Simultaneous Bilateral Cochlear Implantation in Adults: A Multicenter Clinical Study

Ruth Litovsky, Aaron Parkinson, Jennifer Arcaroli, and Carol Sammeth

Objective: **To determine the efficacy of "simultaneous" bilateral cochlear implantation (both implants placed during a single surgical procedure) by comparing bilateral and unilateral implant use in a large number of adult subjects tested at multiple sites.**

Design: **Prospective study of 37 adults with postlinguistic onset of bilateral, severe to profound sensorineural hearing loss. Performance with the bilateral cochlear implants, using the same speech processor type and speech processing strategy, was compared with performance using the left implant alone and the right implant alone. Speech understanding in quiet (CNCs and HINT sentences) and in noise (BKB-SIN Test) were evaluated at several postactivation time intervals, with speech presented at 0° azimuth, and noise at either 0°, 90° right, or 90° left in the horizontal plane. APHAB questionnaire data were collected after each subject underwent a 3-wk "bilateral deprivation" period, during which they wore only the speech processor that produced the best score during unilateral testing, and also after a period of listening again with the bilateral implants.**

Results: **By 6-mo postactivation, a significant advantage for speech understanding in quiet was found in the bilateral listening mode compared with either unilateral listening modes. For speech understanding in noise, the largest and most robust bilateral benefit was when the subject was able to take advantage of the head shadow effect; i.e., results were significantly better for bilateral listening compared with the unilateral condition when the ear opposite to the side of the noise was added to create the bilateral condition. This bilateral benefit was seen on at least one of the two unilateral ear comparisons for nearly all (32/34) subjects. Bilateral benefit was also found for a few subjects in spatial configurations that evaluated binaural redundancy and binaural squelch effects. A subgroup of subjects who had asymmetrical unilateral implant performances were, overall, similar in performance to subjects with symmetrical hearing. The questionnaire data indicated that bilateral users perceive their own performance to be better with bilateral cochlear implants than when using a single device.**

Conclusions: **Findings with a large patient group are in agreement with previous reports on smaller groups, showing that, overall, bilateral implantation offers the majority of patients advantages when listening in simulated adverse conditions.**

(Ear & Hearing 2006;27;714–731)

University of Wisconsin, Madison, Wisconsin (R.L.); Cochlear Americas, Englewood, Colorado (A.P., J.A.); University of Colorado, Boulder, Colorado (C.S.).

Persons with bilateral severe to profound sensorineural hearing loss have traditionally received a single cochlear implant. To date, health care professionals have recommended unilateral, rather than bilateral, cochlear implant fittings for these patients for several reasons, including: 1) cost/reimbursement issues, 2) preservation of one ear for future technologies, 3) additional risk of two, or extended, surgeries, and 4) lack of sufficient objective and/or subjective evidence documenting bilateral cochlear implant benefit. Although unilateral use of cochlear implants has been quite successful in providing reasonably good speech understanding in quiet, adult users often experience increased difficulty understanding speech in a noisy environment (e.g., Fetterman & Domico, 2002; Firszt, Holden, Skinner, et al., 2004), and they are placed at a distinct disadvantage when sound is coming from the direction of their nonimplanted ear.

Normal-hearing persons are known to benefit substantially from binaural hearing when listening to speech in noisy environments. When both ears are functional, speech intelligibility in noise can improve dramatically compared with unilateral listening. Many complex factors contribute to the ability to separate speech signals from background noise including signal and masker characteristics, and degree of hearing impairment (for a review, see Bronkhorst, 2000). There are, however, three specific components of bilateral hearing that are known to potentially contribute to an advantage (see Durlach & Colburn, 1978; Dillon, 2001). The first component of bilateral hearing is related to the physical "head shadow effect." When speech and competing noise are spatially separated, the signal-to-noise ratio (SNR) at each ear is disparate due to differential filtering of sounds (primarily high frequency) by the physical presence of the head. If both ears are functional the listener can selectively attend to the ear with the most favorable SNR (i.e., the ear opposite to the noise source) to maximize speech recognition performance (as compared with the un-

0196/0202/06/2706-0714/0 • Ear & Hearing • Copyright © 2006 by Lippincott Williams & Wilkins • Printed in the U.S.A.

favorable situation where only the ear with the poorer SNR is functional).

Another component of bilateral hearing is commonly called the "binaural squelch effect" (or "binaural unmasking"). If there is functional input from both ears, the auditory system potentially can combine the information to form a better central representation than that available with only monaural input. This occurs when inter-aural timing and intensity cues arise under conditions of spatial separation of signal and noise. These binaural cues are utilized in centrally-mediated source segregation mechanisms that can significantly improve speech understanding.

A third component of bilateral hearing, known as "binaural redundancy" or "summation" is thought to occur when speech and noise originate from the same location. Binaural redundancy refers to the auditory system's ability to centrally combine and derive benefit from duplicate representations of the same signal to the two ears. Hearing threshold is known to improve for binaural versus monaural presentation to normal ears, resulting in increased perceptual loudness.

For many years, research on binaural hearing focused on the investigation of bilateral versus unilateral hearing aid use (e.g., Carhart, 1958, Byrne & Dermody, 1975; Byrne, 1981; Schreurs & Olsen, 1985). This research has shown that, to a large extent, the bilateral advantages that exist for individuals with normal hearing also exist for bilateral hearing aid users, even those with severe hearing impairments (e.g., Day, Browning, & Gatehouse, 1988). As a result, clinical fitting of bilateral hearing aids has become the standard in recent years.

Bilateral advantages in persons wearing a hearing aid on the ear contralateral to a unilateral cochlear implant have also been investigated in adults (e.g., Armstrong, Pegg, James, et al., 1997; Ching, Psarros, Hill, et al., 2001; Tyler, Parkinson, Wilson, et al., 2002a; Ching, Incerti, & Hill, 2004; Iwaki, Matsushiro, Mah et al., 2004; Laszig, Aschendorff, Stecker, et al., 2004; Senn, Kompis, Vischer, et al., 2005) and children (Litovsky, Johnstone, Godar, et al., 2006a; 2006b). Bilateral advantages generally occur for persons whose residual hearing in the nonimplanted ear is sufficient to result in benefit from amplification. However, many cochlear implant users have little or no usable hearing in the nonimplanted ear and therefore cannot benefit from even the most high powered hearing aid on the contralateral ear. Thus, interest in bilateral cochlear implantation for persons with bilateral severe to profound hearing loss has been steadily growing over the last decade.

A number of studies have now examined speech recognition ability of adults using bilateral cochlear implants (Green, Mills, Bell et al., 1992; Lawson, Wilson, Zerbi, et al., 1998; Mawman, Ramsden, Saeed, et al., 2000; Müller, Schön, & Helms, 2002; Schön, Müller, & Helms, 2002; Gantz, Tyler, Rubinstein et al., 2002; Tyler, Gantz, Rubenstein et al., 2002b; Au, Hui, & Wei, 2003; van Hoesel & Tyler, 2003; Dorman & Dahlstrom, 2004), and fewer studies have reported on pediatric bilateral cochlear implant use (Litovsky et al., 2006a; 2006b; Vermeire, Brokx, Van de Heyning, et al., 2002; Kuhn-Inacker, Shehata-Deiler, Müller, et al., 2004). Some of these reports were only single case studies, however, and most evaluated only a small group of subjects, partly because bilateral cochlear implantation has remained relatively sparse. A recent study (Schleich, Nopp & D'Haese, 2004) on 18 German-speaking adults who received bilateral Med-El Combi 40/40+ cochlear implants showed significant bilateral benefits in speech understanding scores across a number of measures. Litovsky et al. (2004) evaluated 17 adults who had been implanted bilaterally with Nucleus 24 cochlear implants, and found a significant bilateral advantage for speech-in-noise testing when noise was presented nearer to the poorer ear, but not when it was presented to the better ear. In general, results across the studies to date have indicated that bilateral cochlear implants provide benefit for understanding speech in noise for many subjects under certain listening conditions, but direct comparison across studies is made difficult by differences in subjects, stimuli, and methodologies used.

Subjects using bilateral cochlear implants have also been found to have significantly improved abilities to identify source locations (directionality or localization ability) compared with unilateral implant use (Gantz et al., 2002; van Hoesel, Ramsden, & O'Driscoll, 2002; van Hoesel & Tyler, 2003; Litovsky et al., 2004; Schleich, Nopp & D'Haese, 2004). In addition, anecdotal reports have indicated that most subjects prefer wearing both implants and report improved sound clarity and/or quality for bilateral compared with unilateral implant use (Green et al., 1992; Mawman et al., 2000; Gantz et al., 2002). To our knowledge, however, subjective data have not been collected using a structured questionnaire approach with substantial numbers of bilateral cochlear implant users.

This report is the largest-scale study to date comparing bilateral and unilateral Nucleus 24 cochlear implant use. This multi-site investigation evaluated a large number of adult subjects who received both of their cochlear implants during a single surgery, an approach commonly referred to as "simultaneous implantation" (as opposed to "sequential implantation", whereby implantation of the two ears occurs at different times, often months or years apart). Simultaneous implantation offers an important experimental control, whereby both ears adjust to the new form of sound processing over the same time period, along with any ability to process sounds arriving from the two ears. In this study, speech understanding was evaluated in quiet and in the presence of competing speech babble-noise. Speech babble-noise was selected to simulate aspects of difficult listening situations such as those identified in Cherry's classic exposition of the "cocktail party problem" (Cherry, 1953; see also Bronkhorst, 2000; Hawley, Litovsky, & Culling, 2004). In addition, formal questionnaire responses were used to evaluate the subjects' perception of their real world performance with bilateral implants versus their performance when using only their best-performing unilateral implant.

TABLE 1. Demographic data for the 37 subjects in this study

	Mean	SD	Range
Age at implant (yr):	53.6	15.3	26.6–86.8
Duration of severe to profound hearing loss (yr):			
• Right Ears	5.5	3.9	1 mo–15 yr
• Left Ears	5.6	4.0	1 mo–15 yr
Gender:	No. of subjects		
• Male subjects	14		
• Female subjects	23		
Etiology*:	No. of subjects		
• Unknown	22		
• Familial/genetic	8		
• Other	3		
• Meniere's disease	1		
• Meningitis	1		
• Noise exposure	1		
• Ototoxic drugs	1		

** Etiology was the same for the right and left ear of each subject.*

MATERIALS AND METHODS

Subjects

Thirty-seven adults with postlinguistic onset of bilateral, severe to profound sensorineural hearing loss (most hearing thresholds from about 70 dB HL to "no response") were enrolled in this study across 11 U.S. investigational sites, all of which were well-known cochlear implant centers with experienced clinical teams. All subjects were aged 18 yr or older and had no more than 15 yr of severe to profound hearing loss. They also were required to have ≤50% open-set sentence recognition using HINT sentences in the best-aided condition (consistent with currently approved criteria for unilateral cochlear implantation). None of the subjects had prior cochlear implantation but all had tried conventional hearing aids.

Demographic information on the subjects is presented in Table 1. There was a broad age range at implantation, and also a broad range of durations of the severe to profound degree of hearing loss. Sixty-two percent of the subjects were female. Etiology of the hearing loss was usually reported as "unknown".

Implant and External Equipment

All subjects were implanted bilaterally with Nucleus® 24 Contour™ cochlear implants (Cochlear Ltd., Sydney, Australia), which consist of an array of 22 half-banded intracochlear electrodes molded into a preformed shape that follows the curve of the cochlea. A stylet keeps the electrode array straight during insertion. Once the stylet is withdrawn, the array assumes its natural curved shape within the cochlea. The implant also consists of two extracochlear reference electrodes: one is on the body of the receiver/stimulator, and the other is a ball electrode on a separate lead that is placed under the temporalis muscle.

Subjects were fitted with either bilateral body-worn SPrint™ speech processors or bilateral ear-level ESPrit™ speech processors. Speech processors were programmed using standard clinical procedures with either the SPEAK (Spectral PEAK), ACE™ (Advanced Combination Encoder), or CIS (Continuous Interleaved Sampling; Wilson, Finley, Lawson, et al., 1991) speech-processing strategies. The choice of speech processor type and processing strategy was determined via patient preference and cochlear implant team decision, but in all cases both speech processors for a given subject were of the same type and were programmed with the same strategy. Table 2 summarizes the speech processor types and speech processing parameters used by the subjects for whom complete data are presented here.

TABLE 2. Speech processor types, strategies, and parameters at 6-mo postactivation for the 34 subjects with complete 6-mo data. For a given subject, these were the same for both the right and left ear implants

Speech processor type	Strategy	Rate per channel	Maxima	No. of subjects
SPrint™	ACE	900	8	6
		900	10	2
		900	12	1
		1200	12	1
	CIS	900	12	1
		1800	8	1
ESPrit™ 3G	SPEAK	250	8	2
		250	10	1
	ACE	900	8	9
		900	10	3
		900	12	4
		1200	8	1
ESPrit™ 24	SPEAK	250	8	2

Test Procedures

Clinicians at each site were carefully trained on the procedures by the same investigator, and data collection was monitored to ensure compliance to the protocol. All testing was conducted in standard clinic sound-treated test booths, with speech and noise stimuli delivered through standard clinical audiometers and loudspeakers, placed at approximately 1 meter from the center of the subject's head and at ear level. Calibration was conducted using standard procedures with sound level meters using the speech materials from the test. Subjects were seated facing a speaker positioned at 0° azimuth, and instructed not to move their heads during testing.

Preoperatively, aided speech understanding in quiet was evaluated on all subjects using their own hearing aids. The hearing aids were verified to be functioning properly, and determined to be appropriately fit according to the judgment of the subject's audiologist. Subjects were evaluated in the following conditions: right-aid alone, left-aid alone and bilateral aids. The purpose of this testing was to establish a baseline level of auditory function for comparison to postsurgical performance with cochlear implants.

Subjects received both cochlear implants during a single surgical procedure. After a sufficient healing period, initial programming and activation of both devices occurred on the same day.

Loudness Level Adjustment

It is well known that perceived loudness of sounds is likely to increase when listening bilaterally compared with unilaterally, due to 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 bilaterally compared to unilaterally via cochlear implants. 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. Therefore, in an attempt to reduce any 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.

Specifically, before testing at each time interval (1-, 3-, and 6-mo postactivation), the right and left speech processors were programmed independently using standard clinical procedures. Volume settings were at comfortable loudness for conversational speech stimuli presented from a loudspeaker in the frontal position, without reported discomfort for loud environmental noises. Subsequently, both speech processors were activated together with the volume settings initially set to zero for each processor, with incremental increases until a comfortable bilateral listening level was reached. In addition, the subject verified that sound from the loudspeaker in front appeared to be spatially centered. Finally, comparisons were made by alternating stimulation between each of the unilateral programs and the bilateral stimulation, while 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. Although this approach could be improved in future work, at the time that these data were collected, standardized methods for loudness level adjustments in bilateral cochlear implant users were not available.

When equal loudness is attempted, an important issue that must be acknowledged but that has not been directly handled is the issue of compression in the implant systems used here. Automatic gain control (AGC) algorithms are activated for signals reaching approximately 67 dB SPL. This was generally not a problem because the signals used here were kept below those levels, however, the levels at which AGC is activated vary between subjects, and might have resulted in individual differences in loudness perception.

Speech Understanding in Quiet

Speech understanding in quiet was assessed in the two unilateral and the bilateral listening conditions, at 1-, 3-, and 6-mo postactivation. Two different speech materials were used: the Consonant-Nucleus-Consonant (CNC) Monosyllabic Word Test (Peterson & Lehiste, 1962) and sentence lists from the Hearing In Noise Test (HINT; Nilsson, Soli, & Sullivan, 1994). The CNC test results (one list per condition) were scored for percent correct of words (50 words/list) and percent correct of phonemes (150 phonemes/list). The HINT sentences (two lists per listening condition; 10 sentences/list) were scored for percent of key words correctly identified. Both speech materials were presented from a loudspeaker at 0° azimuth (frontal) at a fixed level of 65 dB SPL.

Speech Understanding in Noise

Speech understanding in noise was assessed in the two unilateral and the bilateral listening conditions, at 3- and 6-mo postactivation. Testing was completed under three noise conditions: 1) speech and noise both at 0° azimuth (frontal), 2) speech at 0° azimuth and noise from the right side at +90°

azimuth, and 3) speech at 0° azimuth and noise from the left side at −90° (or 270°) azimuth. Auto-sensitivity and noise reduction functions in the speech processors were deactivated to avoid automatic alterations to the test levels of the background noise.

The BKB-SIN Test (BKB-Speech In Noise Test; Etymotic Research, 2005) was used, in which the corpus consists of the Bamford-Kowal-Bench sentences (Bench, Kowal, & Bamford, 1979), presented in four-talker babble noise. The 36 sentence lists in the test are divided into 18 equally-difficult pairs of sentence lists. Each list is made up of 8-10 sentences that each have 3 or 4 key words, Speech reception threshold (SRT), which is referred to as the SNR-50, is defined as the signal-to-noise ratio (SNR) required for the subject to repeat 50% of the key words correctly. Speech was presented at 65 dB SPL and the level of the noise was varied in 3 dB steps at fixed SNRs, beginning at +21 dB SNR (very easy), and descending to 0 or −6 dB SNR (very difficult), depending on the list. To maximize reliability of the results, two list pairs were administered in each listening and noise condition (with results averaged) for a total of 18 list pairs (36 lists) per subject; no list was presented to a subject twice within a test session. The test conditions and lists were randomized for each subject, and based on the equal difficulty among these test materials an assumption was made that order effects would be absent or very small.

Data Analysis of Speech Understanding in Noise

Results were analyzed by group as well as by comparison of individual subjects' results across different combinations of listening and noise conditions, as follows:

1) To estimate bilateral benefits resulting from "binaural redundancy" the effect of adding the second ear when the speech and noise were both at 0° azimuth (frontal) was examined by comparing each subject's unilateral SRTs with the bilateral SRT.
2) To estimate bilateral benefits resulting from "head shadow" the effect of adding the ear with the more favorable SNR (the ear opposite the noise source) was examined when noise was at ±90° to the right or left. With the noise on the right, the SRTs when listening with the right implant alone were compared to the SRTs in the bilateral condition. With the noise on the left, the score for the left implant alone were compared to the bilateral score.
3) To estimate bilateral benefit resulting from "binaural squelch" the effect of adding the ear with the poorer SNR (the ear on the same side as the noise source) was examined when noise was at ±90° azimuth to the right or left. When the noise was on the right, SRTs for the left implant alone were compared to the bilateral SRTs (addition of the right implant, *towards* the noise). With the noise on the left, SRTs for the right implant alone were compared to the bilateral SRTs (addition of the left implant, *towards* the noise).

It is important to note that there are undoubtedly overlapping contributions of the bilateral processing components within these comparisons, because it is not possible to completely separate out the various bilateral effects when listening in the soundfield. For example, for the comparisons intended to estimate bilateral advantage primarily related to the head shadow effect, there is likely also some contribution from the binaural squelch effect (and vice versa). Nevertheless, the selected comparisons represent an approach that has commonly been used in the bilateral cochlear implant research literature in an attempt to examine the potential contribution of each binaural processing component (e.g., Müller et al., 2002; Tyler et al., 2002b; Gantz et al., 2002; van Hoesel & Tyler, 2003), and can reasonably be expected to represent the primary contribution of each.

When tested on unilateral speech recognition performance, although most subjects had the same (or similar) performance across their two ears, some subjects showed relatively large asymmetries. For those patients with asymmetries a "better ear effect" may also have been a factor in the results of the comparisons used to estimate bilateral advantages (see Litovsky et al., 2004). That is, when the better ear was the one added in to create a bilateral listening condition, any improved performance compared to the unilateral score could reflect both the bilateral benefit and the better ear effect. To examine how much impact postoperative performance asymmetry between the ears had on the results, two subsets of the subjects were selected for further analysis. Specifically, data from a group of subjects that had highly symmetrical BKB-SIN unilateral performance between the ears were compared to data from a group of subjects who showed large unilateral performance asymmetry between the ears.

Subjective Questionnaire

Subjective information was gathered using the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire (Cox & Alexander, 1995). It was deemed important to have subjects fill out the questionnaire based on recent real-world experience with the listening condition under test, rather than having to rely on memory. Thus, after the 3-mo postactivation evaluation the subjects underwent a 3-wk "bilateral deprivation" period, during which they wore only one speech processor (unilateral use). Their other speech processor remained at the clinic during this period of time. The speech processor worn for the 3-wk deprivation period was that of the subject's better-performing ear, based on their speech recognition performance at the 1- and 3-mo postactivation intervals. If there was little or no performance difference between the ears, the subject was allowed to choose which speech processor to keep during the deprivation period. At the end of the deprivation period, subjects returned to the clinic and were administered the "aided" portion of the APHAB questionnaire, responding according to their recent experiences while wearing only one cochlear implant (unilateral condition).

Subsequently, subjects were again given both speech processors to use for approximately two additional months, ending approximately at the 6-mo postactivation evaluation. At that time, the aided portion of the APHAB was administered again, however subjects answered the questions according to their recent experience using bilateral implants. The conventional use of the APHAB in hearing aid research is to compare aided versus unaided performance. When only aided scores are obtained, it is important to "anchor" perception to the comparison condition. In this study the focus was on comparing between bilateral and unilateral implant use. To remind subjects of their sentiments during the unilateral use period, their previous APHAB answers were made available while they responded to the same questions with reference to the bilateral condition. This facilitated internal scaling for individual participants, an approach that is consistent with the recommendations of the authors of the APHAB questionnaire (Cox & Alexander, 1995). It is notable that, to ensure recent experience with the tested listening condition, the APHAB was administered for the bilateral condition with about 2 mo longer duration of use of the implants than for the unilateral listening condition. Because speech scores typically improve over time postimplantation, a potential confounding factor might have been introduced in the results, as will be discussed more extensively below.

Finally, not all subjects were tested at every interval due to scheduling difficulties or cancellations, so the number of subjects was reduced for some comparisons. One subject was not tested at the 1-mo postactivation interval, two subjects were not tested at the 6-mo postactivation interval, and one subject was not tested at both the 3- and 6-mo evaluation intervals. For a few subjects, due to time constraints, some but not all tests were completed at a given interval.

Results

Speech Understanding in Quiet

Results (mean +1 SE) from the CNC and HINT sentence testing in quiet (average across two lists) are shown in Figures 1 and 2, respectively. These data include comparisons for the three listening conditions for 33 subjects who were able to contribute complete data sets across the four time intervals. Before parametric statistical analysis, individual percent correct scores were subjected to arcsine transformation to normalize the variance (Studebaker, 1985). A two-way general linear model repeated measures analysis of variance (AOV; SPSS statistical software package, version 11.5) was conducted on each of the transformed measures with the main variables being time intervals (preoperatively, 1-, 3-, and 6-mo postactivation) and listening conditions (left alone, right alone, and bilateral). A test for the sphericity assumption (Mauchly's) was also conducted, and if this assumption was not met, the Greenhouse-Geisser correction was applied to determine overall significance for the AOV. For significant interactions and main effects, simple-effects AOVs were conducted holding the factors of time (interval) and/or listening condition constant. An alpha level of $p \leq 0.05$ was used with the Bonferroni correction applied to post-hoc paired-samples t-tests (two-tailed).

For the CNC word scores, significant main effects were found for time and listening condition (both at $p < 0.0001$), and there was a significant interaction between the two variables ($p = 0.005$). Holding listening condition constant, there were significant

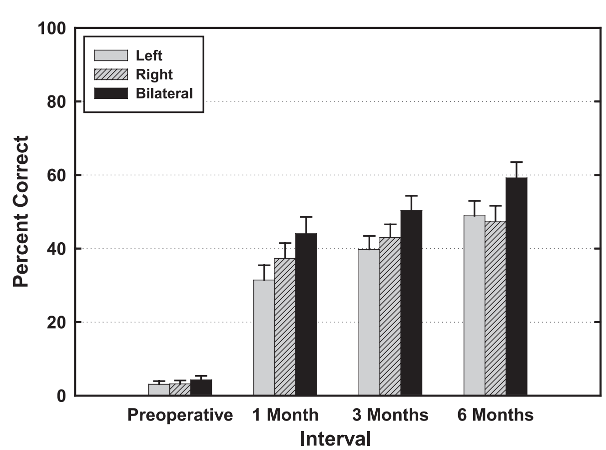

Figure 1. Mean (+1 SE) percent correct CNC word scores in quiet in the left ear alone, right ear alone, and bilateral listening conditions for the 33 subjects with complete data across the preoperative (hearing aids), and 1-, 3-, and 6-mo postactivation intervals.

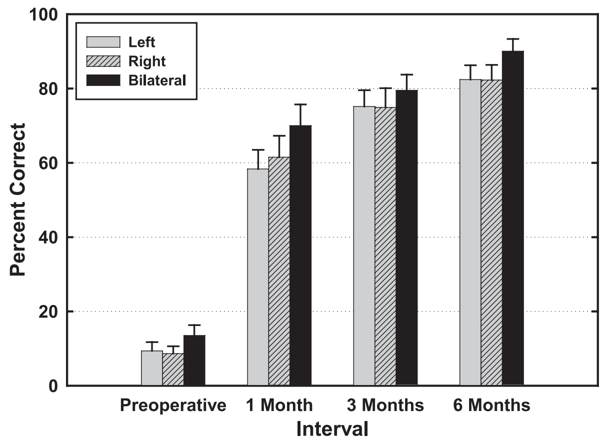

Figure 2. Mean (+1 SE) percent correct HINT sentences-in-quiet scores in the left ear alone, right ear alone, and bilateral listening conditions for the 33 subjects with complete data across the preoperative (hearing aids), and 1-, 3-, and 6-mo postactivation intervals.

effects for time for left-alone, right-alone and bilateral conditions (all at $p < 0.0001$). Post-hoc testing revealed that all postoperative intervals were significantly better than the preoperative (hearing aids) interval for all three listening conditions. Additionally, for the left-alone and bilateral conditions, the 3- and 6-mo postactivation intervals were significantly better than the 1-mo postactivation interval, and the 6-mo interval was significantly better than the 3-mo interval. The same result was found for the right-alone condition except that the 3- and 6-mo results did not differ significantly. Holding the factor time constant, there were no significant effects of listening condition preoperatively. In contrast, there were significant effects at all postoperative intervals (1 mo, $p = 0.001$; 3 mo, $p < 0.0001$; 6 mo, $p < 0.0001$). Post-hoc testing revealed that the bilateral condition was significantly better than either unilateral condition at all postoperative intervals. No significant differences were found between the left-alone and right-alone conditions at any interval.

For HINT sentences, the AOV indicated significant main effects of time and listening condition ($p < 0.0001$), but no significant interaction between the two factors. For the factor time, post-hoc testing revealed that all paired comparisons reached the level of significance ($p < 0.008$) except for the 3-mo versus 6-mo comparison for the right ear. For the factor listening condition, post-hoc testing revealed that the bilateral condition was significantly better than either unilateral condition at all time intervals except at 3-mo postactivation. No significant differences were found between the left-alone and right-alone conditions at any time interval.

The trends in the mean data can also be seen when individual subjects' performances are evaluated. For example, at the 6-mo interval, CNC measures showed that 32/33 subjects (97%) had a higher bilateral score compared with at least one of the unilateral scores, and 21 subjects (64%) had a better bilateral score than both unilateral scores. In one subject (#21), the bilateral CNC score was the same as one unilateral score and poorer than the other unilateral score by only 2%. Similarly, at the 6-mo interval, HINT scores showed that 31/33 subjects (94%) had a higher bilateral score compared with at least one of the unilateral scores, and 19/33 subjects (58%) had a better bilateral score than both unilateral scores. Two subjects (#5 and #11) had bilateral HINT scores that were either the same as the unilateral scores or poorer by $\leq 3\%$. For both CNCs and HINT, in cases where bilateral implants outperformed unilateral, individual improvements in scores were sometimes as high as 20% to 40% for bilateral listening.

Finally, results for CNCs scored as phonemes showed trends across time and listening conditions that were the same as those seen for the CNCs scored as words. At the 6-mo postactivation interval, for example, the mean CNC phoneme score was 66.2% (S.E. = 3.5) for the left implant alone, 66.2% (S.E. = 3.7) for the right implant alone, and 74.6% (S.E. = 3.5) for the bilateral condition. For brevity, then, the CNC phoneme results are not presented further herein.

Speech Understanding in Noise

Descriptive statistics for the BKB-SIN test results obtained at 3- and 6-mo postactivation are shown in Table 3 for each of the nine test conditions (3 listening conditions × 3 noise locations) for 29 subjects with complete data on this task across both postactivation intervals. Note that because the BKB-SIN scores are in dB SNR for 50% correct key-word speech recognition (SNR-50), a *lower* value indicates *better* performance. As expected, there was an overall improvement in performance over time under all listening conditions, except for bilateral listening with noise front (0° azimuth). Also, group average data show that performance is worse when noise is from the frontal location compared with the noise being on either side (±90° azimuth), supporting the notion that spatial separation of the speech and noise enhances performance. Across all three noise locations for both time intervals, performance was better in the bilateral listening condition than either unilateral listening condition. Because the same trends were seen across listening conditions for the 3-mo and the 6-mo results, for brevity the 3-mo data are not further presented.

At the 6-mo interval, there were a total of 34 subjects with complete BKB-SIN data across the nine measures. A two-way general linear model repeated-

TABLE 3. Descriptive statistics on the BKB-SIN results in dB SNR for speech reception threshold and listening conditions for those 29 subjects with complete data at both 3-mo and 6-mo postactivation. Note that a *smaller* number indicates *better* performance on this task

	3-mo postactivation									6-mo postactivation								
	Unilateral left implant			Unilateral right implant			Bilateral implants			Unilateral left implant			Unilateral right implant			Bilateral implants		
	Noise left	Noise right	Noise front	Noise left	Noise right	Noise front	Noise left	Noise right	Noise front	Noise left	Noise right	Noise front	Noise left	Noise right	Noise front	Noise left	Noise right	Noise front
Mean	12.58	8.91	13.60	8.65	12.04	12.75	7.18	7.22	10.49	10.35	7.87	12.97	5.79	10.96	11.42	3.75	6.14	10.51
Minimum	−1.25	−1.75	5.75	−4.25	−0.50	4.25	−4.75	−2.75	2.75	−1.25	−2.50	6.00	−4.00	0.75	3.50	−5.50	−3.00	3.75
Maximum	22.75	22.25	23.50	23.00	23.50	23.50	23.25	21.25	22.00	23.50	23.00	23.00	21.25	22.75	23.25	20.50	18.75	23.00
SD	6.73	6.70	5.21	7.55	6.92	5.69	8.10	7.10	5.01	6.01	6.48	5.06	6.80	6.06	5.17	6.29	6.29	5.22
SE	1.25	1.24	0.97	1.40	1.28	1.06	1.50	1.32	0.93	1.12	1.20	0.94	1.26	1.13	0.96	1.17	1.17	0.97

SD, standard deviation; SE, standard error.

measures AOV was conducted with the Greenhouse-Geisser correction applied when the sphericity assumption was not met. There were significant main effects found for listening condition and noise location (both at $p < 0.0001$), and a significant interaction between these factors ($p < 0.0001$). Holding listening condition constant, the AOV revealed significant effects of noise location for left implant alone, right implant alone, and bilateral (all at $p < 0.0001$). Paired samples t-tests (2-tailed) were done using the Bonferroni correction. For the left-implant condition performance was significantly worse with noise in front compared with noise on either side, and significantly better for noise from the right than noise from the left. Similarly, in the right-implant condition performance was significantly poorer with the noise in front than on either side, and better for noise from the left than from the right. For the bilateral listening condition performance was significantly poorer for noise from the front than from either side, but there was no difference between noise from the left and from the right.

Holding noise location constant, the AOV revealed significant effects of listening condition for noise from the left and right (both at $p < 0.0001$), and from the front ($p = 0.001$). Post-hoc paired samples t-tests using the Bonferroni correction suggest that with noise on the left performance was better in the right-implant alone than the left implant condition, and the bilateral condition produced significantly better performance than either unilateral condition. With noise from the right performance was significantly better when using the left implant alone than the right implant alone, and better with bilateral than either unilateral condition. For noise from the front, there was no significant difference between the right and left implant alone conditions, or between bilateral listening and the left-implant condition; however, bilateral was significantly better than the right-implant condition.

Results from individual subjects were also examined in terms of the three bilateral effects described above. For each subject, comparisons between conditions were deemed significant if the difference score was greater than 3.1, the critical difference value derived from pilot testing of the BKB-SIN Test in adult cochlear implant users (Etymotic Research, 2005, pp. 14–15). This critical value is defined as the difference between SRTs (SNR-50) estimated for 2 list pairs (4 lists) in each condition with a 95% confidence interval.

Speech and Noise at 0° Azimuth: Binaural Redundancy Effect

If performance in this speech/noise configuration is better in the bilateral condition than with either

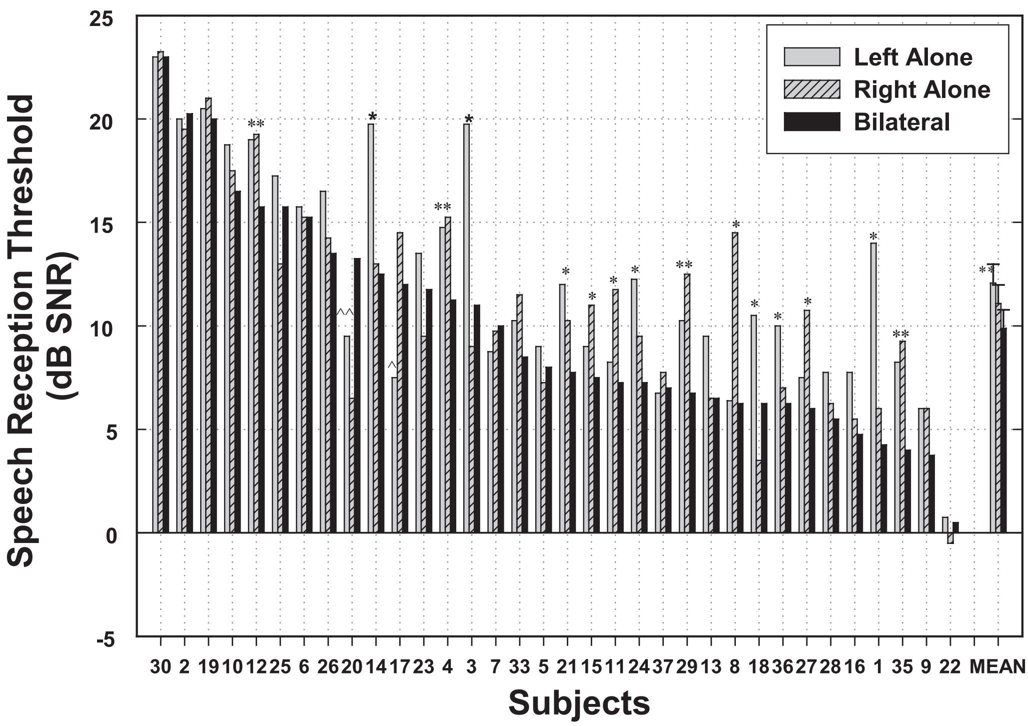

Figure 3. Individual (*N* = 34) and group mean (+1 S.E.) dB SNRs needed for SRT on the BKB-SIN Test at 6-mo postactivation for the condition in which speech and noise were both at 0° azimuth (to assess the "binaural redundancy effect"). Note that a *lower* number indicates *better* performance on this task. Results are sorted by bilateral scores, with an asterisk indicating an individual significant benefit for bilateral versus unilateral. A circumflex symbol represents an individual significant bilateral decrement. The double asterisk indicates significance of the bilateral versus left implant alone comparison.

ear alone, bilateral benefit is attributed primarily to the "binaural redundancy effect." Individual data and the group mean (+1 S.E.) at 6-mo postactivation are shown in Figure 3 for the 34 subjects with complete data for this condition. Individual subjects' results are grouped to include right, left and bilateral listening modes, and rank-ordered according to performance in the bilateral condition. These data are in dB SNR for 50% key-word correct recognition (SRT) so that *lower* values indicate *better* performance.

AOV and post-hoc paired t-tests on group means using the Bonferroni correction suggest that there was no significant difference between the bilateral and right condition, but that the bilateral condition was significantly better than the left condition ($p < 0.017$). Examination of individual subjects' data showed that 15/34 subjects (44%) demonstrated a significant bilateral advantage over one of the two unilateral conditions; 2/34 subjects (6%) showed a significant decrement in the bilateral condition relative to a unilateral score for this listening condition; 17/34 subjects (50%) showed no effect.

Noise at 90° Azimuth: Head Shadow Benefit

To evaluate head shadow benefits, performance in the bilateral condition and unilateral conditions with the worse SNR were compared and difference scores were obtained for each subject. Individual data and group mean (+1 S.E.) at 6-mo postactivation are shown in Figure 4. The light-shaded bars represent the amount of bilateral advantage (in dB SNR) in the noise-left condition, comparing left-ear with bilateral (right ear added); the dark-shaded bars represent the amount of bilateral advantage in the noise-right condition, comparing right-ear with bilateral (left ear added). In Figure 4 a *higher* positive difference value indicates *greater* bilateral benefit.

On average, head shadow effects were 4.95 dB for noise-right (standard deviation {S.D.} = 3.6) and 6.34 dB for noise-left (S.D. = 3.8); hence, a slightly greater advantage in the noise-left condition. Paired t-tests comparing SRTs in the bilateral and the two unilateral conditions indicated significantly better performance in the bilateral condition than either left- or right-only condition ($p < 0.0001$). When applying the critical difference of 3.1 dB to individual subjects' data, 32/34 (94%) subjects demonstrated a significant bilateral advantage for at least one of the head-shadow comparisons. Further, 15/34 (44%) subjects had a significantly better bilateral score than both unilateral scores. No subjects showed a significant decrement for bilateral listening compared to either unilateral condition.

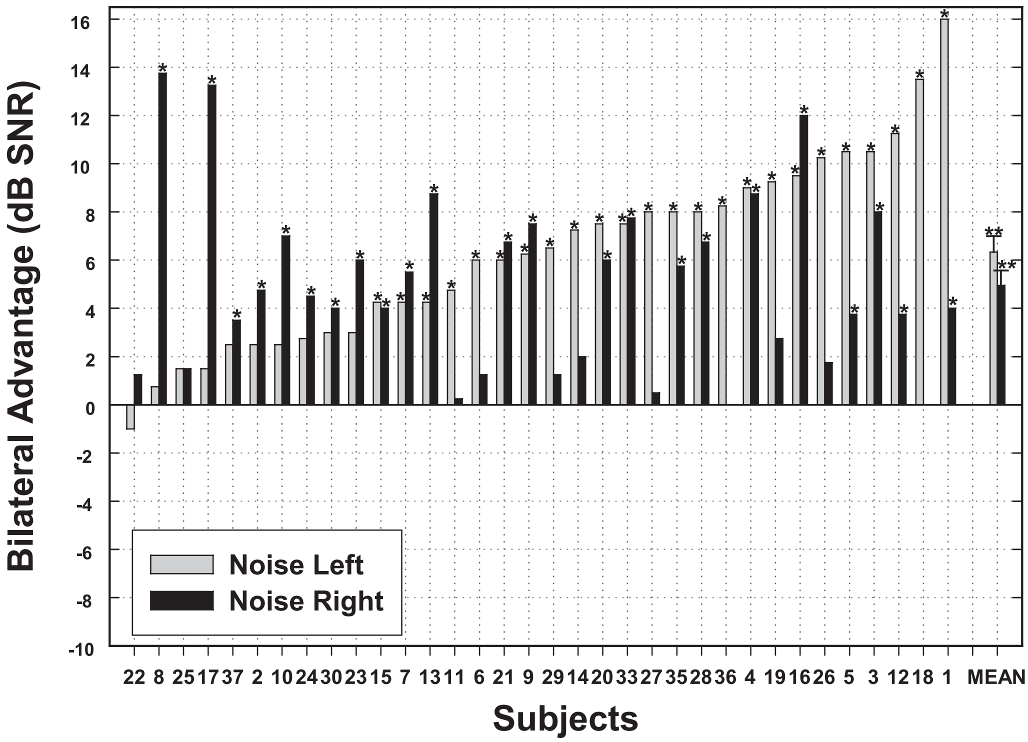

Figure 4. Individual ($N = 34$) and group mean (+1 S.E.) results on the BKB-SIN test at 6 mo postactivation for the condition in which speech was at 0° azimuth, noise was at 90° azimuth, and the ear with the better SNR (i.e., that opposite the noise) was added for the bilateral condition (to assess the "head shadow effect"). Results in this figure are shown as *difference* scores between the bilateral and unilateral results, sorted from worst to best. Note that a *larger* difference indicates *greater* bilateral benefit. The light-shaded bars represent the amount of bilateral benefit when the bilateral score (in dB SNR) with noise to the left was subtracted from the left-implant alone score (in dB SNR). The darker bars represent the amount of bilateral benefit in dB SNR when the bilateral score with noise to the right was subtracted from the right-implant alone score. A single asterisk indicates an individual significant benefit for bilateral versus unilateral. The double asterisks indicate significant mean differences for the comparisons between the bilateral condition and the unilateral ear conditions.

Noise at 90° Azimuth: Binaural Squelch Effect

To evaluate binaural squelch, performance in the bilateral condition and unilateral conditions with the better SNR were compared and difference scores were obtained for each subject. Individual data and group mean (+1 S.E.) at 6-mo postactivation are shown in Figure 5. The light-shaded bars represent the amount of bilateral advantage (in dB SNR) in the noise-left condition, comparing right-ear with bilateral (left ear added); the dark-shaded bars represent the amount of bilateral advantage in the noise-right condition, comparing left-ear with bilateral (right ear added); a *higher* and positive difference value indicates *greater* bilateral benefit.

On average, binaural squelch effects were 1.96 dB for noise-right (S.D. = 3.3) and 1.94 dB for noise-left (S.D. = 2.7) conditions. Paired t-tests comparing SRTs in the bilateral and right or left unilateral conditions were statistically significant ($p < 0.0001$ for the right; $p = 0.002$ for the left). When applying the critical difference of 3.1 dB to individual subjects' data, 16/34 (47%) subjects demonstrated a significant bilateral advantage for at least one of the unilateral comparisons, and 4/34 (12%) subjects had a better bilateral score than both unilateral scores. Finally, 2/34 (6%) subjects showed a significant decrement in the bilateral condition; one subject (#25) had a minor decrement in the other unilateral condition as well, although the other subject (#11) showed a significant bilateral advantage in the other unilateral condition.

Subjects with Asymmetrical Ear Performance

Numerous subjects differed in their ability to listen with either ear alone. In an attempt to interpret the results from a perspective that takes into account the possible impact of asymmetry, subjects were categorized into two distinct groups, depending on their performance with the BKB-SIN when the speech and noise were both from 0° azimuth. The "Ear Asymmetry" group (10/34 subjects; 29.4%) had a difference between their two unilateral scores of 3.1 dB (SNR-50) or greater. The "Ear Symmetry" group (24/34 subjects; 70.6%) showed less than a 3.1

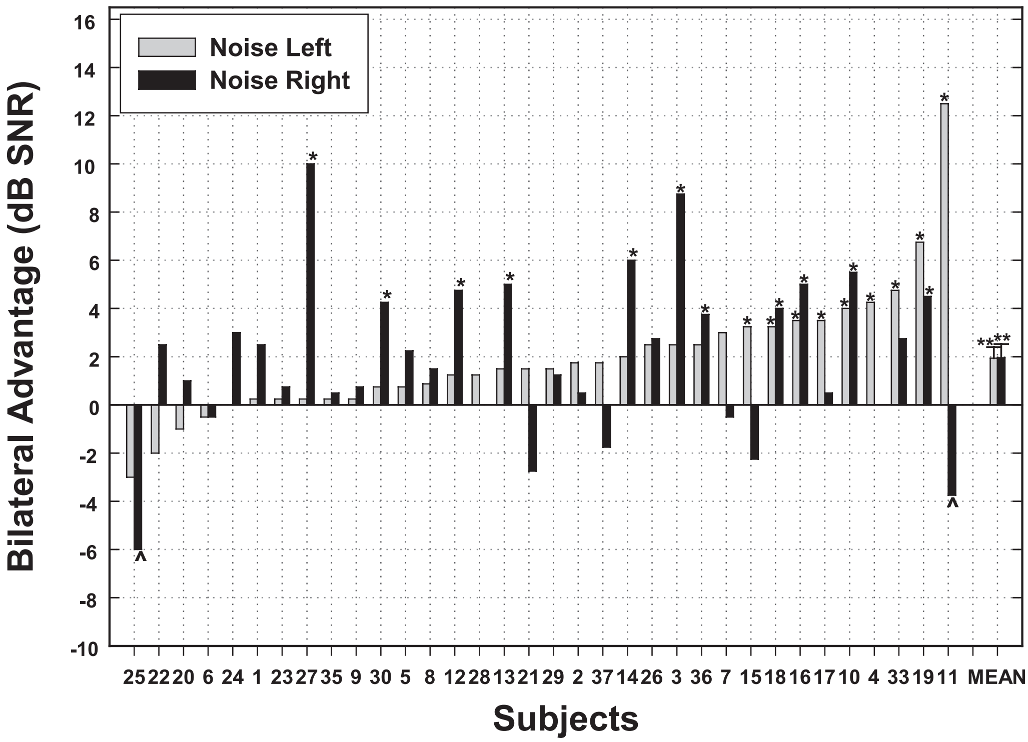

Figure 5. Individual (*N* = 34) and group mean (+1 S.E.) results on the BKB-SIN test at 6 mo postactivation for the condition in which speech was at 0° azimuth, noise was at 90° azimuth, and the ear with the poorer SNR (i.e., same side as noise) was added for the bilateral condition (to assess the "binaural squelch effect"). Results in this figure are shown as *difference* scores between the bilateral and unilateral results, sorted from worst to best. Note that a *larger* difference indicates *greater* bilateral benefit. The light-shaded bars represent the amount of bilateral benefit when the bilateral score (in dB SNR) with noise to the left was subtracted from the right-implant alone score (in dB SNR). The darker bars represent the amount of bilateral benefit in dB SNR when the bilateral score with noise to the right was subtracted from the left-implant alone score (in dB SNR). A single asterisk represents an individual significant advantage for the bilateral versus unilateral condition. A circumflex symbol represents an individual significant bilateral decrement. The double asterisks indicate significant mean differences for the comparisons between the bilateral condition and the unilateral ear conditions.

dB difference between the two unilateral conditions. Although some of the subjects in the "Ear Symmetry" group had small asymmetries that may be of interest and possibly of greater significance on other measures, the criterion that was applied here demarcated between minor effects and statistically meaningful effects.

For the Ear Asymmetry group, SRTs in the noise-front condition are compared in Figure 6 for the two unilateral conditions (labeled better-ear and poorer-ear) and the bilateral condition. Group means for the two groups of subjects (asymmetry and symmetry) are shown to the right. It should be noted that the 24 subjects with symmetry also have 'better' and 'poorer' ears plotted separately as mean values; their scores were simply assigned to those categories based on which ear had a lower/higher SRT even though the actual differences were nonsignificant. In the individuals with asymmetry, mean performance was better (lower SRTs) in the bilateral condition than either unilateral condition. In addition 8/10 (80%) of the subjects had a significantly better bilateral score than that for the poorer-ear, but none had a significantly better bilateral score compared with the better ear. One subject (#18) showed a significant decrement for bilateral listening relative to their better performing ear. Group means for this measure, which reflects binaural redundancy, show that while the group with asymmetry performed better with two ears compared only with the poorer-ear condition, the 24 subjects with relative symmetry in their BKB-SIN unilateral performances performed better bilaterally compared with either of the ears.

Figure 7 shows individual results for the asymmetry group, and mean data for both groups, for the head shadow effect. The light-shaded bars represent the amount of bilateral advantage (dB SNR) when the noise was nearer to the better-ear compared with bilateral (poorer ear added). The dark-shaded bars represent the amount of bilateral advantage when the noise was nearer to the poorer-ear compared with bilateral implants (better ear added). A *higher* difference value indicates *greater* bilateral

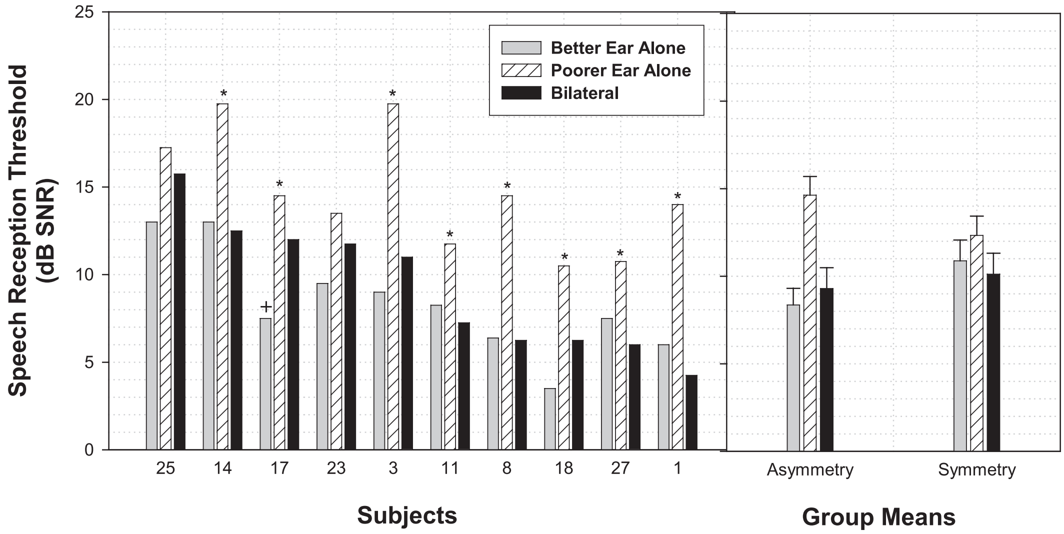

Figure 6. Results for the Ear Asymmetry Group ($N = 10$ subjects with significant unilateral performance differences between the ears) in the same format as Figure 3 to assess the "binaural redundancy effect", except that results are shown here for better ear and poorer ear based on unilateral condition performance on this task. Asterisk symbols indicate an individual significant benefit for bilateral versus unilateral. A cross symbol represents an individual significant bilateral decrement (subject #17 in the better-ear condition). On the right side of the graph are means and standard errors for the Ear Asymmetry Group and for the Ear Symmetry Group ($N = 24$).

benefit. In the asymmetry group, critical values were reached for 6/10 (60%) of individuals when the noise was near the poor ear, and for 5/10 subjects when the noise was nearer the better ear. For two subjects (#1 and #3), a significant bilateral advantage was seen compared to both the better and poorer unilateral ears. Group means for the two groups suggest that the bilateral advantage is greater in the asymmetry group when the noise is near the poorer ear (thus, the better ear is added for the bilateral condition); in the symmetry group the advantages are similar for the two ears, confirming the use of the noise-front condition to determine poorer and better ears.

Figure 8 shows individual results for the asymmetry group, and mean data for both groups, for the binaural squelch effect. The light-shaded bars represent the amount of bilateral advantage (dB SNR)

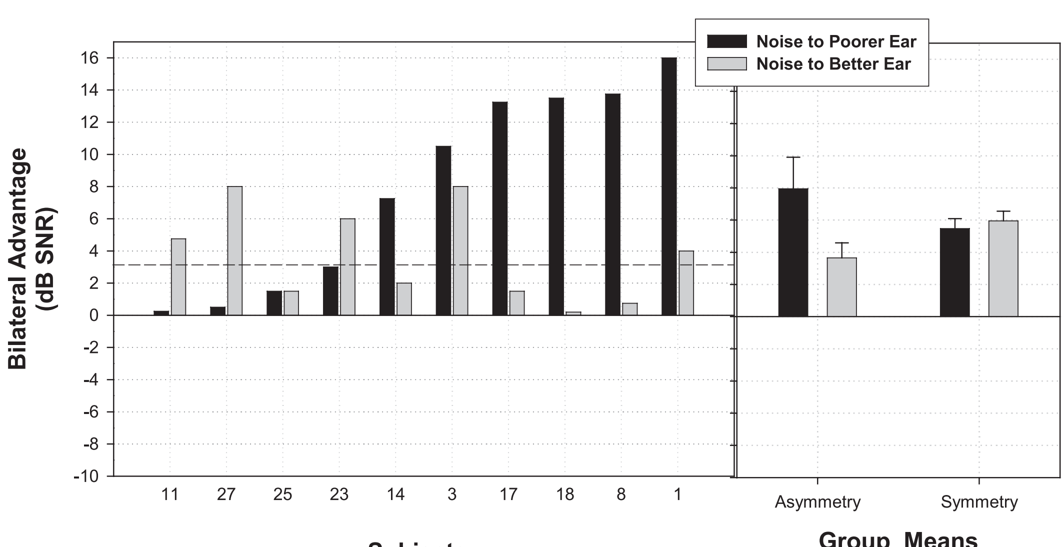

Figure 7. Results for the Ear Asymmetry Group ($N = 10$) in the same format as Figure 4 to assess the "head shadow effect", except that results are shown here for better ear and poorer ear(based on unilateral implant performances for frontal noise). Individual results are sorted in order from worst to best scores for noise on the poorer ear side. Individual bilateral advantage values above the horizontal bar are statistically significant. On the right side of the graph are means and standard errors for the Ear Asymmetry Group and for the Ear Symmetry Group ($N = 24$).

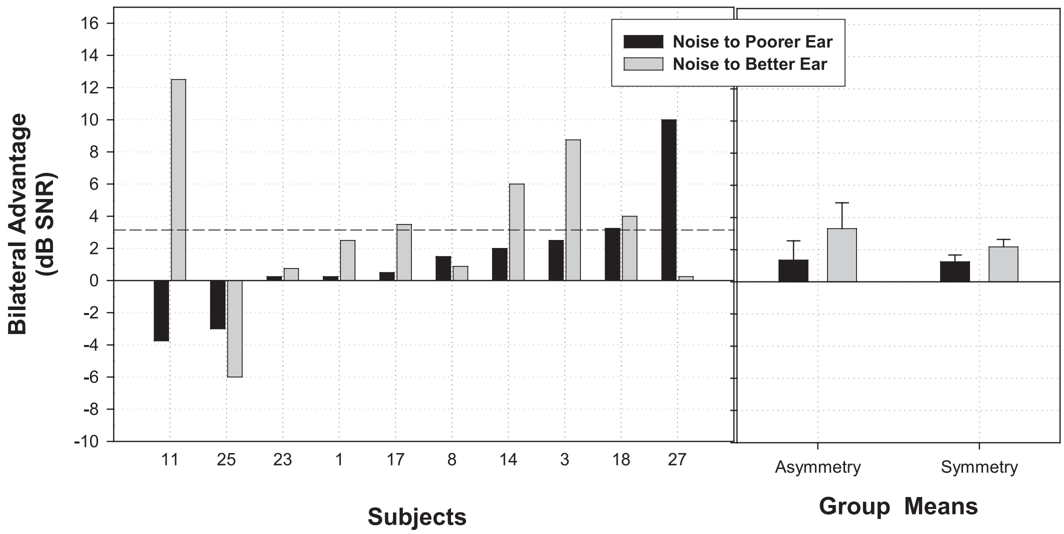

Figure 8. Results for the Ear Asymmetry Group ($N = 10$) in the same format as Figure 5 to assess the "binaural squelch effect", except that results are shown here for better ear and poorer ear (based on unilateral implant performances for frontal noise). Individual results are sorted in order from worst to best scores for noise on the better ear side. Individual bilateral advantage values above the horizontal bar are statistically significant. On the right side of the graph are means and standard errors for the Ear Asymmetry Group and for the Ear Symmetry Group ($N = 24$).

compared with listening with the better-ear alone, and dark-shaded bars represent the amount of bilateral advantage compared with listening with the poorer-ear alone. A *higher* difference value indicates *greater* bilateral benefit. Critical difference values were reached in 2/10 individuals in the bilateral versus poorer-ear condition, and in 5/10 individuals in the bilateral versus better-ear condition. In addition, 2 subjects (20%) showed a significant decrement for bilateral listening (one for the better-ear and one for the poorer-ear), although one of these subjects had a significant benefit for the other ear. Group means indicate that in the asymmetry group bilateral advantages were larger when the noise was nearer the better ear. Overall, the binaural squelch effect size for both groups is smaller than the head shadow effect seen in Figure 7.

Finally, it is important to note also that some subjects with significant asymmetry across ears in postoperative results had little or no asymmetry in their preoperative hearing aid scores, so that it would have been difficult to predict a priori which ear would be the "better" performer postoperatively for purposes of unilateral implantation. Further, a few subjects produced a differing pattern of better/poorer ear designation across different speech tests in this study, so, for example, the ear with best performance on the HINT sentences-in-quiet was not necessarily the same as the ear with best performance on a BKB-SIN task. The reason for a better ear discrepancy across speech materials in some subjects is unknown, but may relate to differences in the test materials or procedures, test-retest variability, and the relative sensitivity of the test to the conditions under comparison. In any case, for these subjects, designation of "better" ear would not be clear even postoperatively.

Abbreviated Profile of Hearing Aid Benefit (APHAB)

Complete APHAB data were collected on 30 of the 37 subjects. The standard APHAB "benefit score" (the difference between unaided and aided answers) was not used; rather, only "aided" answers were obtained with reference to each subject's real world listening experiences with their best unilateral implant and with bilateral implants. For purposes of data analysis, numeric indicators were coded 1 through 7 to represent questionnaire answers A through F (responses ranging from "never" to "always"). Note that because several of the individual APHAB questions have "reversed" answers, these were transposed before analysis so that all larger numeric responses indicated better perceived performance. The APHAB consists of four subscales: ease of communication (EC), reverberant listening conditions (RV), background noise (BN), and aversiveness to sounds (AV). The average of all the transposed numeric answers for an individual for a given subscale was calculated and used as the value in analysis. Mean group results (+1 S.E.) are shown in Figure 9 for each subscale for the best unilateral implant versus the bilateral implants.

Due to the fact that questionnaire responses are ordinal rather than ratio level data, the nonpara-

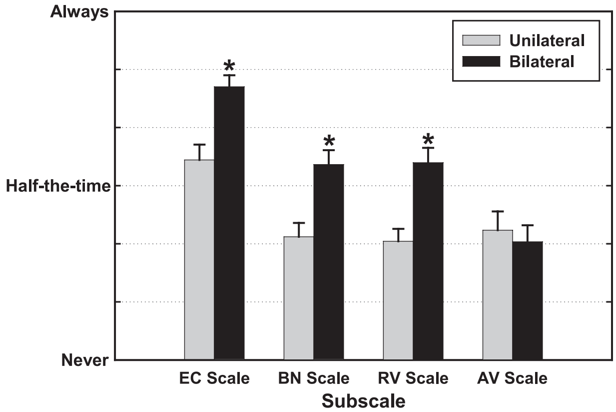

Figure 9. Mean (+1 S.E.) scores on the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire results, by subscale, for the 30 subjects with data for both wearing only the best unilateral implant, and for wearing bilateral implants. A higher value (towards "always") indicates better perceived performance. An asterisk indicates significant bilateral benefit compared with the unilateral condition.

metric Wilcoxon Signed-Ranks Test for matched pairs (2-tailed) was chosen to compare results across the unilateral and bilateral listening conditions, for each subscale. These analyses indicated statistical significance, in the direction of more favorably perceived performance with bilateral cochlear implants than with the best unilateral implant, on the EC, BN and RV subscales (all at $p < 0.0001$). The difference on the AV subscale was not significant ($p > 0.05$), a finding possibly influenced by the loudness level matching done in this study. A positive rank (indicating better bilateral than unilateral result) was found for 25 out of the 30 subjects (83%) for the EC subscale, with 2 subjects (6%) having tied ranks (same score unilateral and bilateral) and 3 subjects (10%) having a negative rank (unilateral better than bilateral). For the BN subscale, there was a positive rank for 26 subjects (87%), with 1 subject (3%) having tied ranks, and 3 subjects (10%) having a negative rank. For the RV subscale, 29 of the 30 subjects (97%) had positive ranks with the remaining 1 subject (3%) having a negative rank. For the AV subscale, which did not show a significant difference, positive ranks were found for 17 of the 30 subjects (57%), tied ranks for 6 subjects (20%), and negative ranks for 7 subjects (23%). Examination of individual data revealed that all subjects had a preference for bilateral listening on at least one of the three key subscales (EC, BN, and RV), with the majority preferring bilateral on all three subscales.

DISCUSSION

This study was aimed at evaluating performance in a relatively large number of adults with postlingually acquired deafness, who received bilateral Nucleus 24 cochlear implants in a manner that provided hearing to both ears on the same day (simultaneous approach). This group represents a unique subset of patients whose outcomes are important to understand. Of the 37 initial participants, 34 were tested at the 6-mo postactivation interval, and these results are the focus of the present study. All subjects who had 6-mo postactivation test scores for speech understanding in quiet, speech understanding in noise, and questionnaire data, showed a significant benefit of bilateral implants on at least one of the measures, and many showed consistent benefit across all of the measures; no subjects performed consistently poorer with bilateral than with either of the unilateral conditions.

The strongest and most robust bilateral advantage was seen when the ear opposite to the noise was added to the ear with the worse SNR, in other words, a benefit due to the head shadow effect. Although there were additional, smaller contributions from binaural squelch for some subjects, a key benefit of bilateral cochlear implants appears to be related to the beneficial aspect of having hearing on both sides so that the ear with the more favorable environmental SNR is always available.

These results are consistent with previous reports in smaller patient groups (e.g., Gantz et al., 2002; Müller et al., 2002; Schön et al., 2002; Tyler et al., 2002b; Litovsky et al., 2004). For example, Gantz et al. (2002) studied 10 adults who underwent simultaneous (in a single operation) implantation, using similar speech measures and conditions as in the current study. At 1 yr postactivation all subjects benefited from the head shadow effect, but only 2 of 10 subjects demonstrated benefits due to binaural summation or squelch. Similar preponderances for head shadow benefits compared to other binaural effects have been reported recently with 5 Med-El patients (Senn et al., 2005) and in a multi-center study conducted in Europe with 22 simultaneously- and 15 sequentially-implanted recipients of the Nucleus 24 device (Laszig et al., 2004).

To a large extent, results from the present study cannot be directly compared with those obtained in numerous other studies. One issue is the difference in methodologies across studies, such as the use of fixed SNR that, in previous studies may have resulted in ceiling effects (patients performing so well with their unilateral implant that there is no room for significant improvement with the bilateral implants), as opposed to the variable SNR approach used in the present study. There are also differences across studies in cochlear implants and speech processing strategies, speech and noise test materials, study design factors (including whether or not binaural loudness equalization was attempted), and patient populations evaluated. Despite these differences, there is clearly a uniformity across laboratories, languages/continents and device types, in the undisputable robustness of the head shadow effect, and relatively smaller benefits from binaural processing, when present.

Reasons for a failure to see large benefits due to binaural processing effects are important to consider. On one level, improvements in clinical mapping of bilateral devices are likely required to provide optimal configurations that maximize harmonious handling of the signals to the two ears. This is important because bilateral implant users are not typically mapped using bilateral approaches that maximize functioning in free field. One problem, for example, is the lack of synchrony between right and left compression algorithms. Wide dynamic-range compression circuits are commonly used to map the input dynamic-range into a limited output range. Independent bilateral compression can introduce temporal and level distortions, both monaural and bilateral, that would limit individual listeners' ability to show maximal benefit on measures of speech understanding in noise such as those used here. This might be particularly problematic for sources that are spatially separated, whereby one of the devices is in head-shadow and not compressing, whereas the other device is near the source and therefore entering compression. Future work should focus more deliberately on the effects that compression has on these abilities, and on ways in which bilateral fitting can be optimized.

On another level of experimental design, when direct stimulation is applied to individual electrode pairs, patients with bilateral implants have shown sensitivity to interaural timing cues on the order of 50 to 200 μsec. For some subjects, these values are near or within normal limits and certainly within the range of physiologically relevant azimuthal directionally-dependent cues (van Hoesel, Tong, Hollow, et al., 1993; Long, Eddington, Colburn, et al., 2003; van Hoesel & Tyler, 2003; van Hoesel, 2004; Laback, Pok, Baumgartner et al., 2004; Long, Carlyon, Litovsky et al., 2006). To achieve binaural processing cues that facilitate source segregation in noise, such as the binaural squelch effect and binaural summation, prerequisite conditions must exist at the level of the hardware (speech processors and microphones). The importance of maximizing binaural cues at the level of the hardware stems from the well-known biological fact that binaural cross-correlators at the level of the brain stem extract information regarding the source direction and segregate various sources into separate channels to enhance speech intelligibility (e.g. Shinn-Cunningham, Schickler, Kopco et al., 2001; Lane & Delgutte, 2005).

Today's cochlear implant hardware is not optimally designed to extract binaural cues and deliver them to the auditory system with high fidelity. Constraints placed by hardware design include the following limitations: (1) At the level of the microphone, as was mentioned above, in a typical commercial bilateral cochlear implant system two separate systems are worn in the two ears. Because the compression in the two processors can be independent, variation in sound level in the environment will result in inter-aural cues that are inconsistent and inappropriate for the actual source locations. (2) Commercial cochlear implant sound-processors have to date been designed to work with pulsatile, nonsimultaneous multi-channel cochlear implants. Signal processing includes band-pass filtering of the signal, followed by envelope extraction. A rate of stimulation is then selected and fixed; however, that rate may differ from the rate at which that information is sampled (update rate). Such strategies therefore do not preserve fine-timing information in the signals in each of the channels, creating a situation that is highly dissimilar from the natural way in which binaural cues are extracted by the binaural auditory system. Although in some cases envelope cues can provide some binaural advantages (e.g., Bernstein & Trahiotis, 2002), the loss of fine-structure information might have significant consequences on performance (van Hoesel, 2004). (3) At the clinical level, devices in the two ears are mapped independently, and at the moment little is known about optimization of mapping strategies for performance on tasks that depend on binaural cues.

It is possible, even likely, that binaural processing and speech understanding in noise could be improved with the use of correlated speech processors, or with the use of a bilateral speech processing strategy. While some attempts have been made (e.g., van Hoesel & Tyler, 2003; van Hoesel, 2004), their potency remains to be demonstrated.

It is important to also consider whether long-term deprivation in the patients tested here can account for lack of effects due to binaural processing. While this is unlikely because bilateral implant users with postlingual deafness generally are sensitive to interaural cues (van Hoesel, 2004; Long, Eddington, Colburn et al., 2003; Long, Carlyon Litovsky et al., 2006) further work is needed to determine how that sensitivity is applied in real-world measures. For instance, sensitivity to interaural cues seems to degrade at higher stimulation rates where speech processors are operating (van Hoesel & Tyler, 2003). An important factor to bear in mind is the fact that patients tested here had only 6 mo of postactivation

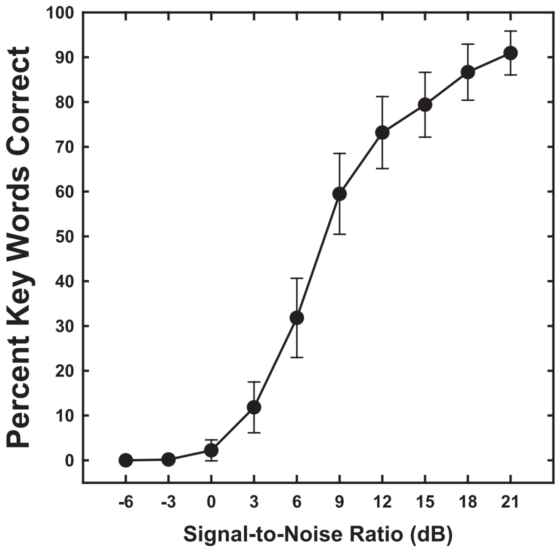

Figure 10. BKB-SIN Test Performance-Intensity (PI) function (±1 S.E.) for data collected from 19 unilateral cochlear implant recipients listening with both speech and noise from a single loudspeaker placed at 0° azimuth.

experience, and a longer period of acclimatization to bilateral implants may be required for further improvement in performance.

In an attempt to connect this work with functional improvements for the patients, the question one should ask is whether these results pertain to experiences of listeners in complex "real world" acoustic environments. In addition, is a 3 dB improvement in SNR when listening with bilateral versus unilateral implants potentially useful in an applied setting? When attempting to translate quantitatively small effects into useful improvements in speech understanding in a realistic auditory environment, we consider the Performance-Intensity (PI) function for stimuli used in the present study. Figure 10 shows BKB-SIN pilot data collected on 19 adult unilateral cochlear implant recipients, who had similar profiles to the subjects in this study, with speech and noise from the front. In the steep, central portion of the PI function, a change of 3 dB in SNR translates into an average improvement of 28% in speech understanding. Such an improvement might well be crucial for a cochlear implant recipient who is struggling to communicate in a noisy environment, particularly when the noise sources and locations may be complex.

Regarding asymmetries, most subjects in this study had relatively similar performance in the two unilateral ear conditions, but 10/34 subjects showed significant asymmetries in the SRT measures when speech and noise emanated from the front. Bilateral advantage for these subjects occurred primarily when the unilateral condition was the poorer ear, and the better ear was added in the bilateral condition, which is consistent with a prior report by Litovsky et al. (2004). Asymmetries do not by necessity imply poorer performance overall, because some of the patients with symmetrical hearing had worse performance than patients with asymmetries. This is evident from individual SRT data (Figure 6), whereby some of the subjects with large asymmetries had the best scores (i.e., were able to obtain 50% correct speech recognition at the least favorable SNRs). This is also reinforced in the bilateral advantage data (Figure 7-8), where the overall values are similar between the two groups if combined across conditions. Asymmetry in head shadow can be attributed to the overall greater improvement in performance in the noise-near-poorer-ear condition, and asymmetry in binaural squelch effect can be attributed to the overall greater improvement in performance in the noise-near-better-ear condition. The reason for asymmetrical performance is hard to pinpoint, but candidate explanations include differences in electrode position within the cochlea, neural survival, possibly differences in success of mapping strategies, and other unknown determinants of success.

From a clinical perspective, one should ask whether asymmetries predict poorer bilateral outcomes. Results from here, and from Gantz et al. (2002), would suggest that predictability of postimplantation bilateral performance from the 'better' ear preoperatively is not reliable. Second, in everyday communication it is not always possible to situate oneself so that the better ear has the best environmental SNR. In situations such as noisy restaurants in which listeners are likely to be surrounded by talkers and noises from multiple directions, functioning with a single implanted ear is likely to pose significant challenges. Finally, it might be argued that when a better ear effect is present bilateral implantation ensures that the better-performing ear will always be implanted.

With regard to subjective impressions, subjects believed that they performed better with bilateral cochlear implants than with only their best unilateral implant in real world situations, as evidenced by results from the Ease of Communication, Background Noise, and Reverberation subscales of the APHAB questionnaire. A limitation that must be acknowledged however, is a possible confounding factor in the study design used for questionnaire administration. Because it was considered important to administer the questionnaire immediately after the subject had experienced the tested listening condition, the APHAB was administered for the bilateral condition with approximately 2 mo longer duration of implant use compared with the unilateral condition. Because postimplantation speech understanding scores did improve over time for many of the subjects, this may have partly influenced their perception of benefit. The difference in scores on the APHAB results between bilateral and unilateral listening were so large across the subjects and three subscales, however, that it is unlikely that the difference in time of administration was the sole factor contributing to the differences that were measured. A further, anecdotal indication regarding preference is that many of the subjects were very reluctant to be without their second implant during the "deprivation" period, because they believed they performed better while wearing both devices.

In conclusion, results from this study provide both objective and subjective support for bilateral implantation in postlingually deafened adults with bilateral, severe to profound hearing losses. Additional studies in the area of bilateral cochlear implantation are still needed to address important topics not studied here. For example, pitch matching of electrode arrays between ears and bilateral speech processing strategies may enhance bilateral benefit. In addition, although the data from this study are very encouraging, further studies are needed to verify bilateral benefit for other subject populations such as prelinguistically deafened adults, adults implanted bilaterally with sequential surgeries that may be many years apart, and the pediatric cochlear implant population.

ACKNOWLEDGMENTS

The authors would like to thank the following clinics and their patients for the time and effort they devoted to this study: California Ear Institute, Dallas Otolaryngology Associates, Ear Medical Group, Houston Ear Research Foundation, Lippy Group for Ear, Nose and Throat, Medical College of Wisconsin, Midwest Ear Institute, NYU Cochlear Implant Center, University of Iowa, University of Texas Southwestern Medical Center, Vanderbilt Bill Wilkerson Center, and The Listen for Life Center at Virginia Mason. We would also like to acknowledge the contributions of Peter Busby and Lesley Whitford of the Cooperative Research Center for Cochlear Implant and Hearing Aid Innovation in Melbourne, Australia, Mead Killion and Patty Niquette of Etymotic Research, Martyn Hyde of the University of Toronto, and Christine Menapace, Denise Black and Bay Pham of Cochlear Americas. This study was supported by Cochlear Americas, Englewood, Colorado.

Address for correspondence: Ruth Litovsky, University of Wisconsin, Waisman Center, Room 521, 1500 Highland Avenue, Madison WI 53705. E-mail: litovsky@waisman.wisc.edu.

Received January 14, 2005; accepted May 28, 2006.

REFERENCES

Armstrong, M., Pegg, P., James, C., Blamey, P. (1997). Speech perception in noise with cochlear implant and hearing aid. *American Journal of Otology*, *18*, S140–S141.

Au, D. K., Hui, Y., Wei, W. I. (2003). Superiority of bilateral cochlear implantation over unilateral cochlear implantation in tone discrimination in Chinese patients. *American Journal of Otolaryngology*, *24*, 19–23.

Bench, J., Kowal, A., Bamford, J. (1979). The BKB (Bamford-Kowal-Bench) sentences lists for partially hearing children. *British Journal of Audiology*, *13*, 108–112.

Bernstein, L. R., Trahiotis, C. (2002). Enhancing sensitivity to interaural delays at high frequencies by using "transposed stimuli". *Journal of the Acoustical Society of America*, *112*, 1026–36.

Bronkhorst, A. (2000). The cocktail party phenomenon: a review of research on speech intelligibility in multiple-talker conditions. *Acustica*, *86*, 117–128.

Byrne, D., Dermody, P. (1975). Binaural hearing aids. *Hearing Instruments*, *26*:*22*, 23–36.

Byrne, D. (1981). Clinical issues and options in binaural hearing aid fitting. *Ear and Hearing*, *2*, 187–193.

Carhart, R. (1958). The usefulness of the binaural hearing aid. *Journal of Speech and Hearing Disorders*, *23*, 42–51.

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. *Journal of the Acoustical Society of America*, *25*, 975–979.

Ching, T. Y. C., Incerti, P., Hill, M. (2004). Binaural benefits for adults who use hearing aids and cochlear implants in opposite ears. *Ear and Hearing*, *25*, 9–21.

Ching, T. Y. C., Psarros, C., Hill, M., Dillon, H., Incerti, P. (2001). Should children who use cochlear implants wear hearing aids in the opposite ear? *Ear and Hearing*, *22*, 365–380.

Cox, R. M., Alexander, G. C. (1995). The Abbreviated Profile of Hearing Aid Benefit. *Ear and Hearing*, *16*, 176–183.

Day, G. A., Browning, G. G., Gatehouse, S. (1988). Benefit from binaural hearing aids in individuals with a severe hearing impairment. *British Journal of Audiology*, *22*, 273–277.

Dillon, H. (2001). Binaural and bilateral considerations in hearing aid fitting. In: *Hearing Aids* (pp. 370–403). Turramurra, Australia: Boomerang Press.

Dorman, M. F., Dahlstrom, L. (2004). Speech understanding by cochlear-implant patients with different left- and right-ear electrode arrays. *Ear and Hearing*, *25*, 191–194.

Durlach, N. I., Colburn, H. S. (1978). Binaural phenomena. In: E. C. Carterette & M. P. Friedman (Eds.), *Handbook of Perception, Volume IV* (pp. 365–466). New York: Academic Press.

Etymotic Research (2005). BKB-SIN Speech-in-Noise Test, Version 1.03 (Compact Disk). Etymotic Research, 61 Martin Lane, Elk Grove Village, IL 60007.

Fetterman, B., Domico, E. (2002). Speech recognition in background noise of cochlear implant patients. *Otolaryngology-Head and Neck Surgery*, *126*, 257–263.

Firszt, J., Holden, L., Skinner, M., Tobey, E., Peterson, A., Wolfgang, G., Runge-Samuelson, C., Wackym, A. (2004). Recognition of speech presented at soft to loud levels by adult cochlear implant recipients of three cochlear implant systems. *Ear and Hearing*, *25*, 375–387.

Gantz, B., Tyler, R., Rubinstein, J., Wolaver, A., Lowder, M., Abbas, P., Brown, C., Hughes, M., Preece, J. (2002). Binaural cochlear implants placed during the same operation. *Otology and Neurotology*, *23*, 169–180.

Green, J. D., Mills, D. M., Bell, B. A., Luxford, W. M., Tonokawa, L. L. (1992). Binaural cochlear implants. *American Journal of Otology*, *13*, 502–506.

Iwaki, T., Matsushiro, N., Mah, S. R., Sato, T., Yasuoka, E., Yamamoto, K., Kubo, T. (2004). Comparison of speech perception between monaural and binaural hearing in cochlear implant patients. *Acta Oto-laryngologica*, *124*, 358–362.

Kuhn-Inacker, H., Shehata-Deiler, W., Müller, J., Helms, J. (2004). Bilateral cochlear implants: a way to optimize auditory perception abilities in deaf children? *International Journal of Pediatric Otorhinolaryngology*, *68*, 1257–1266.

Laback, B., Pok, S. M., Baumgartner, W. D., Deutsch, W. A., Schmid, K. (2004). Sensitivity to interaural level and envelope time differences of two bilateral cochlear implant listeners using clinical sound processors. *Ear and Hearing*, *25*, 488–500.

Laszig, R., Aschendorff, A., Stecker, M., Müller-Deile, J., Maune, S., Dillier, N., et al. (2004) Benefits of bilateral electrical stimulation with the nucleus cochlear implant in adults: 6-month postoperative results. *Otology and Neurotology*, *25*, 958–68.

Lawson, D. T., Wilson, B. S., Zerbi, M., van den Honert, C., Finley, C., FarmerJ. C. McElveenJ. T. Rousch, P. A. (1998). Bilateral cochlear implants controlled by a single speech processor. *The American Journal of Otology*, *19*, 758–761.

Litovsky, R. Y., Parkinson, A., Arcaroli, J., Peters, R., Lake, J., Johnstone, P., Yu, G. (2004). Bilateral cochlear implants in adults and children. *Archives of Otolaryngology Head & Neck Surgery*, *130*, 648–655.

Litovsky, R. Y., Johnstone, P. M., Godar, S., Agrawal, S., Parkinson, A., Peters, R., Lake, J. (2006a). Bilateral cochlear implants in children: localization acuity measured with minimum audible angle. *Ear and Hearing*, *27*, 43–59.

Litovsky, R. Y., Johnstone, P. M., Godar, S. P. (2006b). Benefits of bilateral cochlear implants and/or hearing aids in children. *Int J Audiol*, 45 (Suppl), 78–91.

Long, C. J., Carlyon, R. P., Litovsky, R. Y., Downs, D. H. (2006). Binaural Unmasking with Bilateral Cochlear Implants. *J Assoc Res Otolaryngol*, 2006, [Epub ahead of print].

Long, C. J., Eddington, D. K., Colburn, H. S., Rabinowitz, W. M. (2003). Binaural sensitivity as a function of interaural electrode position with a bilateral cochlear implant user. *Journal of the Acoustical Society of America*, *114*, 1565–74.

Mawman, D. J., Ramsden, R. T., Saeed, S. R., O'Driscoll, M., Adams, T., Aplin, D. Y. (2000). Bilateral cochlear implantation - a case report. *Advances in Otorhinolaryngology*, *57*, 360–363.

Müller, J., Schön, F., Helms, J. (2002). Speech understanding in quiet and noise in bilateral users of the MED-EL COMBI 40/40+ cochlear implant system. *Ear and Hearing*, *23*, 198–206.

Nilsson, M., Soli, S. D., Sullivan, J. (1994). Development of the Hearing In Noise Test for the measurement of speech reception thresholds in quiet and in noise. *Journal of the Acoustical Society of America*, *95*, 1085–1099.

Nopp, P., Schleich, P, D'Haese, P. (2004). Sound localization in bilateral users of MED-EL COMBI 40/40+ cochlear implants. *Ear and Hearing*, *25*, 205–214.

Peterson, F. E., Lehiste, I. (1962). Revised CNC lists for auditory tests. *Journal of Speech and Hearing Disorders*, *27*, 62–70.

Schleich, P., Nopp, P, D'Haese, P. (2004). Head shadow, squelch, and summation effects in bilateral users of the MED-EL COMBI 40/40+ cochlear implant. *Ear and Hearing*, *25*, 197–204.

Schön, F., Müller, J., Helms, J. (2002). Speech reception thresholds obtained in a symmetrical four-loudspeaker arrangement from bilateral users of MED-EL cochlear implants. *Otology & Neurotology*, *23*, 710–714.

Schreurs, K. K., Olsen, W. O. (1985). Comparison of monaural and binaural hearing aid use on a trial period basis. *Ear and Hearing*, *6*, 198–202.

Senn, P., Kompis, M., Vischer, M., Haeusler, R. (2005). Minimum audible angle, just noticeable interaural differences and speech intelligibility with bilateral cochlear implants using clinical speech processors. *Audiology and Neuro-Otology*, *10*, 342–52.

Shinn-Cunningham, B. G., Schickler, J., Kopco, N., Litovsky, R. (2001). Spatial unmasking of nearby speech sources in a simulated anechoic environment. *The Journal of the Acoustical Society of America*, *110*, 1118–1129.

Studebaker, G. A. (1985). A "rationalized" arcsine transform. *Journal of Speech and Hearing Research*, *28*, 455–62.

Tyler, R. S., Parkinson, A. J., Wilson, B. S., Witt, S., Preece, J. P., Noble, W. (2002a). Patients utilizing a hearing aid and a cochlear implant: Speech perception and localization. *Ear and Hearing*, *23*, 98–105.

Tyler, R. S., Gantz, B. J., Rubinstein, J. T., Wilson, B. S., Parkinson, A. J., Bolaver, A., Preece, J. P., Witt, S., Lowder, M.W. (2002b). Three-month results with bilateral cochlear implants. *Ear and Hearing*, *23*(1, suppl.):80S–89S.

van Hoesel, R. J. M. (2004). Exploring the benefits of bilateral cochlear implants. *Audiology and Neuro-Otology*, *9*, 234–246.

van Hoesel, R. J. M., Clark, G. M. (1997). Psychophysical studies with two binaural cochlear implant subjects. *Journal of the Acoustical Society of America*, *102*, 495–507.

van Hoesel, R., Ramsden, R, O'Driscoll, M. (2002). Sound-direction identification, interaural time delay discrimination and speech intelligibility advantages in noise for a bilateral cochlear implant user. *Ear and Hearing*, *23*, 137–149.

van Hoesel, R. J. M., Tong, Y. C., Hollow, R. D., Clark, G. M. (1993). Psychophysical and speech perception studies: a case report on a bilateral cochlear implant subject. *Journal of the Acoustical Society of America*, *94*, 3178–3189.

van Hoesel, R. J. M., Tyler, R. S. (2003). Speech perception, localization, and lateralization with bilateral cochlear implants. *Journal of the Acoustical Society of America*, *113*, 1617–1630.

Vermeire, K., Brokx, J. P., Van de Heyning, P. H., Cochet, E., Carpentier, H. (2002). Bilateral cochlear implantation in children. *International Journal of Pediatric Otorhinolaryngology*, *67*, 67–70.

Wilson, B. S., Finley, C. C., Lawson, D. T., Wolford, R. D., Eddington, D. K., Rabinowitz, W. M. (1991). Better speech recognition with cochlear implants. *Nature*, *352*, 236–238.