Availability of Binaural Cues for Bilateral Implant Recipients and Bimodal Listeners with and without Preserved Hearing in the Implanted Ear

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Key Words

Binaural cues · Bilateral cochlear implant · Bimodal hearing · Hearing preservation patients

Abstract

The purpose of this study was to examine the availability of binaural cues for adult, bilateral cochlear implant (CI) patients, bimodal patients and hearing preservation patients using a multiple-baseline, observational study design. Speech recognition was assessed using the Bamford-Kowal-Bench Speech-in-Noise (BKB-SIN) test as well as the AzBio sentences [Spahr AJ, et al: Ear Hear 2012;33:112–117] presented in a multi-talker babble at a +5 dB signal-to-noise ratio (SNR). Test conditions included speech at 0° with noise presented at 0° (S_0N_0), 90° (S_0N_{90}) and 270° (S_0N_{270}). Estimates of summation, head shadow (HS), squelch and spatial release from masking (SRM) were calculated. Though none of the subject groups consistently showed access to binaural cues, the hearing preservation patients exhibited a significant correlation between summation and squelch whereas the bilateral and bimodal participants did not. That is to say, the two effects associated with binaural hearing – summation and squelch – were positively correlated only for the listeners with bilateral acoustic hearing. This finding provides evidence for the supposition that implant recipients

with bilateral acoustic hearing have access to binaural cues, which should, in theory, provide greater benefit in noisy listening environments. It is likely, however, that the chosen test environment negatively affected the outcomes. Specifically, the spatially separated noise conditions directed noise toward the microphone (mic) port of the behind-the-ear (BTE) hearing aid and implant processor. Thus, it is possible that in more realistic listening environments for which the diffuse noise is not directed toward the processor/hearing aid mic, hearing preservation patients have binaural cues for improved speech understanding.

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Introduction

There are a number of published studies documenting the respective benefits of bilateral cochlear implantation, bimodal hearing and hearing preservation cochlear implantation. Several studies have documented summation, head shadow (HS), binaural squelch (also commonly termed binaural unmasking) and spatial release from masking (SRM) for bilateral cochlear implant (CI) recipients [Schleich et al., 2004; Litovsky et al., 2006; Wackym et al., 2007; Buss et al., 2008; Zeitler et al., 2008; Eapen et al., 2009]. Since binaural hearing is not required for HS or

SRM, the only effects that are solely indicative of binaural hearing are summation and squelch. In previous studies with bilateral-implant recipients, squelch estimates were quite small – in most cases ranging from 0.9 to 1.9 dB for adaptive or pseudoadaptive measures [Schleich et al., 2004; Litovsky et al., 2006] and 8–18 percentage points for fixed signal-to-noise ratio (SNR) measures [Laszig et al., 2004; Buss et al., 2008; Eapen et al., 2009; Verhaert et al., 2012].

In contrast to bilateral-implant users, bimodal listeners, without preserved hearing in the implanted ear, have exhibited greater variability and generally more modest estimates of the use of binaural cues. In a meta-analysis of 13 studies examining adult bimodal listeners, Schafer et al. [2007] reported significant bimodal summation (bimodal vs. CI alone) of 14 percentage points across studies for fixed SNR measures. For adaptive speech reception thresholds (SRTs), both Gifford and Dorman [2012] and Morera et al. [2012] demonstrated 3-dB summation effects for 11 and 15 adult bimodal listeners, respectively.

Estimates of binaural squelch for bimodal listeners have been much less frequently reported than what has been typically reported in the literature for bilateral-implant recipients. Schafer et al. [2007] evaluated 3 studies [Tyler et al., 2002; Dunn et al., 2005; Morera et al., 2005] in a meta-analysis reporting squelch as the performance difference for the CI alone with noise directed to the hearing aid (HA) S_0N_{HA} versus the bimodal condition in the same noise configuration (S_0N_{HA}). Using this, they calculated a mean squelch estimate of 10.1 percentage points across the 3 studies, found to be not statistically significant. Using the same squelch calculation for squelch in an adaptive SRT, Morera et al. [2012] reported significant estimates of squelch ranging from 2.6 to 3.6 dB, over two test sessions. They reported, however, that these estimates were largely driven by the results for 2 bimodal participants who demonstrated much better speech recognition performance with the HA over the implanted ear.

Bimodal listeners have demonstrated a similar magnitude of HS effect to bilateral-implant recipients, but with different estimates across ears, as expected, given the asymmetry in performance across the HA and CI ears. In a meta-analysis of 6 studies referencing the CI ear and 3 studies referencing the HA ear, Schafer et al. [2007] showed significant mean estimates of an HS of 17.4 percentage points for the implanted ear and 61.1 percentage points for the HA ear.

Unilateral-implant recipients with preserved hearing in the implanted ear (hearing preservation patients) have been shown to exhibit significant benefits for speech recognition with various noise sources [Dunn et al., 2010;

Gifford et al., 2010; Dorman et al., 2012; Gifford et al., 2013; Rader et al., 2013], horizontal-plane localization [Dunn et al., 2010] and preserved interaural time differences [Gifford et al., 2013]. Thus, there is some evidence that these patients have access to binaural cues. However, no published study has attempted to compare these patients to patients with bilateral CIs and patients with bimodal hearing regarding the availability of binaural cues.

The hypothesis underlying this project was that implant recipients with bilateral acoustic hearing would exhibit significantly greater summation and squelch than either bilateral CI patients or bimodal listeners (who do not have preserved hearing in the implanted ear). Our hypothesis was driven by our finding of access to interaural time difference cues [Gifford et al., 2013] in hearing preservation patients and the fact that interaural spectral ‘mismatch’, caused by disparate electrode insertion depths and electrode-to-neural interfaces for bilateral recipients, has been shown to negatively affect squelch and summation [Yoon et al., 2012]. Thus, the primary objective of the study was to examine the availability of binaural cues for adult bilateral CI recipients and bimodal listeners, both with and without preserved hearing in the implanted ear.

Materials and Methods

Subjects

Demographic information for the 81 study participants is shown in tables 1–3 for the 30 bilateral, 35 bimodal and 16 hearing preservation participants, respectively. Variables provided include age at testing, gender, implant type, experience with implants, aided Speech Intelligibility Index at 60 dB SPL as provided by the Audioscan Verifit real-ear measures and Consonant Nucleus Consonant (CNC, [Peterson and Lehiste, 1962]) monosyllabic word recognition performance at 60 dBA. Of note is that not all of the implanted electrodes for the hearing preservation were specifically designed for hearing preservation purposes. Nevertheless, with minimally traumatic surgical techniques and patients having more preoperative hearing to potentially preserve, postoperatively we are going to be encountering more clinical patients with measurable, and aidable, hearing in the implanted ear. For the hearing preservation patients, the inclusion criteria specified audiometric thresholds of 80 dB hearing level or better, at ≤ 250 Hz. This criterion was based on two factors. The first was the half-gain rule, as the maximum low-frequency gain for most in-the-ear (ITE) HAs is approximately 40 dB. The second basis for this criterion was that previous studies have shown that the majority of the electroacoustic stimulation- or bimodal-based benefit is derived from acoustic hearing at ≤ 250 Hz [Henry and Ricketts, 2003; Dawson et al., 2004; Zhang et al., 2010].

Participants ranged in age from 19 to 90 years with a mean age of 60.5 years. Of 30 bilateral participants, 26 received their implants in sequential surgeries. For all 81 participants, there was an average of 4.6 years (range 0.5–21.0 years) experience with the first implant. For the sequential bilateral participants, the average ex-

Table 1. Bilateral participant demographic information including age at testing, years of electric experience for the 1st and 2nd implants, implants, processors and CNC monosyllabic word recognition (% correct) in the 1st CI, 2nd CI and in the bilateral condition

Subject	Age	Years exp 1st CI	Years exp 2nd CI	Implants	Processors	CNC 1st CI	CNC 2nd CI	CNC bilateral
1	50	3.3	2.6	CI24RE(CA) ×2	Freedom ×2	88	80	84
2	69	13.3	8.9	CI22M, CI24RCA	Freedom ×2	76	72	72
3	56	4.9	2.9	CI24RE(CA) ×2	Freedom ×2	88	80	84
4	46	10.5	4.1	C1.2, HR90K	Platinum BTE, Harmony	66	50	78
5	59	9.9	4.8	CI24RE(CA) ×2	Freedom ×2	56	72	90
6	52	8.8	2.7	CII, HR90K	Harmony ×2	80	44	92
7	59	19.7	7.6	CI22M, CI24RE(CA)	Freedom ×2	60	22	70
8	53	4.6	2.7	CI24RE(CA) ×2	Freedom ×2	74	80	84
9	22	3.4	3.4	CI24RE(CA) ×2	Freedom ×2	98	72	94
10	19	1.7	1.7	CI24RE(CA) ×2	Freedom ×2	98	90	98
11	47	21.0	3.1	CI22M explanted-reimplanted CI24RE(CA), CI512	CP810 ×2	60	50	80
12	19	9.2	4.0	CI24RCS, CI24RE(CA)	Freedom ×2	74	66	92
13	75	5.6	1.4	CI24RE(CA), CI512	Freedom, CP810	76	76	86
14	63	19.6	1.2	CI22M, CI512	Freedom, CP810	66	88	94
15	51	0.6	0.5	HR90K ×2	Harmony ×2	80	78	92
16	48	2.8	1.5	CI24RE(CA) ×2	Freedom ×2	80	68	84
17	62	6.6	1.4	HR90K ×2	Harmony ×2	70	48	80
18	59	7.1	0.7	HR90K ×2	Harmony ×2	82	70	90
19	67	2.5	1.2	CI24RE(CA) ×2	Freedom ×2	92	84	92
20	65	3.7	3.0	HR90K ×2	Harmony ×2	96	82	96
21	62	8.0	2.9	CI24RE(CA) ×2	Freedom ×2	36	56	58
22	60	2.4	2.1	Sonata (H) ×2	Opus2 ×2	74	74	78
23	37	1.1	0.9	CI512 ×2	CP810 ×2	94	90	96
24	63	0.9	0.7	CI512 ×2	CP810 ×2	46	46	72
25	55	7.5	2.0	CI24RE(CA), CI512	CP810 ×2	74	88	92
26	29	8.3	8.1	HR90K ×2	Harmony ×2	42	68	78
27	45	8.5	8.5	Sonata (H) ×2	Opus2 ×2	84	78	86
28	61	2.8	0.6	Sonata (H) ×2	Opus2 ×2	64	46	72
29	50	9.3	9.3	Combi40+ (H) ×2	Tempo+ ×2	84	66	90
30	50	2.1	1.0	Sonata (H) ×2	Opus2 ×2	48	40	40
Mean	51.8	7.0	3.2	N/A	N/A	73.5	67.5	83.1
SD	14.3	5.5	2.7	N/A	N/A	16.6	17.3	12.4

Participants who were simultaneously implanted are shaded in bold. SD = Standard deviation; Years exp = years of experience; N/A = not applicable.

perience with the second implant was 3.2 years (range 0.5–9.3 years) with a mean difference between the two implants of 4.4 years (range 0.1–18.4 years). Though the CNC monosyllabic-word recognition scores are not demographic in nature, they were included here to characterize outcomes for what is generally considered the most commonly reported metric for English-speaking recipients. More detail will be provided for CNC monosyllabic-word recognition in the Results section.

Individual and mean audiograms for the nonimplanted ears of the unilateral-implant recipients, with and without preserved acoustic hearing in the implanted ear, are shown in figure 1a. Figure 1b displays individual and mean postoperative audiograms for the implanted ear for the participants with preserved acoustic hearing in the implanted ear. Audiograms were obtained for all participants immediately prior to experimentation.

Methods

Speech perception was assessed during one or two visits, depending upon listener preference, using recorded stimuli presented in a sound-treated booth at a calibrated level of 60 dBA. For the 3 participants preferring to participate over two test sessions, the period between sessions was between 1 day and 1 week. Participants used their everyday CI programs and were not permitted to manipulate settings during testing. For Nucleus® implant recipients, all participants used the ‘EVERYDAY’ setting which makes use of the default directional microphone (mic) setting with the addition of Autosensitivity and Adaptive Dynamic Range Optimization [Dawson et al., 2004]. Test conditions for the Speech-in-Noise (SIN) testing included speech at 0° with noise presented at 0° (S₀N₀), 90° (S₀N₉₀) and 270° (S₀N₂₇₀). All three listening conditions were completed for each individual ear as well as for the bi-

Table 2. Bimodal participant demographic information including age at testing, years of electric experience, implant, processor, aided Speech Intelligibility Index (SII) at 60 dB SPL and CNC monosyllabic word recognition (% correct) in the HA, CI and bimodal conditions

Subject No.	Age years	Years exp CI	Implant	Processor	Aided SII	CNC HA	CNC CI	CNC bimodal
1	76	2.1	CI24RE(CA)	Freedom	26	22	54	80
2	82	1.0	CI24RE(CA)	Freedom	51	28	64	48
3	39	4.8	CI24RCA	Esprit 3G	21	38	84	96
4	74	6.2	CI24RE(CA)	Freedom	4	0	84	84
5	64	1.9	HR90K	Harmony	22	0	80	90
6	66	1.5	CI24RE(CA)	Freedom	10	0	90	90
7	58	5.5	HR90K	Harmony	19	0	90	78
8	70	4.8	CI24RCA	Freedom	28	0	92	86
9	82	1.8	CI24RE(CA)	Freedom	22	2	68	60
10	65	1.3	CI24RE(CA)	Freedom	12	0	90	80
11	77	0.6	CI24RE(CA)	Freedom	29	24	84	84
12	76	1.0	CI24RE(CA)	Freedom	17	14	50	60
13	34	0.8	CI24RE(CA)	Freedom	36	10	80	84
14	90	1.0	CI24RE(CA)	Freedom	36	20	74	84
15	50	0.5	HR90K	Harmony	40	30	88	88
16	76	13.2	CI24RE(CA)	Freedom	18	6	74	74
17	47	10.7	CI24M	Freedom	15	6	72	82
18	41	3.2	HR90K	Harmony	7	0	88	82
19	52	0.6	CI512	CP810	43	54	98	98
20	64	0.8	CI512	CP810	20	8	84	86
21	78	5.6	CI24RE(CA)	Freedom	20	2	52	68
22	69	2.1	CI24RE(CA)	Freedom	35	26	92	90
23	74	5.9	CI24RE(CA)	Freedom	15	0	80	76
24	79	0.9	CI24RE(CA)	Freedom	16	10	50	72
25	84	7.3	Combi40+	Tempo+	6	0	78	68
26	62	0.6	CI24RE(CA)	Freedom	15	0	46	72
27	68	6.4	CI24RCA	Freedom	21	18	94	90
28	72	5.3	CI24RE(CA)	Freedom	28	6	92	88
29	86	0.8	CI512	CP810	33	22	38	64
30	68	1.9	CI512	CP810	23	0	68	84
31	68	3.5	HR90K	Harmony	37	18	74	80
32	72	3.4	CI24RE(CA)	Freedom	15	0	76	84
33	73	2.2	CI512	CP810	28	30	91	94
34	79	10.7	CI24RCA	CP810	38	34	60	78
35	64	5.3	HR90K	Harmony	40	6	90	96
Mean	68.0	3.6	N/A	N/A	24.2	12.4	76.3	80.5
SD	13.5	3.2	N/A	N/A	11.4	13.9	15.8	11.2

lateral, best-aided condition (bilateral, bimodal or CI + bilateral HAs).

For unilateral-implant recipients wearing HAs in one or both ears, HA audibility was verified for 60-dB-SPL speech immediately prior to experimentation using real-ear measurements with NAL-NL1 prescriptive targets [Dillon et al., 1998]. Participants for whom HAs were undershooting target audibility by >5 dB at one or more frequencies had their HAs reprogrammed to match NAL-NL1 targets. For participants whose own HAs could not be adjusted due to lack of reserve gain or incompatibility with NOAH programming software, laboratory stock HAs (Phonak Naida III UP with deactivated Sound Recover, i.e. non-

linear frequency compression) were programmed and used for testing purposes. This occurred for 6 of the bimodal subjects (18, 23, 24, 25, 32 and 33). For these 6, testing was only completed with the stock HAs programmed to NAL-NL1 target audibility.

For BKB-SIN, the SNR-50 – or the SNR at which approximately 50% correct performance would be expected – was recorded for each condition. Two paired lists (e.g. 1A/B and 2A/B) were presented for each listening condition with the average SNR-50 across the paired lists reported as mean performance per participant. For the AzBio sentences at +5 dB SNR, performance was recorded in percent words correct. Two 20-sentence lists

Fig. 1. Individual and mean audiometric thresholds (in dB) obtained on the day of testing for the nonimplanted ears of the bimodal and hearing preservation patients as well as the implanted ear of the hearing preservation patients. Error bars represent ± 1 standard deviation.

Table 3. Hearing preservation participant demographic information including age at testing, years of electric experience, implant, processor, aided Speech Intelligibility Index (SII) at 60 dB SPL in both the implanted and nonimplanted ears and CNC monosyllabic word recognition (% correct) in the following conditions: HA in implanted ear (ipsi HA), HA in nonimplanted ear (contra HA), CI only, CI + ipsi HA, CI + contra HA and CI + bilateral HAs

Subject No.	Age years	Years exp CI	Implant	Processor	Aided SII non-CI ear	Aided SII CI ear	CNC ipsi HA	CNC contra HA	CNC CI only	CNC CI + ipsi HA	CNC CI + contra HA	CNC CI + bilateral HA
1	71	1.1	Hybrid L24	Hybrid Freedom	31	24	24	26	68	82	74	78
2	70	4.7	CI24RCA	Freedom	18	6	0	10	94	90	98	94
3	69	1.0	Hybrid S8	Hybrid Freedom	57	44	16	50	42	74	78	82
4	52	0.7	CI512	CP810	46	9	6	54	98	96	98	98
5	49	4.5	CI24RE(CA)	Freedom	30	10	4	4	90	90	96	98
6	79	1.7	CI24RE(CA)	Freedom	12	16	0	26	80	92	96	94
7	61	2.1	Hybrid L24	Hybrid Freedom	32	34	21	48	76	94	90	88
8	61	1.0	CI512	CP810	19	6	10	30	84	82	80	84
9	45	1.4	Sonata (H)	Opus2	30	6	2	44	82	84	82	84
10	53	4.0	Hybrid S8	Hybrid Freedom	38	34	28	36	44	60	62	80
11	58	6.4	CI24RCA	CP810	31	16	18	24	82	86	84	86
12	52	2.0	Hybrid S8	Hybrid Freedom	32	12	12	48	62	58	86	86
13	34	4.1	CI24RCA	Esprit 3G	35	9	2	28	80	84	88	90
14	52	1.4	Hybrid L24	Hybrid Freedom	44	36	26	52	76	90	88	88
15	77	0.6	Sonata (H)	Opus2	22	12	0	14	48	56	46	56
16	83	0.9	CI422	CP810	29	15	0	12	26	42	40	46
Mean	58.9	2.4	N/A	N/A	31.6	18.1	10.6	31.6	70.8	78.8	80.4	83.3
SD	12.5	1.8	N/A	N/A	11.2	12.4	10.23	16.1	20.7	16.1	17.4	14.0

were run for each listening condition with the average performance across the two lists recorded for each participant. Listening conditions were counterbalanced across participants in each listener group with the list numbers chosen in a quasi-random manner.

In addition to the SIN testing, CNC word recognition was also assessed for all 81 subjects for each ear individually as well as in the

bilateral, best-aided condition. For the hearing preservation subjects, additional listening conditions were tested including a HA in the implanted ear (ipsilateral HA), a CI plus an ipsilateral HA, a CI plus a contralateral HA (commonly termed the 'bimodal' condition), as well as a CI plus bilateral HAs (i.e. bilateral best-aided). All speech stimuli were presented at a calibrated level of 60 dBA.

Results

CNC Word Recognition

As shown in tables 1–3, CNC word recognition performance was obtained for all 81 participants in each individual ear condition and the bilateral, best-aided condition. Mean ‘implant only’ performance across all 81 participants was 72.3% with a range of 26–98% correct.¹ Considering the poorer-hearing ear for all participants, mean CNC word recognition was 35.3% with a range of 0–90% with the lowest scores belonging to the unilateral-implant recipients’ nonimplanted ears. Considering the bilateral, best-aided condition (i.e. all devices, both ears) for all 81 participants, mean CNC word recognition was 82.0% with a range of 40–98% correct.

For CNC word recognition, a two-way, repeated-measures analysis of variance (ANOVA) was completed with the subject group (bimodal, bilateral and hearing preservation groups) and listening condition (better ear, poorer ear and bilateral best-aided) as variables. For this analysis, the better-hearing ear for the hearing preservation patients was defined as the implant plus the ipsilateral HA (see table 3) and the bilateral best-aided condition included both ears with all available devices. In other words, the bilateral best-aided condition included the implant plus bilateral HAs for the hearing preservation subjects. The ANOVA revealed a significant effect of subject group [$F_{(2, 78)} = 21.1$, $p < 0.001$], listening condition [$F_{(2, 78)} = 437.7$, $p < 0.001$] and a significant interaction [$F_{(4)} = 65.0$, $p < 0.001$]. Post hoc multiple comparisons using the Holm-Sidak test revealed no significant difference across the 3 subject groups for the better-hearing ear ($p > 0.26$ for all comparisons). Considering the bilateral best-aided condition, there was also no significant difference across the 3 groups ($p > 0.24$ for all comparisons). Not unexpectedly, however, there was a significant difference for the poorer-

hearing ear, with the bilateral subjects achieving significantly higher levels of word recognition than both the bimodal ($t = 14.7$, $p < 0.001$) and the hearing preservation subjects ($t = 7.0$, $p < 0.001$). The hearing preservation subjects scored significantly higher than the bimodal subjects ($t = 4.7$, $p < 0.001$) for the poorer-hearing ear which reflects lower (i.e. better) audiometric thresholds in the nonimplanted ears for the hearing preservation participants (fig. 1) and associated higher (i.e. better) aided Speech Intelligibility Index values (see tables 2, 3).

Summation for CNC word recognition can be estimated by subtracting the score for the better-hearing ear from the bilateral, best-aided score. Summation estimates were 6.1, 4.3 and 4.4 percentage points for the bilateral, bimodal and hearing preservation subjects, respectively. Statistical analysis was completed for summation estimates across subject groups. A Kruskal-Wallis ANOVA on ranks was completed as the assumption of normality was not met. There was no significant difference [$H_{(2)} = 1.6$, $p = 0.45$] across the 3 subject groups for summation observed with CNC word recognition in quiet.

Speech-in-Noise: S_0N_0

With reference to the BKB-SIN scores shown in figure 2a, mean SNR-50 for the better-hearing ear was 6.8 dB for bilateral, 7.2 dB for bimodal and 7.4 dB for hearing preservation subjects. Mean SNR-50 for the poorer-hearing ear was 10.0 dB for bilateral, 19.3 dB for bimodal and 15.0 dB for hearing preservation subjects. For the best-aided condition, mean SNR-50 was 5.8 dB for bilateral, 6.3 dB for bimodal and 5.3 dB for hearing preservation subjects. A two-way ANOVA was completed with listening condition and subject group as the variables. The analysis revealed a significant main effect of listening condition [$F_{(2)} = 129.8$, $p < 0.001$], subject group [$F_{(2)} = 23.5$, $p < 0.001$] and a significant interaction [$F_{(2)} = 17.1$, $p < 0.001$]. Post hoc analysis using the Holm-Sidak statistic showed no difference across the 3 subject groups for either the better-hearing ear or the best-aided condition ($p > 0.11$ for all comparisons). There were significant differences across the subject groups for the poorer-hearing ear with all subject groups being significantly different from one another ($p < 0.001$ in all cases).

With reference to the AzBio sentence recognition at +5 dB SNR (fig. 2b), mean performance (in percent correct) for the better-hearing ear was 56.8% for bilateral, 49.2% for bimodal and 60.1% for hearing preservation subjects. Mean performance for the poorer-hearing ear was 36.1% for bilateral, 5.7% for bimodal and 16.7% for hearing preservation subjects. For the best-aided condi-

¹ For most sequentially implanted recipients, the better-performing ear was the first implanted ear. For 20 of the 26 of the sequentially implanted bilateral recipients (77% of the study bilateral population), the first implanted ear was the better-performing ear (i.e. subjects 1–7, 11–13, 15–20, 22–24, 28 and 29). Out of these 20 participants, 3 (6, 7 and 17) exhibited statistically significant CNC word recognition performance for the 1st implanted ear based on a binomial distribution model [Thornton and Raffin, 1978]. Of the 6 sequentially implanted bilateral recipients for whom the 1st implanted ear did not exhibit the best performance (i.e. subjects 5, 8, 14, 21, 25 and 26), 3 demonstrated a significantly poorer performance with the 1st implanted ear using the binomial distribution statistic [Thornton and Raffin, 1978]. All sequentially implanted patients reported having first implanted their poorer-hearing ear on the basis of preoperative audiometric thresholds and/or speech recognition performance. Except for the 3 subjects demonstrating significantly poorer performance with the 1st implanted ear, all of them reported a preference for the 1st implanted ear.

Fig. 2. Box and whisker plots for BKB-SIN (SNR-50; **a**) and AzBio at +5 dB (% correct; **b**) for the S_0N_0 listening condition. The box extends from the 25th to the 75th percentile with the horizontal

line in the middle representing the median. The whiskers extend from the minimum to the maximum value for all individual data thus displaying the range of scores for any given condition.

Fig. 3. Box and whisker plots for BKB-SIN (in dB; **a**) and AzBio at +5 dB (in percentage points; **b**). The box extends from the 25th to the 75th percentile with the horizontal line in the middle repre-

senting the median. The whiskers extend from the minimum to the maximum value for all individual data thus displaying the range of scores for any given condition.

tion, mean performance was 65.5% for bilateral, 58.6% for bimodal and 65.9% for hearing preservation subjects. As with the BKB-SIN results in the S_0N_0 condition, a two-way ANOVA was completed with listening condition and subject group as the variables. The analysis revealed a significant main effect of listening condition [$F_{(2,231)} = 116.2$, $p < 0.001$], subject group [$F_{(2,2)} = 15.9$, $p < 0.001$] and a significant interaction [$F_{(2,4)} = 4.4$, $p = 0.002$]. Holm-Sidak post hoc analysis showed no difference across the 3 groups for either the better-hearing ear or the best-aided condition ($p > 0.10$ for all comparisons). There were sig-

nificant differences across the groups for the poorer-hearing ear, with all 3 groups being significantly different from one another (bilateral vs. bimodal, $p < 0.001$; bilateral vs. hearing preservation, $p = 0.001$; bimodal vs. hearing preservation, $p = 0.04$).

Summation

Estimates of summation were gathered from figure 2 as the difference between the better-hearing ear and best-aided condition. Box and whisker plots are shown in figure 3. For BKB-SIN (fig. 3a), mean summation was 1.0,

Fig. 4. Box and whisker plots for BKB-SIN (SNR-50) for the bilateral (a), bimodal (b) and hearing preservation subjects (c) for the spatially separated listening conditions with S_0N_{90} and S_0N_{270} .

0.9 and 1.9 dB for the bilateral, bimodal and hearing preservation participants, respectively. Individual estimates of summation ranged from -3.5 to 7.3 dB for bilateral, -2 to 4 dB for bimodal and -1.5 to 6.0 dB for hearing preservation participants. A one-way ANOVA revealed no difference across the subjects groups in terms of summation effects ($F_{(2)} = 1.7$, $p = 0.18$). For AzBio sentence rec-

ognition at +5 dB (fig. 3b), mean summation was 8.5, 9.5 and 5.4 percentage points for the bilateral, bimodal and hearing preservation subjects, respectively. Individual estimates of summation ranged from -13 to 52 percentage points for bilateral, -13 to 25 percentage points for bimodal and -12 to 42 percentage points for hearing preservation participants. As with BKB-SIN, a one-way ANOVA revealed no difference across the groups ($F = 0.62$, $p = 0.54$).

Speech-in-Noise: Spatially Separated Listening Conditions

Figure 4 displays box and whisker plots for BKB-SIN scores (SNR-50) for the bilateral, bimodal and hearing preservation subjects for the spatially separated listening conditions (S_0N_{90} and S_0N_{270}). Figure 5 displays the same box and whisker plots as figure 4 but for AzBio sentence recognition at +5 dB SNR. With the data shown in figures 2, 4 and 5, we are able to calculate estimates of HS, SRM and squelch.

Head Shadow

Estimates of HS were calculated as follows:

Bilateral Subjects

HS for 1st CI = score for 1st CI (noise to 2nd CI) - score for 1st CI (noise to 1st CI).

HS for 2nd CI = score for 2nd CI (noise to 1st CI) - score for 2nd CI (noise to 2nd CI).

Bimodal Subjects

HS for CI ear = score for CI ear (noise to HA ear) - score for CI ear (noise to CI ear).

HS for HA ear = score for HA ear (noise to CI ear) - score for HA ear (noise to HA ear).

Hearing Preservation Subjects

HS for CI ear = score for CI ear (noise to non-CI ear) - score for CI ear (noise to CI ear).

HS for non-CI ear = score for non-CI ear (noise to CI ear) - score for non-CI ear (noise to non-CI ear).

Estimates of HS are shown in figure 6 for BKB-SIN and AzBio at +5 dB SNR, respectively. For BKB-SIN, mean HS for the bilateral CI recipients was 7.6 and 5.3 dB for the 1st and 2nd implanted ears, respectively. Mean HS for the bimodal listeners was 7.6 and 3.3 dB for the CI and HA ears, respectively. Mean HS for the hearing preservation subjects was 5.0 and 4.8 dB for the CI and non-CI ears, respectively. A two-way ANOVA with subject

Fig. 5. Box and whisker plots for AzBio sentences at +5 dB (percent correct) for the bilateral (a), bimodal (b) and hearing preservation subjects (c) for the spatially separated listening conditions with S_0N_{90} and S_0N_{270} .

group and listening condition (poorer vs. better ear) revealed no effect of subject group [$F_{(2, 231)} = 1.2$, $p = 0.30$], a significant effect of listening condition [$F_{(2, 2)} = 7.7$, $p = 0.006$] and no interaction [$F_{(2, 2)} = 2.4$, $p = 0.09$]. Thus there was no difference in HS across the subject groups, but estimates were significantly greater for the better-hearing ear.

For AzBio at +5 dB SNR, mean HS for the bilateral CI recipients was 34.7 and 32.9 percentage points for the 1st and 2nd implanted ears, respectively. Mean HS for the bimodal listeners was 36.6 and 7.1 percentage points for the CI and HA ears, respectively. Mean HS for the hearing preservation subjects was 22.0 and 11.8 percentage points for the CI and non-CI ears, respectively. A two-way ANOVA completed with subject group and listening condition revealed a significant effect of subject group [$F_{(2, 231)} = 8.7$, $p < 0.001$], a significant effect of listening condition [$F_{(2, 2)} = 14.0$, $p < 0.001$] and a significant interaction [$F_{(2, 2)} = 8.2$, $p < 0.001$]. Holm-Sidak post hoc analysis revealed that the HS estimates were significantly greater for the bilateral-implant recipients than for the bimodal ($t = 3.4$, $p = 0.001$) and hearing preservation ($t = 3.8$, $p = 0.0002$) participants. There was no significant difference across the 3 subject groups for the better-hearing ear ($p > 0.05$ for all comparisons). There were significant differences across the subject groups for the poorer-hearing ear with each group being significantly different from the others (bilateral vs. bimodal, $p = 0.03$; bilateral vs. hearing preservation, $p = 0.03$; bimodal vs. hearing preservation, $p = 0.01$).

Spatial Release from Masking

Estimates of SRM were calculated as follows:

Bilateral Subjects

SRM for 1st CI = score for 1st CI (noise to 2nd CI) – score for 1st CI (noise at 0°).

SRM for 2nd CI = score for 2nd CI (noise to 1st CI) – score for 2nd CI (noise at 0°).

Bimodal Subjects

SRM for CI ear = score for CI ear (noise to HA ear) – score for CI ear (noise at 0°).

SRM for HA ear = score for HA ear (noise to CI ear) – score for HA ear (noise at 0°).

Hearing Preservation Subjects

SRM for CI ear = score for CI ear (noise to non-CI ear) – score for CI ear (noise at 0°).

SRM for non-CI ear = score for non-CI ear (noise to CI ear) – score for non-CI ear (noise at 0°).

For All Subject Groups, SRM in the Best-Aided Condition

SRM for best-aided = score for best-aided condition (noise to poorer ear) – score for best-aided condition (noise at 0°).

Fig. 6. Box and whisker plots displaying estimates of HS for BKB-SIN (in dB; **a**) and AzBio at +5 dB SNR (in percentage points; **b**) for the poorer ear, better ear and best-aided conditions.

Fig. 7. Box and whisker plots displaying estimates of SRM for BKB-SIN (in dB; **a**) and AzBio at +5 dB SNR (in percentage points; **b**) for the best-aided condition.

Estimates of SRM in the best-aided condition are shown in figure 7 for BKB-SIN and AzBio at +5 dB SNR, respectively. For BKB-SIN, mean SRM for the bilateral CI recipients was 3.5 and 3.8 dB for the 1st and 2nd implanted ears, respectively, and 5.1 dB for the bilateral best-aided condition. Mean SRM for the bimodal listeners was 5.7 and 1.5 dB for the CI and HA ears, respectively, and 4.9 dB for the bimodal best-aided condition. Mean SRM for the hearing preservation subjects was 4.0 and 2.1 dB for the CI and non-CI ears, respectively, and 3.8 dB for the best-aided condition (CI + bilateral HA). A one-way ANOVA completed for SRM observed revealed no effect of subject group for the better-hearing ear [$F_{(2)} = 1.4$, $p = 0.25$] or for the best-aided condition [$F_{(2)} = 1.3$, $p = 0.29$], but a significant effect of group for the poorer-hearing ear [$F_{(2)} = 11.1$, $p < 0.001$]. For the poorer-hearing ear, post hoc testing (Holm-Sidak) revealed that the SRM of bimodal subjects was significantly poorer than that of both

bilateral ($t = 4.5$, $p = 0.00002$) and hearing preservation ($t = 3.0$, $p = 0.004$) subjects, but that the bilateral and hearing preservation groups were not different ($p = 0.49$).

For AzBio at +5 dB SNR, mean SRM for the bilateral CI recipients was 20.9 and 16.3 percentage points for the 1st and 2nd implanted ears, respectively, and 20.4 percentage points for the best-aided condition. Mean SRM for the bimodal listeners was 19.9 and 2.7 percentage points for the CI and HA ears, respectively, and 14.1 percentage points for the best-aided condition. Mean SRM for the hearing preservation subjects was 8.4 and 11.5 percentage points for the CI and non-CI ears, respectively, and 10.0 percentage points for the best-aided condition. A one-way ANOVA completed for SRM observed revealed no effect of subject group for the better-hearing ear [$F_{(2)} = 2.2$, $p = 0.12$] or for the best-aided condition [$F_{(2)} = 0.14$, $p = 0.87$], but a significant effect of group for the poorer-hearing ear [$F_{(2)} = 13.3$, $p < 0.001$]. For the poorer-

Fig. 8. Box and whisker plots displaying estimates of SRM for BKB-SIN (in dB; **a**) and AzBio at +5 dB SNR (in percentage points; **b**) for the best-aided condition.

hearing ear, Holm-Sidak post hoc analysis revealed that the SRM estimates were significantly greater for the bilateral-implant recipients than for both the bimodal ($t = 5.2$, $p < 0.0001$) and the hearing preservation ($t = 2.2$, $p = 0.049$) participants.

Squelch

Estimates of squelch were calculated as follows:

Bilateral Subjects

Squelch for 1st CI = score for bilateral CI (noise to 2nd CI) – score for 1st CI (noise to 2nd CI).

Squelch for 2nd CI = score for bilateral CI (noise to 1st CI) – score for 2nd CI (noise to 1st CI).

Bimodal Subjects

Squelch for CI ear = score for bimodal (noise to HA ear) – score for CI ear (noise to HA ear).

Squelch for HA ear = score for bimodal (noise to CI ear) – score for HA ear (noise to CI ear).

Hearing Preservation Subjects

Squelch for CI ear = score for best aided (noise to non-CI ear) – score for CI ear (noise to non-CI ear).

Squelch for non-CI ear = score for best aided (noise to CI ear) – score for non-CI ear (noise to CI ear).

Squelch estimates for BKB-SIN and AzBio at +5 dB are shown in Figures 8a and b, respectively. For BKB-SIN, because a lower score represents better performance, squelch estimates obtained via the above-referenced equations yielded negative numbers for positive squelch and positive numbers for negative squelch. For ease of reporting and interpretation, all squelch estimates for the BKB-SIN metric have been inverted, such that positive squelch will be reported as positive numbers and vice versa. For BKB-SIN, mean squelch for the bilateral CI recipients was 0.9 and 2.3 dB for the 1st and 2nd implanted ears, respectively. Mean squelch for the bimodal listeners was –0.7 and 10.4 dB for the CI and HA ears, respectively. Mean squelch for the hearing preservation subjects was 0.5 and 7.2 dB for the CI and non-CI ears, respectively. A two-way ANOVA completed with subject group and listening condition revealed an effect of subject group [$F_{(2)} = 12.3$, $p < 0.001$], listening condition [$F_{(1)} = 99.9$, $p < 0.001$] and a significant interaction [$F_{(2, 1)} = 26.7$, $p < 0.001$]. Holm-Sidak post hoc analysis revealed that the squelch estimates were significantly lower for the bilateral-implant recipients than both the bimodal ($t = 3.4$, $p = 0.001$) and hearing preservation ($t = 3.8$, $p = 0.0002$) participants – an effect that was driven primarily by the non-CI ears for the bimodal and hearing preservation participants. There was no significant difference across the 3 subject groups for the better-hearing ear ($p > 0.006$ for all comparisons). There were significant differences across the subject groups for the poorer-hearing ear with all 3 groups being significantly different from one another (bilateral vs. bimodal, $p < 0.0001$; bilateral vs. hearing preservation, $p < 0.001$; bimodal vs. hearing preservation, $p = 0.006$).

For AzBio sentence recognition at +5 dB SNR, mean squelch estimates for the bilateral CI recipients were 6.1 and 7.2 percentage points for the 1st and 2nd implanted ears, respectively. Mean squelch for the bimodal participants was 0.2 and 32.7 percentage points for the CI and HA ears, respectively. Mean squelch for the hearing preservation subjects was 1.7 and 42.1 percentage points for the CI and non-CI ears, respectively. Statistical analysis revealed a significant effect of subject group [$F_{(2)} = 5.7$, $p = 0.004$], a significant effect of listening condition [$F_{(1)} = 47.2$, $p < 0.001$] and a significant interaction [$F_{(2,1)} = 11.9$, $p < 0.001$]. Post hoc analysis using the Holm-Sidak test revealed that squelch was significantly lower for the bilateral-implant recipients than both the bimodal ($t = 2.8$, $p = 0.0017$) and the hearing preservation ($t = 3.0$, $p = 0.003$) participants – as discussed above with BKB-SIN, this outcome was primarily driven by the non-CI ears for the bimodal and hearing preservation participants. There was no difference across the 3 subject groups for the better-hearing ear ($p > 0.25$ for all comparisons). There was a significant difference across the subject groups for the poorer-hearing ear with the bilateral group demonstrating significantly less squelch than both bimodal listeners ($p < 0.001$) and hearing preservation ($p < 0.001$) participants.

Discussion

The results of this study were largely consistent with previous reports in the literature examining availability of binaural cues for adults with bilateral implants. Mean estimates of HS for the implanted ears were consistent with previous reports in the literature ranging from 5.0 to 7.6 dB for the pseudoadaptive BKB-SIN (e.g. Gantz et al. [2002], Muller et al. [2002], Schon et al. [2002], Schleich et al. [2004] and Litovsky et al. [2006]) and 22.0–36.6 percentage points for AzBio sentences at +5 dB (e.g. Buss et al. [2008] and Eapen et al. [2009]). Mean estimates of squelch for the bilateral-implant patients were also consistent with previous reports ranging from 0.9 to 2.3 dB for the BKB-SIN measure [Schleich et al., 2004; Litovsky et al., 2006] and 6.1–7.2 percentage points for AzBio sentence recognition at +5 dB SNR [Buss et al., 2008; Eapen et al., 2009]. Summation was also roughly consistent with previous reports for bilaterally implanted adults, though slightly lower in this study, with mean summation being 1.0 dB for BKB-SIN [Schleich et al., 2004; Litovsky et al., 2006; Zeitler et al., 2008] and 8.5 percentage points for AzBio sentences at +5 dB SNR [Buss et al., 2008; Eapen et

al., 2009]. Thus the results of our study with simultaneous and sequential bilateral-implant recipients replicate the findings of previous reports – most of which examined bilateral recipients who had received their implants in the same surgery.

Considering these effects for the unilateral-implant participants, estimates of HS, squelch and SRM were not significantly different from what was observed in the bilateral-implant recipients – when considering the implanted ear. Estimates of summation were also not different for the bimodal and hearing preservation subjects with acoustic hearing compared to the bilateral-implant users.

Considering the nonimplanted ear for bimodal and hearing preservation participants, estimates of squelch were significantly greater than what was observed for any of the implanted ears. The reason for this seemingly paradoxical finding is related to the underlying assumption of symmetry in performance across ears. That is to say, squelch provides information regarding improvement in speech understanding provided by adding an ear with a poorer SNR. For the bimodal and hearing preservation patients, the improvement gained by adding the implanted ear was disproportionately greater than the improvement gain for bilateral-implant users, given that the CI ear yields significantly greater speech understanding than the nonimplanted ears. So the squelch estimates for the bimodal and hearing preservation listeners simply do not provide an accurate description as the ear with the better SNR was neither the better-performing ear nor equivalent in performance to the ear with the poorer SNR. For this reason, Morera et al. [2012] suggested the use of a modified equation for describing bimodal squelch effects as follows:

$$\text{squelch} = \text{bimodal score (noise to non-CI ear)} - \text{CI score (noise to non-CI ear)}$$

This is the equation we used to describe squelch for the implanted ears of bimodal and hearing preservation patients for which mean estimates were –0.7 and 0.5 dB for BKB-SIN and 0.2 and 1.7 percentage points for AzBio sentences at +5 dB.

Given that some hearing preservation patients have been shown to exhibit some preserved sensitivity to interaural time differences for low-frequency stimuli [Gifford et al., 2013], it is reasonable to ask why the hearing preservation patients in our study failed to exhibit summation and, more importantly, squelch. A number of potential explanations for this finding are likely. One may relate to the degree of summation effects that could be used in the listening paradigm used here. As seen in fig-

Fig. 9. Individual squelch estimates of hearing preservation patients are plotted as a function of summation for BKB-SIN (dB; **a**) and AzBio +5 dB (percentage points; **b**). Diagonal dashed lines represent a linear regression function representing the Pearson correlation coefficient shown in each panel.

ure 3, the range of measurable summation for the hearing preservation patients was quite variable, with some exhibiting summation effects of 6 dB for BKB-SIN and 42 percentage points for AzBio at +5 dB. By completing correlation analyses for summation and squelch for all listener groups in our study, there was a significant positive correlation observed between summation and squelch for the hearing preservation patients (BKB-SIN $r = 0.54$, $p = 0.04$; AzBio $r = 0.71$, $p = 0.01$) as displayed in figure 9. The correlation analyses for the bilateral and bimodal participants, however, were not significant for either speech metric. One could contend that these data support our hypothesis that implant recipients with preserved acoustic hearing in the implanted ear should have greater access to binaural cues. In other words, those implant recipients with bilateral acoustic hearing who exhibit summation effects in our experimental paradigm were also more likely to benefit from binaural squelch than both bilateral-implant recipients and bimodal listeners.

Another possible reason for the lack of binaural effects for the hearing preservation patients is the chosen test environment. Our study incorporated the classic experimental design for calculating HS and squelch including the following: S_0N_0 , S_0N_{90} and S_0N_{270} . Presenting noise directly to the side of the listener, as in S_0N_{90} and S_0N_{270} , is not the best choice of conditions given the mic port location for CI processors and behind-the-ear (BTE) HAs.

Festen and Plomp [1986] demonstrated that the BTE mic location negatively affected SNR by 2 dB when speech was presented at 0° compared to $\pm 90^\circ$. In other words, the physical SNR at the mic will be lower (i.e. poorer) with noise originating at 90° or 270° compared to having both speech and noise at 0° . As 14 of the 16 hearing preservation patients were Nucleus implant recipients, the premise of mic location affecting the outcomes in the chosen test environment may appear flawed given that directional mics have been used in cochlear processors since the introduction of the FreedomTM processor. In a description of the polar patterns of the Freedom processor, Patrick et al. [2006] showed that with speech at 0° and noise at 90° , the signal at 90° was still approximately 2-dB higher than the signal at 0° azimuth. Thus, the experimental setup had the potential to artificially inflate estimates of HS and negatively impact estimates of squelch for all subject groups in our study as well as in all previous studies for which noise was presented directly to the side of the listener. In a more diffuse-noise condition – as experienced in everyday listening environments – it may be the case that hearing preservation patients would benefit from binaural squelch.

Finally, another possible reason for the lack of binaural effects for the hearing preservation patients was the heterogeneity of electrode arrays and the range of hearing thresholds in the implanted ear. As mentioned in the Subjects section, not all of the electrodes implanted for hear-

ing preservation were specifically designed for this purpose. Neither the Nucleus perimodiolar arrays nor the Sonata H (i.e. standard) electrodes were designed with hearing preservation in mind, despite having met the inclusion criteria for our study. Further investigation will continue to determine whether the purportedly atraumatic electrodes yield binaural benefit, namely summation and squelch, for implant recipients with preserved hearing.

Conclusion

We hypothesized that preserved acoustic hearing in the implanted ear – affording bilateral acoustic hearing – would yield greater access to binaural cues for the hearing preservation participants. Our findings could not reject the null hypothesis. Although our study did not provide evidence for the availability of binaural cues to patients

with hearing preservation, the findings may have been confounded by the test conditions. Specifically, the spatially separated noise conditions directed noise toward the mic port of the BTE HA and implant processor; this negatively affects the SNR compared to the S_0N_0 condition [Festen and Plomp, 1986]. Given that 12 of the 16 hearing preservation listeners exhibited some binaural summation, it is possible that greater access to binaural cues may be present in more realistic listening environments.

Acknowledgements

The research reported here was supported by grant R01 DC009404 from the NIDCD to the first author. Portions of this data set were presented at the 2008 conference of the American Auditory Society in Scottsdale, Ariz., USA and the 13th Symposium on Cochlear Implants in Children (CI2011) in Chicago, Ill., USA.

References

- Buss E, Pillsbury HC, Buchman CA, Pillsbury CH, Clark MS, Haynes DS, Labadie RF, Amberg S, Roland PS, Kruger P, Novak MA, Wirth JA, Black JM, Peters R, Lake J, Wackym PA, Firszt JB, Wilson BS, Lawson DT, Schatzer R, D'Haese PS, Barco AL: Multicenter U.S. bilateral MED-EL cochlear implantation study: speech perception over the first year of use. *Ear Hear* 2008;29:20–32.
- Dawson PW, Decker JA, Psarros CE: Optimizing dynamic range in children using the nucleus cochlear implant. *Ear Hear* 2004;25:230–241.
- Dillon H, Byrne D, Brewer S, Katsch R, Ching TY, Keidser G: NAL nonlinear version 1.01 user manual. National Acoustics Laboratories, 1998.
- Dorman MF, Spahr AJ, Gifford RH, Cook S, Zhang T: Current research with cochlear implants at Arizona State University. *J Am Acad Audiol* 2012;23:385–395.
- Dunn CC, Perreau A, Gantz BJ, Tyler RS: Benefits of localization and speech perception with multiple noise sources in listeners with a short-electrode cochlear implant. *J Am Acad Audiol* 2010;21:44–51.
- Dunn CC, Tyler RS, Witt SA: Benefit of wearing a hearing aid on the unimplanted ear in adult users of a cochlear implant. *J Speech Lang Hear Res* 2005;48:668–680.
- Eapen RJ, Buss E, Adunka OF, Pillsbury HC, Buchman CA: Hearing-in-noise benefit after bilateral simultaneous cochlear implantation continues to improve 4 years after implantation. *Otol Neurotol* 2009;30:153–159.
- Festen JM, Plomp R: Speech-reception threshold in noise with one and two hearing aids. *J Acoust Soc Am* 1986;79:465–471.
- Gantz BJ, Tyler RS, Rubinstein JT: Binaural cochlear implants placed during the same operation. *Otol Neurotol* 2002;23:169–180.
- Gifford RH, Dorman MF: The psychophysics of low-frequency acoustic hearing in electric and acoustic stimulation (EAS) and bimodal patients. *J Hear Sci* 2012;2:33–44.
- Gifford RH, Dorman MF, Brown CA: Psycho-physical properties of low-frequency hearing: Implications for perceiving speech and music via electric and acoustic stimulation. *Adv Otorhinolaryngol* 2010;67:51–60.
- Gifford RH, Dorman MF, Skarzynski H, Lorens A, Polak M, Driscoll CLW, Roland PS, Buchman CA: Cochlear implantation with hearing preservation yields significant benefit for speech recognition in complex listening environments. *Ear Hear* 2013;34:413–425.
- Henry P, Ricketts T: The effects of changes in head angle on auditory and visual input for omnidirectional and directional microphone hearing aids. *Am J Audiol* 2003;12:41–51.
- Laszig R, Aschendorff A, Stecker M, Muller-Deile J, Maune S, Dillier N, Weber B, Hey M, Begall K, Lenarz T, Battmer RD, Bohm M, Steffens T, Strutz J, Linder T, Probst R, Allum J, Westhofen M, Doering W: Benefits of bilateral electrical stimulation with the nucleus cochlear implant in adults: 6-month postoperative results. *Otol Neurotol* 2004;25:958–968.
- Litovsky RY, Parkinson A, Arcaroli J, Sammeth C: Simultaneous bilateral cochlear implantation in adults: a multicenter clinical study. *Ear Hear* 2006;27:714–730.
- Morera C, Cavalle L, Manrique M, Huarte A, Angel R, Osorio A, Garcia-Ibanex L, Estrada E, Morera-Ballester C: Contralateral hearing aid use in cochlear implanted patients: multicenter study of bimodal benefit. *Acta Otolaryngol* 2012;132:1084–1094.
- Morera C, Manrique M, Ramos A, Garcia-Ibanex L, Cavalle L, Huarte A, Castillo C, Estrada E: Advantages of binaural hearing provided through bimodal stimulation via a cochlear implant and a conventional hearing aid: a 6-month comparative study. *Acta Otolaryngol* 2005;125:596–606.
- Muller J, Schon F, Helms J: Speech understanding in quiet and noise in bilateral users of the MED-EL Combi 40/40+ cochlear implant system. *Ear Hear* 2002;23:198–206.
- Patrick JF, Busby PA, Gibson PJ: The development of the Nucleus Freedom cochlear implant system. *Trends Amplif* 2006;10:175–200.
- Peterson GE, Lehiste I: Revised CNC lists for auditory tests. *J Speech Hear Disord* 1962;27:62–70.
- Rader T, Fastl H, Baumann U: Speech perception with combined electric-acoustic stimulation and bilateral cochlear implants in a multi-source noise field. *Ear Hear* 2013;34:324–332.
- Schafer EC, Amlani AM, Seibold A, Shattuck PL: A meta-analytic comparison of binaural benefits between bilateral cochlear implants and bimodal stimulation. *J Am Acad Audiol* 2007;18:760–776.

- Schleich P, Nopp P, D'Haese P: Head shadow, squelch and summation effects in bilateral users of the MED-EL COMBI 40/40+ cochlear implant. *Ear Hear* 2004;25:197–204.
- Schon F, Muller J, Helms J: Speech reception thresholds obtained in a symmetrical four-loudspeaker arrangement from bilateral users of MED-EL cochlear implants. *Otol Neurotol* 2002;23:710–714.
- Spahr AJ, Dorman MF, Litvak LM, Van Wie S, Gifford RH, Loizou PC, Loisele L, Oakes T, Cook S: Development and validation of the AzBio sentence lists. *Ear Hear* 2012;33:112–117.
- Thornton AR, Raffin MJM: Speech discrimination scores modeled as a binomial variable. *J Speech Hear Res* 1978;21:507–518.
- Tyler RS, Parkinson A, Wilson BS, Witt SA, Preece JP, Noble W: Patients utilizing a hearing aid and a cochlear implant: speech perception and localization. *Ear Hear* 2002;23:98–105.
- Verhaert N, Lazard DS, Gnansia D, Bebear JP, Romanet P, Meyer B, Pean V, Mollard D, Truy E: Speech performance and sound localization abilities in Neurelec Digisonic® SP binaural cochlear implant users. *Audiol Neurotol* 2012;17:256–266.
- Wackym PA, Runge-Samuelson CL, Firszt JB, Alkaf FM, Burg LS: More challenging speech-perception tasks demonstrate binaural benefit in bilateral cochlear implant users. *Ear Hear* 2007;28:80S–85S.
- Yoon YS, Li Y, Fu QJ: Speech recognition and acoustic features in combined electric and acoustic stimulation. *J Speech Lang Hear Res* 2012;55:105–124.
- Zeitler DM, Kessler MA, Terushkin V, Roland TJJ, Svirsky MA, Lalwani AK, Waltzman SB: Speech perception benefits of sequential bilateral cochlear implantation in children and adults: a retrospective analysis. *Otol Neurotol* 2008;29:314–325.
- Zhang T, Dorman MF, Spahr AJ: Information from the voice fundamental frequency (F0) region accounts for the majority of the benefit when acoustic stimulation is added to electric stimulation. *Ear Hear* 2010;31:63–69.