaf postlingually. The purpose of this study was to evaluate two functional abilities that are thought to benchmark benefits from having access to inputs in both ears. One of these abilities is that of understanding speech in the presence of competing multitalker babble, whose location is varied relative to the target speech. A second ability is identification of source locations in the horizontal plane. Perhaps because each of these abilities has been shown to improve when normal-hearing listeners can rely on having two ears, they are typically referred to jointly in discussions about

the benefits of binaural hearing and bilateral CIs (van Hoesel 2004; Ching et al. 2006; Litovsky et al. 2006b; Tyler et al. 2007). However, few data are available on the extent to which these abilities are mediated by the same mechanisms or are predictable from one another within a given population of listeners. The extent to which users of two CIs show benefits on measures of localization and speech intelligibility in noise merits comparison given the growing population of persons receiving a second CI. The study also aimed at examining the effects of experience on speech intelligibility after bilateral activation during the first 6 mo after activation of the CIs. From a methodologic perspective, this study also offers new approaches for evaluating change in performance on speech intelligibility measures in individual listeners.

Sound Localization

A novel finding reported in this study is that lateralization, or right-left discrimination, emerges before location identification and thus represents a rudimentary precursor to more fine-grained localization abilities. Localization data were analyzed in a way that highlighted the difference between right/left spatial hemifield discrimination and sound location identification. By 3 mo postactivation of bilateral hearing, 82% of subjects demonstrated bilateral benefit when correct hemifield identification was evaluated. In contrast, a smaller proportion of subjects (47%) showed a bilateral benefit when location identification was examined. As rudimentary localization abilities begin to emerge after bilateral activation, they are more evident when hemifield discrimination is measured. It is possible that the former measure merely requires generalized differences in activation of populations of neurons that are sensitive to stimuli arising from either the right or the left hemifield. In contrast, the latter measure may require the emergence of either a spatial map or a distinctly finer tuning of spatially sensitive neurons to particular source directions. Neurophysiological studies in the brainstem have suggested that one can model discrimination through a pooling mechanism of information across neurons. In contrast, sound localization seems to require more refined mechanisms (Hancock & Delgutte 2004). In addition, emergence of localization abilities and plasticity of neural spatial maps seem to be impacted by the auditory cortex. Evidence suggests that the cortex is particularly important when improvement on sound localization occurs with increased experience and training (King et al. 2007). The extent to which the participants who were tested here and who were unable to localize well would perform better with additional experience remains to be seen. Using the same data, evaluation of localization accuracy across all locations was also conducted, yielding average RMS errors of 28° in the bilateral condition, which is consistent with findings from other studies (van Hoesel & Tyler 2003; Nopp et al. 2004; Schoen et al. 2005; Verschuur et al. 2005; Neuman et al. 2007). In previous studies, listeners with bilateral CIs have typically had exposure to bilateral hearing for more than 6 mo (Nopp et al. 2004; Verschuur et al. 2005; Neuman et al. 2007). Grantham et al. (2007) reported data for listening with an average amount of bilateral experience of 4.5 mo; 12 subjects retested 10 mo later showed no significant improvement. Hence, the 3 mo of experience in postlingually deafened adults may be sufficient for the group as a whole to reach the range of performance reported worldwide for this population. Given the auditory deprivation experienced between the time of onset of deafness and activation of the CIs and the change from acoustic to electric hearing, participants may demonstrate additional improvement with continuing experience. Thus, a possibility that needs to be considered is that some of the listeners tested here may not have reached the level of performance that will ultimately be their best.

The fact that localization errors are significantly smaller in the bilateral listening mode compared with unilateral listening, with as little as 3 mo of experience, contrasts with recent results from children with bilateral implants, in whom sound localization abilities are generally very poor at the 3 mo interval (Litovsky et al. 2006a; Grieco-Calub et al. 2008). There are numerous factors that differentiate between the adults tested here and the children in the aforementioned studies; one of which is their preimplant histories. The vast majority of children tested in studies to date were deaf from a very young age and sequentially implanted. Their exposure to bilateral auditory input was very limited before the 3 mo testing interval. They were thus unlike the adult subjects who were postlingually deaf and had access to bilateral auditory stimulation for numerous years before becoming deaf. Postlingually deaf adults are likely to have been able to develop auditory spatial maps, which facilitated their ability to localize sounds when, after deafness, their hearing was activated with bilateral CIs. The role of early exposure to sound in both ears is an issue worthy of consideration. Grieco-Calub and Litovsky (Reference Note 1) have additionally discovered that 2-yr-old children who were bilaterally implanted by 18 mo of age begin to demonstrate spatial hearing abilities that are within the range seen in their normal-hearing peers, suggesting that early bilateral exposure may play a role in facilitating the emergence of spatial hearing skills. In fact, Nopp et al. (2004) reported that two adult subjects who were bilaterally deafened before 6 yr of age did not show a benefit in sound localization with bilateral CIs, further supporting the importance of early exposure as a determining factor. There are, of course, other variables that distinguish between the adults and children, including numerous nonauditory (cognition, memory, etc.) factors that could account for the differences discussed earlier and that merit further study. An important factor that needs to be better understood is the reason for relatively large errors on the sound localization task in the postlingually deafened adults tested here as well as by others. Even in the best performers, RMS errors are generally greater than horizontal plane errors on sound location identification tasks measured in normal-hearing adults (Hartmann 1983; Good & Gilkey 1996; Hawley et al. 1999). One possibility is that normal-hearing listeners have a very large number of frequency-specific channels for processing information across the two ears. In addition, regardless of the number of channels, frequency-specific acoustic stimulation in normal-hearing listeners is matched between the two ears. In contrast, CI users have only a finite number of electrodes distributed along the tonotopic axis of the cochlea, and the electrode placement can vary dramatically, blurring frequency-matching of bilateral implants. Furthermore, most implant speech processors do not preserve fine-structure information present in speech signals. Rather, they primarily extract and encode the envelope, or the slowly varying amplitude modulation in speech (Wilson et al. 1991). This may make it difficult to use cues for lateralizing sound based on interaural

time differences (ITDs) in the fine structure (carrier) of low-frequency sounds. However, because sound localization can also be achieved using ITDs that exist in the envelopes of high-frequency stimuli (Bernstein 2001), it may still be possible for bilateral CI users to extract ITDs in the envelope (Nuetzel & Hafter 1976; Bernstein & Trahiotis 1985). The caveat is that the cues must be preserved by the processors and presented to the listener with fidelity. Studies in which the processor has been bypassed and coordinated input to specific pairs of electrodes has been achieved suggest that some bilateral CI users have good sensitivity to both ITDs and interaural level differences (ILDs). In fact, ILD sensitivity seems to be, for many bilateral CI users, within normal limits (see van Hoesel 2004 for review). In addition, ILD cues are more likely to be preserved with greater fidelity by the CI processors, making ILDs a more likely candidate for information that is used for sound localization in free field as sounds are transmitted through the clinical processors.

The work presented here raises questions for future studies, which include examination of the extent to which coordinated input to speech processors can preserve ILDs and ITDs in a way that renders them usable on functional tasks such as those discussed here. In addition, a potentially useful area of progress can be the preservation of fine structure in the signal, which might thus preserve ITDs in the signals and potentially provide crucial localization cues.

It might be argued that most everyday tasks that require localization of sound sources can be achieved with the degree of accuracy measured in the average bilateral CI user and that this discussion is therefore most applicable to our understanding of mechanisms. What is important to note, however, is that the present work and all prior studies did not test bilateral CI users in realistic listening environments; that is, testing is typically conducted in quiet, with no background noise, with limited reverberation, and with no competing auditory objects. In normal-hearing persons, localization of sounds in reverberation is known to degrade because of both early- and late-arriving reflections causing interaural decorrelation (Hartmann 1983; Rakerd & Hartmann 1986; Shinn-Cunningham et al. 2005) and is degraded in the presence of background noise as well (Good & Gilkey 1996; Lorenzi et al 1999). Under these more strenuous and challenging situations, important benefits or limits of bilateral CIs might be revealed.

From an applied perspective, the current finding can provide some important guidelines for clinicians and implantees regarding expectations and outcomes after activation of two implants. Essentially, patients with a history similar to those studied here can expect that, during the early stages of bilateral activation, there is a high chance for them to gain benefits for general orientation in an auditory space, but the chance for having more fine-tuned localization acuity is smaller and may emerge and improve with time.

Speech Intelligibility

A striking but unsurprising aspect of the data is the range of SNR over which individual listeners reached threshold, varying from approximately 0 to >20 dB in the bilateral conditions. Variability in performance on speech intelligibility measures is rather characteristic of CI users when tested under unilateral listening conditions (Hochberg et al. 1992; Skinner et al. 1994; Zeng & Galvin 1999; Henry & Turner 2003; Stickney et al. 2004), as well as bilateral CI users (Schleich et al. 2004; Tyler et al. 2007;

Buss et al. 2008). Perhaps more interesting is the improvement in performance with 3 mo additional listening experience.

On the speech-in-babble task, 12 subjects showed improvement in the bilateral listening mode compared with either ear alone, when considering at least one spatial configuration of the babble (left, right, and front). The bilateral benefits described here were broken down according to several well-studied effects, including head shadow, which arises when an ear with a better SNR is added. A typical real-world scenario occurs, for instance, when the target speech is presented from a position in front and the interfering signal is presented from the left; listening with the left ear alone would result in masking, which can be reduced once the right ear (with better SNR) is activated as well. Similar benefits were reported in a number of prior studies (Tyler et al. 2003; Laszig et al. 2004; Schleich et al. 2004). Two of the other benefits of having two ears occur when binaural mechanisms are engaged. Binaural squelch is observed when the second ear is added on the side of the head with a poorer SNR (Middlebrooks & Green 1991; Zurek 1993), and binaural loudness summation effectively renders binaural signals more easily detectable and discriminable from noise than monaural signals (Durlach & Colburn 1978; Moore & Glasberg 2007). It was these effects in particular that seemed to increase with additional listening experience, suggesting that, in the group of participants tested here, plasticity in binaural circuitry rendered larger benefits from bilateral CIs with greater exposure to stimulation.

In one of the two conditions that allowed estimation of binaural summation, there was a decrement (or effectively no change) from 3 to 6 mo; the total number of subjects who received a bilateral benefit when the speech and babble were both in front was 9 (60%) at 3 mo and 8 (53%) at 6 mo postbilateral activation. This finding may be somewhat unusual as it has not been the focus of prior reports on this population. It may, however, be attributable to that condition being the most difficult one in that spatial cues for differentiating between target speech and babble are not available. This slight decrement, along with improvement in the other conditions, suggests that listening experience may have been particularly effective for improvement on advantages that are driven by spatial information. Additional studies are needed to establish whether spatially dependent improvements are likely to grow further with additional experience. Also noteworthy is the large standard deviation bars, suggesting that the magnitude of advantage was quite variable across subjects.

The contribution of each binaural effect to the benefits of bilateral CI stimulation is, to date, not fully understood. Research on sensitivity to interaural cues suggests that, within the small population of bilateral CI users studied, quite a few are capable of extracting interaural time and level differences within the range of normal-hearing persons (van Hoesel & Tyler 2003; van Hoesel 2004; Long et al. 2006). However, the mode of stimulation whereby coordinated input to the two ears occurs is not clinically available in today's processors.

It is noteworthy that when SRT data are considered, the additional 3 mo of experience resulted in improvements in SRTs in both unilateral and bilateral conditions, suggesting that changes in performance that occur over time are not attributable solely to bilateral stimulation. Several studies have shown that speech recognition abilities tend to improve during the first year of

experience in adults with unilateral CIs (Tyler & Summerfield 1996; Pelizzone et al. 1999; Dorman & Ketten 2003).

Finally, one of the novel findings from this study was the relationships between measures of sound localization and performance on the speech intelligibility task. Results suggest that bilateral CI users who are able to localize sounds with small errors when using both devices are also able to make generally good use of speech information in the presence of competing multitalker babble. It is worth noting that correlations of speech abilities with localization errors were found only for the RMS data obtained when two implants were used. However, the correlation values were not restricted to speech abilities when two implants were used. That is, CI users who were best able to localize sounds in the bilateral listening conditions also had the best outcomes on speech intelligibility. These findings suggest that the tasks used here may have probed for best performance under difficult conditions, rather than probing for mechanisms that are specifically driven by the binaural system. The possibility remains that, for those individuals in whom both localization performance and speech intelligibility in the bilateral conditions were good, aspects of binaural hearing were being used in ways that facilitated performance on both types of task. However, the exact binaural mechanisms involved in each task are not necessarily the same. On the speech intelligibility task, half of the binaural advantage is from the "better ear effect," in which the SNR is increased in one ear due to attenuation of the noise from the listener's head (Zurek 1993). The remaining binaural advantage requires mechanisms that enable the auditory system to integrate information from the two ears and thus relies on sensitivity to interaural timing and level cues (Bronkhorst & Plomp 1988; Blauert 1997; Hawley et al. 2004). In fact, improvement in speech intelligibility under binaural conditions has been attributed to the listener's ability to detect a change in the binaural signals provided by the target and masker (Gabriel & Colburn 1981; Durlach et al. 1986; Culling & Summerfield 1995; Culling et al. 2001). The detection of the change in similarity is called incoherence detection. What would be important to capture more rigorously is the extent to which the improvement on bilateral-driven conditions is representative of qualitative patient reports that both directional hearing abilities and ease of listening abilities are considerably better with two CIs than with a single CI (Barton et al. 2006; Litovsky et al. 2006c), and for hearing aid users who are fitted with two aids (Noble & Gatehouse 2006).

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