

# A Meta-analytic Comparison of Binaural Benefits between Bilateral Cochlear Implants and Bimodal Stimulation

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## Abstract

A meta-analytic approach was used to examine sixteen peer-reviewed publications related to speech-recognition performance in noise at fixed signal-to-noise ratios for participants who use bilateral cochlear implants (CIs) or bimodal stimulation. Two hundred eighty-seven analyses were conducted to compare the underlying contributions of binaural summation, binaural squelch, and the head-shadow effect compared to monaural conditions (CI or hearing aid). The analyses revealed an overall significant effect for binaural summation, binaural squelch, and head shadow for the bilateral and bimodal listeners relative to monaural conditions. In addition, all within-condition (bilateral or bimodal) comparisons were significant for the three binaural effects, with the exception of the bimodal condition compared to a monaural CI. No significant differences were detected between the bilateral and bimodal listeners for any of the binaural phenomena. Clinical implications and recommendations are discussed as they relate to empirical findings.

**Key Words:** bilateral, bimodal, cochlear implant, hearing aid

**Abbreviations:** ACE = Advanced Combination Encoders; CI = cochlear implant; CI<sub>95</sub> = 95% confidence interval; CIS = Continuous Interleaved Sampling; SNR = signal-to-noise ratio; SPEAK = Spectral Peak

## Sumario

Se utilizó un enfoque de meta-análisis para examinar dieciséis publicaciones con revisión editorial relacionadas con el desempeño en reconocimiento del lenguaje en medio de ruido a tasas de señal-ruido fijas, para participantes que usaban implantes cocleares bilaterales (IC) o estimulación bimodal. Se condujeron doscientos ochenta y siete análisis para comparar la contribución subyacente de la suma bi-auricular, el chapoteo bi-auricular, y el efecto de sombra de la cabeza, en comparación con las condiciones mono-auriculares (IC y auxiliar auditivo). El análisis reveló un efecto global significativo para la suma bi-auricular, el chapoteo bi-auricular y la sombra de la cabeza para el sujeto con audición bilateral y bimodal, en relación con las condiciones mono-auriculares. Además, todas las comparaciones dentro de la misma condición (bilateral o bimodal) fueron significativas para los tres efectos bi-auriculares, con la excepción de la condición bimodal, comparada con un IC mono-auricular. No se detectaron diferencias significativas entre sujetos en condición bilateral y bimodal para ninguno de los fenómenos bi-auriculares. Las implicaciones clínicas y las recomendaciones se discuten en tanto se relacionan con los hallazgos empíricos.

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**Palabras Clave:** bilateral, bimodal, implante coclear, auxiliar auditivo

**Abreviaturas:** ACE = Codificador de Combinación Avanzada; CI = implante coclear;  $CI_{95}$  = intervalo de confianza 95%; CIS = Muestreo Intercalado Continuo; SNR = tasa señal-ruido; SPEAK = pico espectral

Children and adults who exhibit severe-to-profound hearing loss and do not benefit from amplification may be candidates to receive a cochlear implant (CI). Over time, children and adults with CIs may develop the ability to recognize open-set words in quiet listening situations, but they may perform poorly on a similar task with the introduction of background noise (Davies et al, 2001; Hamzavi et al, 2001; Fetterman and Domico, 2002; Garnham et al, 2002; Schafer and Thibodeau, 2003; Eisenberg et al, 2004; Schafer and Thibodeau, 2004). This reduction in performance is concerning given that users of CIs will encounter deleterious listening situations in their everyday lives. In fact, speech-recognition performance of children and adults with CIs is reduced between 20 and 80 percentage points in the presence of noise as compared to speech understanding in quiet (Davies et al, 2001; Hamzavi et al, 2001; Fetterman and Domico, 2002; Garnham et al, 2002; Schafer and Thibodeau, 2003; Eisenberg et al, 2004; Schafer and Thibodeau, 2004).

One way for an individual to improve speech-recognition performance in noise is to obtain a second CI (i.e., bilateral stimulation) or to use a hearing aid on the non-implant ear (i.e., bimodal stimulation), which is assumed to provide benefits associated with binaural listening.<sup>1</sup> Specifically, speech-recognition performance obtained in quiet and in noise improves in the binaural condition by up to 7 percentage points compared to the monaural condition for children and adults who have normal- or impaired-hearing sensitivity (Nabelek and Pickett, 1974a; Nabelek and Pickett, 1974b; Nabelek and Mason, 1981; Nabelek and Robinson, 1982). Similar binaural-listening benefits are reported for users of bilateral CIs (Gantz et al, 2002; Müller et al, 2002; Schön et al, 2002; Tyler et al, 2002a; Kühn-Inacker et al, 2004; Laszig et al, 2004; Ramsden et al, 2005; Senn et al, 2005) and

bimodal arrangements (Ching, 2000; Tyler et al, 2002b; Ching et al, 2004b; Ching et al, 2005b; Dunn et al, 2005; Holt et al, 2005; Luntz et al, 2005; Morera et al, 2005). The improved performance in noise can be attributed, in part, to three sub-phenomena of binaural listening, which include the central processes of binaural summation and binaural squelch and the physical phenomenon of reducing the head-shadow effect.

Binaural summation is the sensation that a signal is perceptually louder when listening occurs with two ears relative to one (Hirsch, 1948). In listeners with normal- and impaired-hearing sensitivity, the increased sensation in loudness ranges from 3 to 10 dB (Reynolds and Stevens, 1960; Dermody and Byrne, 1975; Marks, 1978; Hall and Harvey, 1985). During the assessment of binaural summation in users of CIs, speech and noise are often presented through the same loudspeaker positioned at 0-degrees azimuth relative to the listener, representing a diotic listening condition. According to empirical evidence, only some individuals who use bilateral CIs or bimodal stimulation will achieve binaural summation. Specifically, researchers report significant differences in summation performance between monaural- and binaural-listening conditions (Ching, 2000; Ramsden et al, 2005), while others report no evidence of summation (Laszig et al, 2004; Morera et al, 2005).

The binaural squelch effect, a second binaural benefit, is the brain's ability to suppress the effect of noise presented from spatially-separated speech and noise sources (e.g., loudspeakers at 45- and 315-degrees azimuth). Binaural squelch is associated with the masking-level difference at the two ears (i.e., dichotic listening), which provides an average improvement of 10 dB for listeners with normal-hearing sensitivity and 1 to 5 dB for those listeners having hearing impairment (Carhart et al, 1967; Levitt and

Rabiner, 1967; Jerger et al, 1984). For users of bilateral implants or bimodal stimulation, a significant binaural squelch effect is present in some studies (Müller et al, 2002; Dunn et al, 2005; Morera et al, 2005) but not in other studies (Gantz et al, 2002; Tyler et al, 2002a; Ramsden et al, 2005; Senn et al, 2005). Given the different outcomes among studies, there is inconclusive data to support the benefit of binaural squelch for listeners using either bilateral implants or bimodal stimulation.

A third binaural benefit, the head-shadow phenomenon, also involves spatial separation of speech and noise stimuli from a physical standpoint. Specifically, this phenomenon relates to the attenuation, particularly of high-frequency sounds, that occurs when a signal directed at one ear must travel around the listener's head to reach the opposite ear. In this task, a target signal is typically presented from a loudspeaker at 0-degrees azimuth, while noise is presented from a loudspeaker placed closest to the test ear. Performance is measured using either a fixed-intensity, percent-correct format or by measuring the signal-to-noise ratio (SNR) required to obtain 50-percent correct on a speech-recognition task. In listeners who have normal hearing, an average 5- to 10-dB SNR improvement has been noted when listening with two ears relative to one (Tillman et al, 1963; Bronkhorst and Plomp, 1989). For listeners with bilateral CIs and bimodal stimulation, binaural head-shadow effects are typically measured by comparing performance in monaural and binaural conditions with noise presented toward the monaural test ear (Gantz et al, 2002; Tyler et al, 2002a).

The binaural head-shadow effect is the most consistently measured benefit of bilateral implants and bimodal input, often yielding large differences between monaural and binaural conditions (Müller et al, 2002; Laszig et al, 2004; Dunn et al, 2005; Morera et al, 2005; Senn et al, 2005). In fact, many researchers support the notion that the advantage of the head-shadow effect occurs more consistently than the binaural benefits of summation and squelch. However, individual participant scores suggest that not every listener in a given experiment achieves significant binaural head-shadow benefit (Gantz et al, 2002; Ramsden et al, 2005).

Despite the reported advantages of binaural hearing (Ching et al, 2001; Ching et al, 2004a; van Hoesel, 2004; Ching, 2005;

International Consensus on Bilateral Cochlear Implants and Bimodal Stimulation, 2005; Peters, 2006), there is no consensus regarding which condition, bilateral or bimodal, is better suited for a given candidate or population. The lack of a consensus is also problematic for some insurance companies because bilateral implantation may be considered an experimental procedure (Let Them Hear Foundation, 2006). In addition, the possibility exists that a candidate could have equal or greater success with bimodal stimulation. Clearly, empirical evidence is needed to differentiate the benefits of bilateral versus bimodal stimulation for potential candidates, and such data should provide recommendations to audiologists and physicians regarding the potential benefits of a second CI or hearing aid on the non-implant ear. Therefore, the aim of this study is to use a meta-analytic approach to quantify the binaural advantage for summation, squelch, and head-shadow effects across studies reported in the literature, as well as examine differences in performance between users of bilateral implants and bimodal stimulation.

## METHODS

### Selection of Studies

Studies for this analysis were obtained using PubMed (NCBI) and ERIC (OCLC First Search) electronic databases, as well as a manual search of references in the published literature between January 2000 and December 2005. Ultimately, 16 studies were identified as appropriate. All studies were written in English and published in peer-reviewed journals. Criteria for inclusion of a study were based on (a) subjects having either bilateral or bimodal input, (b) methodologies that assessed monaural (i.e. CI/ hearing aid) and binaural (i.e. bilateral/bimodal) conditions, and (c) speech-recognition testing performed in noise at fixed SNRs. Data from experiments conducted in quiet listening situations were not included because results often fail to yield significant binaural benefit relative to monaural listening (Tyler et al, 2002a; Dunn et al, 2005; Holt et al, 2005; Ramsden et al, 2005).

In the bilateral condition, we specified the primary ear of the participants in the individual studies using one of three criteria: (a) the information was provided by the authors (Schön et al, 2002; Kühn-Inacker et al, 2004;

Laszig et al, 2004), (b) the better ear was identified in conditions with speech and noise presented from the same loudspeaker (Gantz et al, 2002; Tyler et al, 2002a; Ramsden et al, 2005), or (c) the better ear was selected according to superior speech-recognition performance in quiet (Müller et al, 2002; Senn et al, 2005). The third criterion (c) was used only when the authors did not include a condition in which speech and noise were presented from the same loudspeaker. In the bimodal condition, the implanted ear was considered the primary ear, and the opposite ear was viewed as providing augmentative, or secondary, cues to the listener.

### Identifying Study Statistics

Each condition of a given study was treated as an independent experiment to increase

the sample size (Table 1). That is, the number of experiments was increased from eight studies in the bilateral condition and eight studies in the bimodal condition to 39 experiments in the former (N=631) and 35 in the latter (N=352). Data for each independent experiment included the sample size, mean, and standard deviation for the primary (i.e., CI) and secondary (i.e., secondary CI/hearing aid) conditions.

Each experiment was coded for several variables including sample size, onset of deafness, age of implantation for the primary CI and secondary CI/hearing aid, duration of time between implantation of the primary CI and secondary CI/hearing aid, manufacturer, type of processor, speech-processing strategy, type of speech and noise stimuli, loudspeaker azimuth, and fixed SNR levels. The majority of hearing aids tested in the various experi-

**Table 1. Test Conditions for Bilateral Studies (Top) and Bimodal Studies (Bottom)**

Author (year)	Stimuli	Noise	Signal Speaker	Noise Speaker	Signal Level	Signal-to-Noise Ratio (dB)
Gantz et al (2002)	CUNY	Babble	0°	0°	70 dB SPL	+10 or various
Kühn-Inacker et al (2004)	Bisyllabic Words	Speech	135°, 315°	45°, 225°	MCL	+15
Laszig et al (2004)	HSM	Speech	0°	0°, Sec, Prim	70 dB SPL	+10
Müller et al (2002)	HSM	Speech	0°	90°, 270°	65 dB SPL	+10
Ramsden et al (2005)	CUNY	Babble	0°	0°, Prim, Sec	70 dB SPL	+5 to +15
Schön et al (2002)	HSM	Speech	45°, 225°	135°, 315°	70 dB SPL	+0, +5, +10, +15, +20
Senn et al (2005)	HSM	Speech	0°	90°, 270°	70-74 dB SPL	+5, +15
Tyler et al (2002a)	CUNY, HINT	Did not specify	0°	0°, 90°, 270°	70 dB SPL	Various
Ching et al (2005a)	BKB	Babble	0°, 60° on HA side	0°, 60° CI side	70 dB SPL	+10, +15
Ching et al (2004b)	BKB	Babble	0°, 60° on HA side	0°, 60° CI side	70 dB SPL	+10, +15
Ching et al (2000)	BKB, VCV	Babble	0°	0°	65 dB SPL	+10
Dunn et al (2005)	CUNY	Babble	0°	0°, CI side, HA side	70 dB SPL	+0, +5, +10
Holt et al (2005)	HINT-C	Speech	0°	0°	70 dB SPL	+5
Luntz et al (2005)	CUNY, Common Phrases	Did not specify	0°	0°	55 dB HL	+10
Morera et al (2005)	Disyllabic Words-Spanish	Babble	0°	0°, CI side, HA side	70 dB SPL	+10
Tyler et al (2002b)	CUNY	Babble	0°	0°, CI side, HA side	70 dB SPL	+7, +10, +13

Note: CUNY=City University of New York Sentences; MCL=most comfortable listening level for each person; HSM=Hochmair/Schulz/Moser sentences in German; CI=cochlear implant; HA=hearing aid; Prim=primary CI; Sec=secondary side; BKB=Bamford-Kowal-Bench sentences; VCV=vowel-consonant-vowel syllables; HINT-C=Hearing in Noise Test – Children.

ments employed linear-output processing, omnidirectional microphones, and disabled noise reduction/cancellation or feedback reduction/cancellation algorithms. Participant characteristics are outlined in Appendices A and B, and a summary of test conditions is also provided in Table 1.

As shown in Table 2, data from each experiment were further categorized into one of three loudspeaker-azimuth arrangements as a way to limit potential methodological differences across experiments. Specifically, experiments that determined the binaural-summation effect required that speech and noise be presented from the same loudspeaker positioned directly in front of the listener. Experiments were examined for the binaural-squelch effect when speech was presented from a loudspeaker positioned directly in front of the listener, and noise was presented from a loudspeaker positioned contralateral to the monaural test ear (i.e., closest to the secondary ear during the assessment of the monaural primary CI and closest to the primary ear during the assessment of the monaural secondary CI or hearing aid). Differences in loudspeaker arrangement among experiments complicated the decision as to which methodological condition best represented the evaluation of head-shadow effects. Experiments included in this condition were based on the notion that the greatest head-shadow effects occur when noise is presented on the same side as the monaural test ear. Therefore, all experiments in the analysis of head-shadow effects presented noise ipsilateral to the monaural test ear as suggested by Gantz et al (2002) and Tyler et al (2002a). The majority of these experiments (17/27) presented speech through a loudspeaker at 0-degrees azimuth and noise from a loudspeaker ipsilateral to the monaural test ear (i.e., close to the primary ear during the assessment of the primary CI and close to the

secondary ear during the assessment of the secondary CI or hearing aid). In the remaining experiments, speech and noise loudspeakers were always spatially separated by at least 90-degrees azimuth with noise presented from a loudspeaker on the side of the monaural test ear (Schön et al, 2002; Ching et al, 2004b; Kühn-Inacker et al, 2004; Ching et al, 2005a). Furthermore, Schön et al (2002) report that the primary contribution to the bilateral advantage is head-shadow effect when using loudspeaker arrangements providing similar SNRs at the two ears (i.e. Schön et al, 2002; Kühn-Inacker et al, 2004).

### Data Analysis

For each binaural-listening effect (i.e. summation, squelch, head shadow), mean-weighted averages of percent-correct differences and corresponding 95% confidence intervals ( $CI_{95}$ ) were derived by subtracting the primary (i.e., CI) or secondary monaural conditions (i.e., secondary CI/hearing aid) from the respective binaural condition (i.e., bilateral, bimodal). As summarized in Table 2, this resulted in four relative comparisons: (a) bilateral – primary CI, (b) bimodal – CI, (c) bilateral – secondary CI, and (d) bimodal – hearing aid for each of the three binaural effects. These relative differences allowed for the comparison between individual experiments and provided data on the aggregate performance for a given within-condition arrangement.

Separate analyses were performed for each relative comparison using a random-effects model (Berlin et al, 1988), and a chi-square value was computed to test the null hypothesis that all effects were zero (i.e., no binaural advantage). Forest plots were used to display the results of each experiment and condition for a given analysis, and statistical significance was determined by (1) comparing the upper and lower limits of  $CI_{95}$  to the 0-percent

**Table 2. Summary of conditions used to calculate binaural advantage for summation, squelch, and head shadow.**

Condition	Effect	Binaural advantage
SF/NF	Summation	Bilateral or bimodal condition minus primary CI
SF/NF	Summation	Bilateral or bimodal condition minus secondary CI or HA
SF/NSec	Squelch	Bilateral or bimodal condition minus primary CI
SF/NP	Squelch	Bilateral or bimodal condition minus secondary CI or HA
SF/NP*	Head Shadow	Bilateral or bimodal condition minus primary CI
SF/NSec*	Head Shadow	Bilateral or bimodal condition minus secondary CI or HA

Note: S = Speech stimulus; N = Noise stimulus; F = Loudspeaker positioned directly in front of listener; P = Loudspeaker positioned closest to primary ear; Sec = Loudspeaker positioned closest to secondary ear; \* = Loudspeaker arrangement varied, but loudspeaker used to present speech was at least 90-degrees azimuth from loudspeaker used to present noise; CI=cochlear implant; HA=hearing aid.

difference line and (2) comparing the upper and lower limits of CI<sub>95</sub> among experiments or between relative comparisons. In the former instance, each individual experiment and relative comparison that overlapped with the 0-percent difference line indicated that performance between the binaural and monaural conditions was not significantly different ( $p > .05$ ). In the latter instance, overlapping CI<sub>95</sub> for individual experiments and relative comparisons were also considered not significantly different ( $p > .05$ ). The CI<sub>95</sub> that did not overlap between experiments and relative comparisons indicated acceptance of the alternate hypothesis and were considered statistically significant at an alpha level of .05.

**RESULTS**

A total of 224 average differences and 63 weighted-average differences were calculated for this meta-analysis. A summary of the findings is provided in Table 3. The results in the following three sub-sections are

presented in the following order (1) overall effects, (2) within-condition effects, and (3) between-condition effects. The three sub-sections are followed by results from post-hoc analyses.

**Binaural Summation**

For the overall effect of binaural summation—across all conditions and experiments—a statistically significant ( $\chi^2 [29, 349] = 200.8, p < .0001$ ) weighted average improvement of 21 percentage points (CI<sub>95</sub>  $\pm$  6.4) was calculated. This finding suggests that binaural stimulation, in general, affords a listener improvement in speech recognition in noise ranging from 14.6 to 27.4 percentage points when compared to a monaural secondary CI or hearing aid (Figure 1). Despite a significant finding of binaural summation, relative difference values revealed that 55% (5/9) and 65% (13/20) of experiments that assessed bilateral and bimodal stimulation advantages, respectively, were not statistically sig-

**Table 3. Meta Analyses of Differences Between Binaural and Monaural Condition**

Effect	Group	Monaural Condition	Independent Experiments	Subjects	Weighted Average Difference	Chi-Square	Probability Level
Binaural Summation	Bilateral	SF/NF Primary	5	98	8.9%	10.2	< .0001
		SF/NF Secondary	4	70	24.1%	44.3	< .01
	Bimodal	SF/NF Primary	13	120	14.3%	31.7	< .0001
		SF/NF Secondary	7	61	43.7%	206.6	< .0001
	Combined	Effect	29	349	21.0%	200.8	< .0001
Binaural Squelch	Bilateral	SF/NSec Primary	7	109	7.5%	5.5	< .05
		SF/NP Secondary	5	91	11.3%	12.3	< .001
	Bimodal	SF/NSec Primary	3	26	10.1%	2.8	> .05
		SF/NP Secondary	3	25	45.4%	58.8	< .0001
	Combined	Effect	18	251	15.3%	40.1	< .0001
Head Shadow	Bilateral	SF/NP Primary	12	161	21.4%	71.5	< .0001
		SF/NSec Secondary	6	102	46.4%	261.5	< .0001
	Bimodal	SF/NP Primary	6	94	17.4%	23.7	< .0001
		SF/NSec Secondary	3	26	61.1%	211.6	< .0001
	Combined	Effect	27	383	30.7%	376.4	< .0001

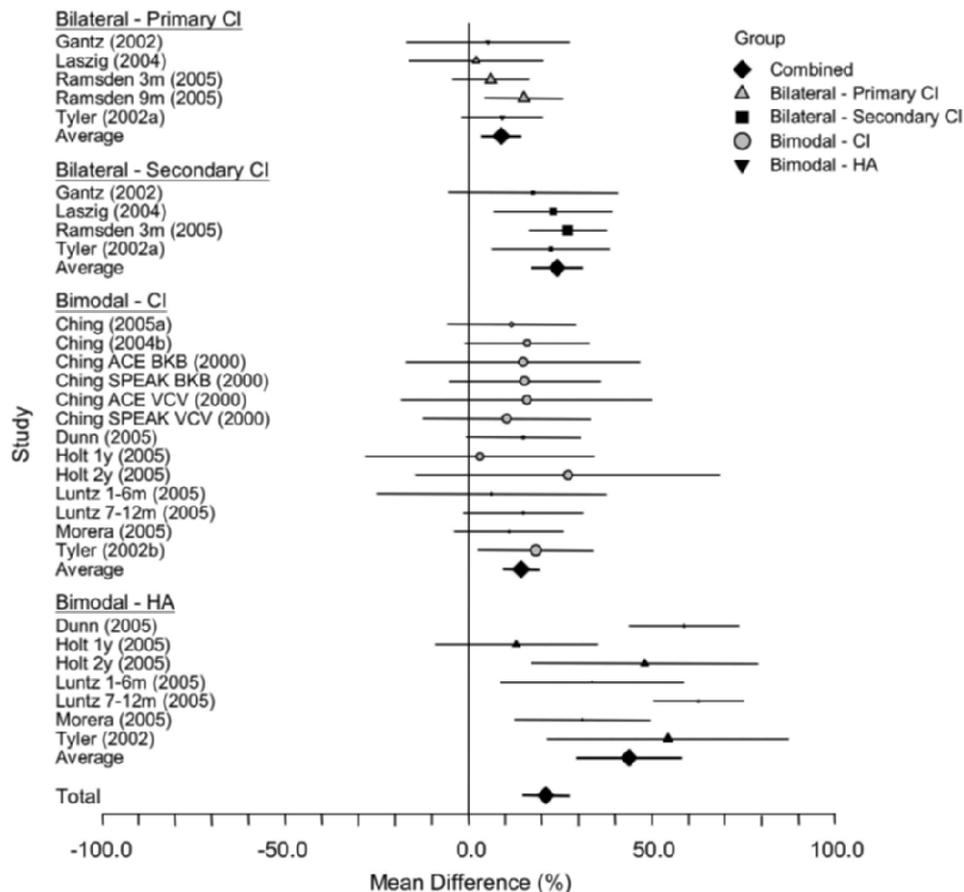
Note: The group and combined-weighted averages were calculated between the binaural and monaural conditions. Some studies had varying speaker arrangements (refer to Table 1). S=speech stimulus; N=noise stimulus; F=loudspeaker positioned directly in front of listener; P=loudspeaker positioned closest to primary ear; Sec=loudspeaker positioned closest to secondary ear.

nificant ( $p > .05$ ) compared to the 0-percent difference line (Figure 1).

In addition to an overall combined effect, a within-condition, binaural-summation effect was evaluated relative to the monaural primary CI. For the bilateral condition, a significant effect ( $\chi^2 [5, 98] = 10.2, p < .01$ ) was found for the bilateral – primary CI comparison (Table 3). Specifically, this finding suggests listening with two CIs improved performance by 8.9 percentage points ( $CI_{95} \pm 5.5$ ) compared to performance obtained with a monaural primary CI on the same speech-recognition task in noise. Likewise, an increase of 14.3 percentage points ( $CI_{95} \pm 5.0$ ) yielded a significant improvement ( $\chi^2 [13, 120] = 31.7, p < .0001$ ) for the bimodal – CI comparison (Table 3). This finding suggests that the speech-recognition performance of listeners in the bimodal condition is expected to improve by about 14 percentage points relative to performance with a monaural CI.

Relative within-condition differences were

also examined for the bilateral and bimodal stimulation minus the secondary CI and hearing aid, respectively. Our rationale for examining this comparison was to derive information about whether performance differences exist between the primary CI and the secondary CI or hearing aid. In the bilateral – secondary CI comparison, results indicate a significant increase in performance of 24.1 ( $CI_{95} \pm 7.1$ ) percentage points ( $\chi^2 [4, 70] = 44.3, p < .0001$ ). Given the large improvement in percentage points for the bilateral – secondary CI condition, the primary CI is most responsible for speech-recognition performance in noise. Performance in the bimodal condition yielded a statistically significant ( $\chi^2 [7, 61] = 206.6, p < .0001$ ) difference of 43.7 percentage points ( $CI_{95} \pm 14.3$ ) when compared to performance obtained monaurally with a hearing aid (i.e. bimodal – hearing aid). The outcome of this finding clearly indicates that in the bimodal condition, the CI provides greater input to the



**Figure 1.** Forest plot depicting the effects of binaural summation for speech and noise presented from the same loudspeaker (SF/NF). CI=cochlear implant, HA=hearing aid, m=months of bilateral/bimodal use, y=years of bilateral/bimodal use, SPEAK=Spectral Peak, ACE=Advanced Combination Encoders, BKB= Bamford-Kowal-Bench sentences; VCV=vowel-consonant-vowel syllables.

brain than a hearing aid with respect to bin-aural integration of speech presented in noise.

Statistical comparisons were also conducted within and between the listening arrangements (i.e. bilateral, bimodal). A comparison between the CI<sub>95</sub> for the bilateral – primary CI condition (i.e., 8.9%) and the bilateral – secondary CI condition (i.e., 24.1%) indicated a significant difference ( $p < .05$ ). Similarly, a comparison between the bimodal – CI condition and the bimodal – hearing aid condition was significant ( $p < .05$ ), as noted by the non-overlapping CI<sub>95</sub>. The similar findings for the within-arrangement comparisons show that the primary CI and the CI are largely responsible for speech-recognition performance in noise of bilateral and bimodal users, respectively.

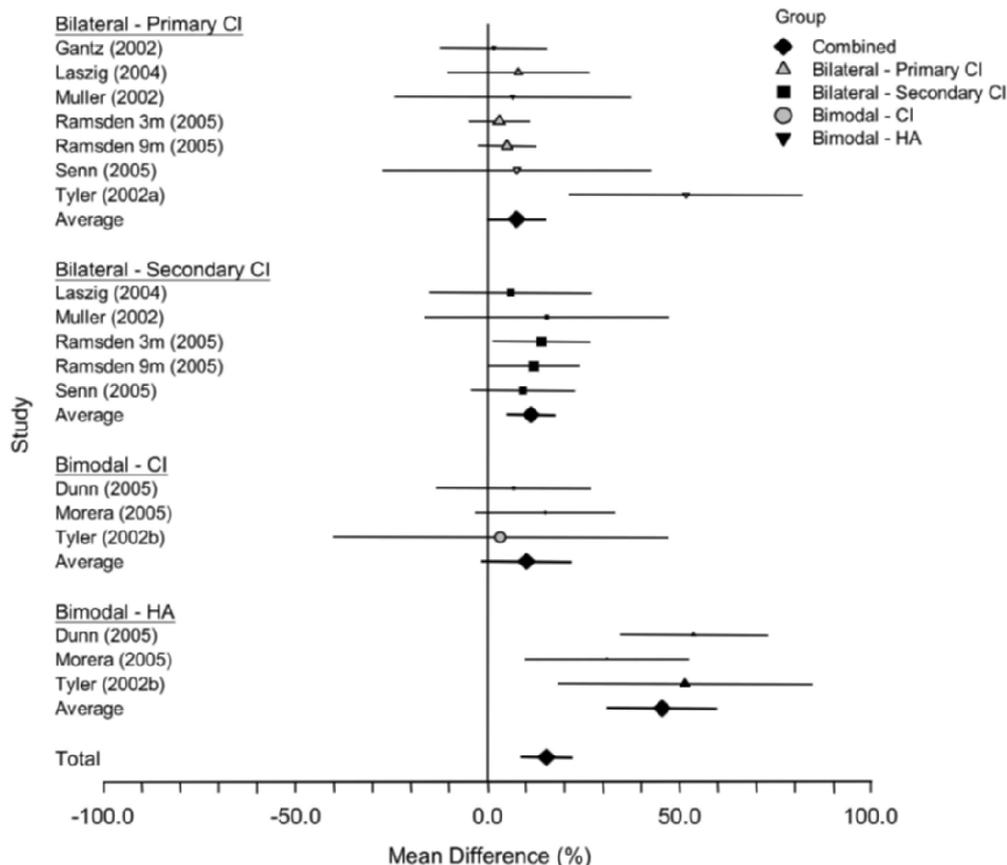
The between-arrangement comparisons show no significant differences ( $p > .05$ ) for the bilateral – primary CI and bimodal – CI conditions, as noted by the overlapping CI<sub>95</sub> (Figure 1). Likewise, the bilateral – secondary CI and bimodal – hearing aid conditions were not significantly different ( $p > .05$ ).

These findings suggest similar summation for the two listening arrangements when compared to the primary or secondary ears alone.

### Binaural Squelch

Figure 2 illustrates the advantages of bin-aural squelch. Overall, the combined effect, across all conditions and experiments, indicates that binaural stimulation significantly improved the listener’s ability to suppress noise by between 8.5 and 22.1 percentage points (15.3%, CI<sub>95</sub> ± 6.8) over monaural-listening conditions ( $\chi^2 [18, 251] = 40.1, p < .0001$ ). Despite the overall effect of squelch, only 39% (7/18) of the individual experiments were statistically significant.

The results for the bilateral – primary CI condition indicate that the two CIs provided listeners with a significant increase of 7.5 percentage points (CI<sub>95</sub> ± 7.7) relative the primary CI alone ( $\chi^2 [7, 109] = 5.5, p < .05$ ). In the bimodal – CI condition, however, an average difference of 10.1 percentage points (CI<sub>95</sub> ± 11.8) resulted in the absence of the squelch effect ( $\chi^2 [3, 26] = 2.8, p > .05$ ). When com-



**Figure 2.** Forest plot of binaural squelch effects when noise was presented contralateral to the monaural test ear. CI=cochlear implant, HA=hearing aid, m=months of bilateral implant use.

paring the results for the bilateral and bimodal conditions minus the secondary CI and hearing aid, respectively, performance in the bilateral ( $\chi^2 [5, 91] = 12.3, p < .001$ ) and bimodal conditions ( $\chi^2 [3, 25] = 58.8, p < .0001$ ) was significantly better than performance obtained monaurally with the secondary CI or hearing aid by 11.3 ( $CI_{95} \pm 6.3$ ) and 45.4 ( $CI_{95} \pm 14.4$ ) percentage points, respectively.

Overlapping  $CI_{95}$  were found between the bilateral – primary CI and the bilateral – secondary CI comparisons, suggesting that two CIs provided the brain with similar acoustic cues for the phenomenon of binaural squelch. However, average performance in the bimodal – hearing aid and the bimodal – CI conditions was significantly different because the  $CI_{95}$  did not overlap. These findings support that the CI provides more information to bimodal users than the hearing aid.

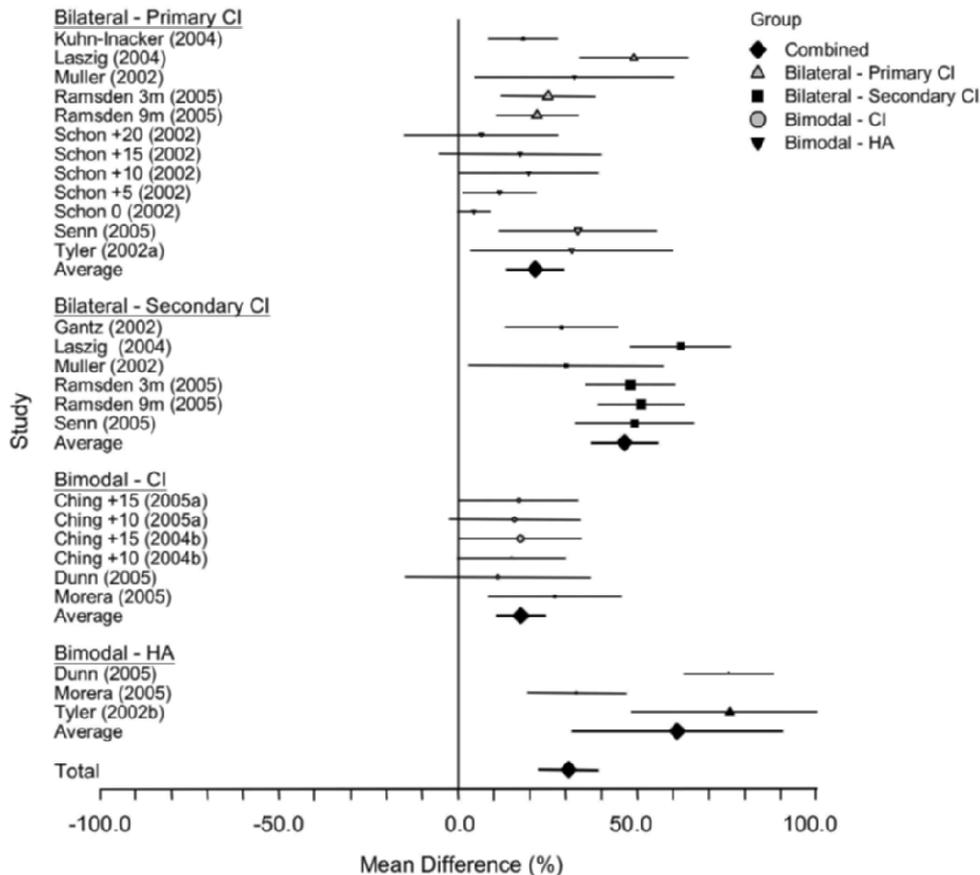
No significant difference ( $p > .05$ ) was noted between the conditions of bilateral – primary CI and bimodal – CI, given the overlapping  $CI_{95}$ . This non-significant effect suggests that the addition of a secondary CI or hearing aid to a primary CI provides the brain with similar acoustic cues for binaural

squelch. It does appear, however, that the secondary CI may result in significant binaural-squelch cues while a hearing aid on the non-implant ear may not. As seen in Figure 2, the mean-weighted difference for the bilateral – secondary CI and bimodal – hearing aid conditions was 11.3 ( $CI_{95} \pm 6.3$ ) and 45.4 ( $CI_{95} \pm 14.4$ ) percentage points, respectively. For increases in performance relative to the secondary-side alone, significantly greater squelch was found for the bimodal condition compared to the bilateral condition.

### Binaural Head-Shadow

The advantage of reducing the head-shadow effect through binaural listening was also examined. Overall, binaural stimulation significantly improved ( $\chi^2 [27, 383] = 376.4, p < .0001$ ) the listener's ability to understand speech in the presence of competing noise by 30.7 percentage points ( $CI_{95} \pm 8.5$ ) relative to all monaural conditions. The majority of individual experiments resulted in significant head-shadow effect with 81% (22/27) of studies showing significant differences.

As shown in Figure 3, the bilateral (21.4%,



**Figure 3.** Forest plot depicting the head-shadow effects when noise was presented ipsilateral to the monaural test ear. Numbers represent signal-to-noise ratios. CI=cochlear implant, HA=hearing aid, m=months of bilateral implant use.

CI<sub>95</sub> ± 8.2) and bimodal (17.4%, CI<sub>95</sub> ± 7.0) conditions were found to lessen the impact of the head-shadow effect significantly relative to performance obtained monaurally with a primary CI ( $\chi^2$  [12, 161] = 71.5,  $p < .0001$ ) or CI ( $\chi^2$  [6, 94] = 23.7,  $p < .0001$ ), respectively.

Larger differences were noted for both the bilateral and bimodal conditions when performance in the secondary CI and hearing aid conditions was subtracted from performance in the binaural condition. The bilateral – secondary CI condition yielded a significant binaural head-shadow effect ( $\chi^2$  [6, 102] = 261.5,  $p < .0001$ ). As shown in Figure 3, bilateral performance was 46.4 percentage points (CI<sub>95</sub> ± 9.4) better than performance with the secondary CI. A statistically significant effect was also found for the bimodal – hearing aid condition ( $\chi^2$  [3, 26] = 211.6,  $p < .0001$ ). The performance with bimodal stimulation was 61.1 percentage points (CI<sub>95</sub> ± 29.5) better than the performance with the monaural hearing aid. These findings were expected given that the performance with a monaural secondary CI or hearing aid often yields poorer scores than those obtained with the primary device.

Performance in the bilateral – primary CI condition (i.e., 21.4%, CI<sub>95</sub> ± 8.2) was compared to the bilateral – secondary CI (i.e., 46.4%, CI<sub>95</sub> ± 9.4), with results yielding a significant difference ( $p < .05$ ) in head-shadow effect. Similarly, when performance in the bimodal – CI condition is compared to performance in the bimodal – hearing aid condition, results indicate a significant difference ( $p < .05$ ). These findings resulted from poorer performance in the monaural secondary CI or hearing aid conditions.

Comparisons between listening arrangements show overlapping CI<sub>95</sub> regardless of the monaural test ear (primary or secondary). Therefore, the effects of head shadow were not significantly different ( $p > .05$ ) across any conditions for listeners who were using bilateral and bimodal arrangements.

### Post-Hoc Analyses

Several post-hoc analyses were conducted to validate our primary results and to examine additional factors that may have contributed to greater binaural benefits. Data for these analyses were also separated according to experiments assessing binaural summation, binaural squelch, and the head-shad-

ow effect. Sufficient data were available to assess (a) age at testing, (b) type of internal implant, (c) type of speech-processing strategy, (d) type of noise stimulus, and (e) effect of SNR. The following is a summary of the post-hoc findings.

### Age at Testing

Data showed no significant differences ( $p > .05$ ) between adults and children in the bimodal condition – primary CI and bimodal – hearing aid conditions for binaural summation. Likewise, no significant differences ( $p > .05$ ) were found between adults and children for the head-shadow effect in the bilateral – primary CI and bimodal – CI conditions. To a lesser degree, this analysis is also representative of findings between populations that were pre- and post-lingually deafened, given that the majority of adults were implanted after the acquisition of language and the majority of children were implanted before acquiring their first language.

### Internal Implant

A post-hoc analysis was conducted to determine whether differences in the internal implants—specifically the Nucleus 24 versus COMBI 40/40+—impacted findings. In the first analysis, binaural squelch was similar ( $p > .05$ ) for the bilateral – primary CI and bilateral – secondary CI comparisons. Head-shadow effect was also examined for users of Nucleus 24 and COMBI 40/40+ internal implants. Mean-weighted differences for the bilateral – primary CI and bimodal – hearing aid conditions were not significantly different ( $p > .05$ ) between the two types of internal implants. Therefore, the type of internal implant did not impact the results of this study.

### Speech-Processing Strategy

Two analyses were conducted to examine the effect of three speech-processing strategies—Advanced Combination Encoders (ACE), Continuous Interleaved Sampling (CIS), Spectral Peak (SPEAK)—on the benefits of binaural squelch and the head-shadow effect for the bilateral – primary CI condition. The ACE and SPEAK strategies are employed in Nucleus 22 and 24 implants manufactured by Cochlear Corporation, and

the CIS strategy was used in COMBI 40/40+ implants manufactured by MED-EL Corporation.

For binaural squelch, mean-weighted averages and  $CI_{95}$  for the speech-processing strategies of CIS, SPEAK, and ACE were neither statistically significant ( $p > .05$ ) nor different for the bilateral – primary CI condition. Significant binaural squelch ( $p < .05$ ) was noted for users of CIS and SPEAK processing strategies in the bilateral – secondary CI condition, while users of the ACE strategy did not show a significant squelch effect ( $p > .05$ ). This finding is likely related to the small number of ACE users ( $N=5$ ) in the analysis, resulting in large  $CI_{95}$ . Overall, this post-hoc analysis suggests that bilateral users of the ACE, SPEAK, and CIS speech-processing strategies receive similar binaural squelch and head-shadow benefit.

### Noise Stimuli

Post-hoc analyses were also conducted to examine whether type of noise used during individual experiments influenced results. With respect to the bilateral – primary CI condition, no significant effect ( $p > .05$ ) of squelch was detected and no differences were noted between speech-weighted noise and multitalker babble, suggesting equal performance in the bilateral and monaural conditions with the two types of noise. However, in the bilateral – secondary CI condition, a significant ( $p < .05$ ) amount of squelch was noted for multitalker babble, while speech-weighted noise did not impact performance significantly ( $p > .05$ ). This result indicates that multitalker babble may be a more sensitive stimulus when assessing the binaural advantage of binaural squelch, especially when examining monaural performance with the secondary CI.

A comparison was also conducted to determine whether the type of noise impacted head-shadow effect for the bilateral condition. For the bilateral – primary CI comparison, a significant effect of head shadow was found for both speech-weighted noise and multitalker babble ( $p < .05$ ). No significant difference ( $p > .05$ ) was found, however, between the two noise conditions. For the bilateral – secondary CI condition, the amount of binaural head shadow did not differ ( $p > .05$ ) between speech-weighted noise and multitalker babble. Lastly, no significant differences were

noted between the bilateral – primary CI and bilateral – secondary CI conditions, as indicated by overlapping  $CI_{95}$ . These findings suggest that both noise types are equally sensitive in the evaluation of head-shadow effect in users of bilateral implants.

### Signal-to-Noise Ratio

Finally, a post-hoc analysis was performed to examine whether differences in binaural benefits may have been affected by the fixed SNRs employed in individual experiments. The SNRs were categorized into the following ranges: 0- to 5-dB SNR, 6- to 10-dB SNR, and 11- to 15-dB SNR.

Binaural summation was evaluated under the SNR categories of 0- to 5-dB and 6- to 10-dB for the bimodal condition. Summation was not statistically significant ( $p > .05$ ) for the bimodal – CI condition when assessing the 0- to 5-dB SNR category, but it was statistically significant ( $p < .05$ ) when assessing the 6- to 10-dB SNR category for the same condition. These SNR categories were not significantly different from one another ( $p > .05$ ), as the  $CI_{95}$  overlapped. For the bimodal – hearing aid condition, testing with both the 0 to 5 dB and the 6 to 10 dB SNRs resulted in significant amounts of summation ( $p < .05$ ). The two SNRs were not significantly different from each other ( $p > .05$ ).

Head-shadow effect was evaluated under three SNR categories: 0- to 5-dB, 6- to 10-dB, and 11- to 15-dB SNR for the bilateral condition. Significant ( $p < .05$ ) head-shadow effects were found for each of the three SNR categories under the bilateral – primary CI condition, with no difference ( $p > .05$ ) among the three SNR categories. Therefore, differences in SNR do not appear to have impacted performance obtained for the binaural head-shadow effect.

## DISCUSSION

The general findings of this study indicate that CI users who are stimulated binaurally—either bilateral or bimodal—will perform significantly better at fixed levels of noise than a listener having a monaural CI or hearing aid. In fact, bilateral and bimodal stimulation was found to provide listeners with an overall average improvement ranging from 15.3 to 30.7 percentage points across the combined effects of binaural summation, bin-

aural squelch, and the head-shadow effects compared to a monaural CI or hearing aid. The binaural-listening improvements were similar between users of bilateral implants and bimodal stimulation. Given the potential benefits of a second CI or a hearing aid on the non-implant ear, audiologists and physicians should recommend binaural stimulation for those CI users who demonstrate benefit from a hearing aid fit on the non-implant ear and for those listeners who show no contraindications for receiving a second CI on the non-implant ear.

### **Binaural Summation and Bilateral/Bimodal Stimulation**

Results from this study demonstrated that the bilateral and bimodal conditions improved speech-recognition performance in noise by an average of 21 percentage points ( $CI_{95} \pm 6.4$ ) compared to a monaural CI or hearing aid. Binaural summation was examined in this study by calculating difference scores between binaural and monaural conditions when speech and noise were presented from the same loudspeaker and positioned directly in front of the listener. The magnitude of binaural summation was heavily influenced by which monaural ear was included in the calculation (primary or secondary), with larger differences found in condition comparisons with the secondary ear. The fact that a second CI or a hearing aid fit on the non-implant ear can provide a significant improvement in SNR for both adults and children is further validation that the window of plasticity is by no means narrow. Future research is needed on the topic of CIs, plasticity, and age limits for binaural benefit, so that audiologists and physicians are better able to make evidence-based candidacy judgments.

Participant characteristics may have affected the amount of binaural summation reported in this analysis. For the bilateral condition, summation performance was significantly better in the bilateral – secondary CI condition compared to performance in the bilateral – primary CI condition. This finding is not surprising because the primary CI is superior alone, resulting in a smaller difference between bilateral and primary CI conditions. The primary CI is often implanted first, receives a longer period of electrical stimulation, and has a shorter period of audi-

tory deprivation. For listeners who are sequentially implanted, performance of the secondary ear is expected to be poorer relative to the primary implanted ear—especially in noise—because of longer auditory deprivation and a shorter acclimatization period (Ramsden et al, 2005; Senn et al, 2005). In fact, Ramsden and colleagues (2005) suggest that on average, the secondary CI may not reach its maximum performance ability until after the first six months of stimulation. Additional variability may be contributed to whether the unaided poorer or better hearing ear received the initial CI. There is no consensus across CI clinics as to which monaural ear should be implanted first. Similar differences may be found for listeners with simultaneous implants. Tyler et al (2002a) found significant interaural differences in performance for simultaneously implanted ears for some participants on a speech-recognition task in noise. However, the authors report that the asymmetry between the two ears did not appear to preclude binaural benefits.

While bimodal stimulation was found to provide binaural advantages, the amount of benefit was directly related to whether monaural listening occurs with a CI or a hearing aid. Recall that binaural summation in the bimodal – hearing aid condition resulted in a mean-weighted difference score of 43.7 percentage points ( $CI_{95} \pm 14.3\%$ ) and the bimodal – CI condition yielded a mean-weighted difference score of 14.3 percentage points ( $CI_{95} \pm 5.0\%$ ). The large disparity between conditions is not surprising, given that the signal output is different for a CI (electrical stimulation) and a hearing aid (acoustical stimulation). Some of this variability may be attributed to distortions present in the amplified signal provided by the hearing aid, as well as by cochlear dead regions and cochlear distortions. Despite the poorer monaural performance seen with both the secondary CI and hearing aid when compared to the primary CI, the summation advantage provided by bilateral and bimodal stimulation was similar, and more importantly, the binaural condition improved the listeners' ability to understand speech in the presence of competing noise relative to a monaural condition.

Performance differences for the bimodal condition might also be related to the amount of residual hearing in the non-implant ear (Tyler et al, 2002b; Morera et al, 2005), the

length of bimodal use (Holt et al, 2005), and variation in loudness between the implant and the prescriptive target used to program the hearing aid (Ching et al, 2001; Ching et al, 2004a; Ching, 2005). An example of how differences in residual hearing can affect binaural performance can be found in Morera et al (2005). Individual analysis of performance indicated that roughly one-half of the participants had significant bimodal benefits relative to their monaural CI. Likewise, one participant in the Tyler et al (2002b) study showed no bimodal benefit, and also received the least benefit from a monaural hearing aid. Varied results from these studies are likely related to the level of hearing sensitivity or the range of frequencies in the non-implant ear that could be successfully amplified with the hearing aid. Furthermore, many bimodal users had residual hearing in the non-implant ear in the low-frequency region only, where it is often difficult to provide sufficient acoustic information for speech recognition in quiet and is further compromised in the presence of background noise.

The amount of benefit obtained for bimodal stimulation may vary as a function of time. Holt et al (2005) found that children's speech-recognition performance significantly increased after two years of bimodal use compared to one year of use. In addition to acclimatization, effects of cortical maturation related to binaural processing may have also contributed to the improved bimodal performance. Findings from the Holt et al (2005) study suggest that evaluating performance after a period of less than two years may not represent the participants' maximum abilities.

Finally, Ching and colleagues (2001, 2004a, 2005) recommend that the perception of loudness should be balanced between a CI and a hearing aid to achieve maximum bimodal benefit. To illustrate the importance of loudness balancing, Ching and colleagues (2001) measured the speech-recognition performance of children under four aided conditions: CI with hearing aid as worn, CI alone, hearing aid alone, and CI with hearing aid adjusted according to individual loudness requirements. A paired-comparison technique was used to identify the frequency-gain response of the hearing aid that was best for speech intelligibility in quiet, and a loudness balancing technique was used to match the loudness of speech in the ear with a hearing

aid to that with a cochlear implant. Results indicated that speech-recognition performance significantly improved for children who used CIs with adjusted hearing aids than when they used cochlear implants alone. These authors concluded by recommending that the frequency-gain response of a hearing aid be adjusted to match loudness in the implanted ear, which should facilitate integration of signals from both ears and lead to better speech perception.

### **Binaural Squelch and Bilateral/Bimodal Stimulation**

The improvement in speech recognition in noise that can be attributed to binaural squelch ranged from an average of 7.5 to 45.4 percentage points for the binaural conditions (i.e., bilateral) relative to monaural conditions. The presence of squelch was examined in this study for speech presented from a loudspeaker positioned directly in front of the listener and noise presented from a loudspeaker opposite the test ear. A comparison between the bilateral – primary CI and bimodal – CI conditions showed overlapping CI<sub>95</sub>, with significant squelch occurring only in the bilateral condition. Dunn et al (2005) suggest a rationale for this slight difference in performance across conditions. These authors conjectured that binaural squelch requires the brain to detect differences in the interaural temporal and spectral cues for speech and noise, and listeners using a combination of electrical and acoustic information (in bimodal arrangements) may not adequately integrate these signals. Integration difficulties may also be prevalent in users of bilateral CIs when noise is perceptually different between ears. Ching and colleagues (2001) report that loudness balancing between an implant and hearing aid or two implants might also affect binaural squelch because unbalanced listening may preclude binaural benefits. Lastly, binaural squelch is expected to improve when the SNR is poorer at the hearing aid or secondary CI and better at the primary CI.

It is also plausible that the sensitivity of speech-recognition materials could have diminished the advantage of binaural squelch. That is, word-recognition test materials lack sensitivity because of the large critical differences needed to deter-

mine significant differences between scores (Raffin and Thornton, 1980). In addition, use of fixed-intensity, speech-recognition materials maximize the likelihood of either floor or ceiling effects.

### **Binaural Head-Shadow Effect and Bilateral/Bimodal Stimulation**

Binaural listening improved speech-recognition performance in noise between an average of 17.4 and 61.1 percentage points for the head-shadow effect compared to a monaural CI or hearing aid alone. The head-shadow effect was calculated by subtracting the average monaural score from the average binaural score for conditions in which noise was presented on the side of the monaural test ear. The reader should note that because we assessed the aggregate performance across several loudspeaker arrangements for this binaural condition, the sampling error and variability may be larger than had we assessed performance for a fixed, single loudspeaker arrangement. However, as shown in Figure 3, the  $CI_{95}$  of the 10 experiments using variable loudspeaker arrangements (Schön et al, 2002; Ching et al, 2004b; Kühn-Inacker et al, 2004; Ching et al, 2005a) are not significantly different from the majority of those obtained with the traditional speaker arrangement for measuring head-shadow effects.

Recall that significant head-shadow effects were detected for both binaural conditions (i.e., bilateral, bimodal) with no differences between these conditions. This finding suggests that the addition of a second CI or hearing aid reduces the head-shadow effect, and emphasizes the need for binaural-listening arrangements. Larger differences, however, were found for both the bilateral and bimodal conditions when the performance with a secondary CI or hearing aid was subtracted from the binaural score. Monaural performance was considerably poorer with the secondary CI and hearing aid, which resulted in a larger effect.

Many of the same factors associated with improving binaural summation are also associated with larger head-shadow effects, including duration of bimodal or bilateral use, residual hearing in the non-implant ear, and performance with the second implant. For instance, binaural head shadow is predominantly a monaural processing effect and affords the listener the ability to hear in speech, particularly on the side having a bet-

ter SNR (Tyler et al, 2002a). The head-shadow effect is also related to differences in residual hearing, especially for listeners who have large interaural asymmetries. That is, listeners having large interaural asymmetries are more likely to process speech differently at the two ears, and their performance in noise depends on which ear is receiving the signal. The findings of Ramsden et al (2005) support this notion according to results of participants with sequential implantation who had significantly improved speech-recognition performance for a monaural primary CI when compared to a monaural secondary CI. When evaluating binaural head-shadow effects with these participants, minimal benefit was found when the monaural test ear was the secondary CI, but significant benefit was measured when the test ear was the primary CI.

### **CONCLUSION**

In this article, the central process of binaural summation and binaural squelch, and the physical process of the head-shadow effect were examined for users of bilateral implants and bimodal stimulation using a meta-analytic approach. Because the impact of each condition was evaluated independently, the reader should exercise caution when interpreting our findings as these effects will inherently occur simultaneously, potentially interacting among one another in the real world. Another important consideration, not included in this meta-analysis, was the effect of localization on binaural-listening arrangements. Several studies have examined these effects and concluded that binaural arrangements (i.e., bilateral, bimodal) allow for a significant increase in localization ability and attention to the desired signal in noisy listening environments (Ching, 2000; Ching et al, 2001; Tyler et al, 2002a; Gantz et al, 2002; Laszig et al, 2004; Ching, 2005; Ching et al, 2005a).

Although the statistical data show concrete evidence for binaural-listening arrangements in noise, subjective comments and reports obtained from study participants, their significant others, and their parents cannot be discounted. Subjective attributes of bilateral participants include increased speech benefit (Senn et al, 2005) and overall preference (Gantz et al, 2002; Tyler et al, 2002a) for two CIs relative to one, as well as reduced stress when participating in conversation (Kühn-Inacker et al, 2004). Comments

from participants regarding bimodal stimulation revealed increased patient confidence and comfort (Ching et al, 2001; Tyler et al, 2002b; Ching et al, 2004a), improved function in everyday life (Ching, 2000), and an increase in speech clarity (Ching et al, 2001). Studies—on both bilateral and bimodal stimulation—indicate that users are subjectively aware and satisfied with the increases in their ability to hear better in noisy listening situations, as well as an improvement in localization (Tyler et al, 2002b; Ching et al, 2004b; Senn et al, 2005).

Because the results of this meta-analysis also revealed that performance in noise for bilateral and bimodal stimulation were similar, we recommend that a bimodal arrangement be attempted as the first-order treatment for patients who are candidates for hearing aid use on the non-implant ear. The presence of bimodal benefits can be determined at substantially lower cost and with less risk to the patient compared to the bilateral-listening arrangement, which can be verified by comparing monaural CI performance to bimodal performance on a speech-recognition task. This comparison should only be performed after loudness has been balanced between the hearing aid and the CI (Ching et al, 2001).<sup>2</sup> For young children, bimodal benefit can be evaluated by using a combination of parental observation checklists of auditory awareness (Zimmerman-Phillips et al, 1997) and electrophysiologic cortical potentials (Sharma et al, 2005).

The addition of a second CI is recommended when there is no benefit from use of a hearing aid on the non-implant ear. Peters (2006) suggests that the risks associated with the second surgery are often overshadowed by the binaural benefits provided to patients. Simultaneous CIs may be ideal for some patients, such as young children during the critical period of speech and language development. Additional candidacy guidelines for bilateral implantation in adults and children are provided by Peters (2006).

Given the results of this meta-analysis and the consistent reports of subjective benefits in the literature, clinical recommendations regarding the use of bimodal or bilateral listening arrangements are supported. Determining the most appropriate binaural arrangement will require individualized speech-recognition testing and other objective and subjective measures.

## NOTES

1. It is important to note that some listeners with CIs may not be able to choose between bilateral and bimodal arrangements. For instance, some users may not benefit from a hearing aid fit on the non-implant ear, or they may encounter contraindications that preclude receiving a second CI.

2. For guidelines on bimodal fittings and loudness balancing, the reader is referred to Ching et al (2001 and 2004a) and Ching (2005).

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## Appendix A.

## Participant Characteristics for Bilateral Studies

Author (year)	N	Onset of Deafness	Duration Deaf Left/Right (years)	Age at 1st CI (years)	Gap: 1st & 2nd CI (years)	Duration CI Use Uni/Bil (years)	Manufacturer Implants	Processor	Strategy
Gantz et al. (2002)	10	Post	18;0 (0;1-37)/ 4;9 (0;1-25)	57 (35-75)	0	1 (1)/ 1 (1)	Cochlear Nucleus 24	ESPrIt24	SPEAK
Kühn-Inacker et al. (2004)	18	Pre, Peri	3;6 (2-6) DNS Lt/Rt	3;6 (2-6)	1;6 (0-4)	3;6 (2-6)/ 1;2 (0;7-2)	MED-EL COMBI 40/40+	TEMPO, TEMPO+	CIS, CIS+
Laszig et al. (2004)	23	Post	10;7 (0;8-41)/ 10;0 (0;8;45)	46 (18-67)	2;2 (0-5)	DNS/ 0;6 (0;6)	Cochlear Nucleus 24	SPrInt, ESPrIt 3G	ACE, SPEAK
Müller et al. (2002)	9	Post	16;0 (1-64)/ 15;4 (2-67)	39 (16-64)	1;2 (0-2;8)	2;9 (0;2-5)/ 1;3 (0;2-3)	MED-EL COMBI 40/40+	TEMPO, TEMPO+	CIS, CIS+
Ramsden et al. (2005)	28	Post	6;1 (1-15)/ 8;5 (1-15)	54 (27-78)	3 (1-7)	3 (1-7)/ 0;9	Cochlear Nucleus 24	ESPrIt, SPrInt	ACE, SPEAK
Schön et al. (2002)	9	Post	13;8 (0;5-62)/ 13;7 (0;5-62)	41 (17-66)	1 (0-2)	DNS/ DNS	MED-EL COMBI 40/40+	TEMPO, TEMPO+	CIS, CIS+
Senn et al. (2005)	5	Pre, Post	DNS	37 (8-51)	2;8 (1-4)	4;3 (2-6)/ 1;5 (1-2)	MED-EL COMBI 40/40+	TEMPO, TEMPO+	CIS, CIS+
Tyler et al. (2002a)	9	Post	3;7 (0;1-25)/ 2;8 (0;1-10)	58 (35-71)	0	0;3	Cochlear Nucleus 24	ESPrIt, SPrInt	ACE, CIS, SPEAK

Note: Data in table are means with the range in parenthesis. Duration Deaf=duration of deafness prior to implantation; Pre=prelingual; Post=postlingual; Peri=perilingual; 1st= first side; 2nd= second side; DNS=did not specify; CI=cochlear implant; Uni=unilateral; Bil=bilateral; CIS+=continuous interleaved sampling; SPEAK=Spectral Peak; ACE=Advanced Combination Encoders.

## Appendix B.

## Participant Characteristics for Bimodal Studies

Author (year)	N	Onset of Deafness	Duration Deaf CI ear (years)	Age at CI (years)	CI Ear Right/Left	Duration CI/ Bimodal Use (years)	Manufacturer Implant	Processor	Strategy	Unaided PTA/HA Type
Ching et al. (2005a)	18	Pre	5;7 (2;3-16;8)	5;7 (2;3-16;8)	12/6	4;4 (1-7;8)/ 1;5 (0;1-6;3)	Cochlear Nucleus 22/24	ESPrIt22/24, Spectra, SPrInt	ACE, SPEAK	105/1chan WDRC
Ching et al. (2004b)	21	Post	28;8 (8-62)	59 (18-81)	10/11	3;7 (1-8;8)/ >0;1	Cochlear Nucleus 22/24	ESPrIt22/24, Spectra, SPrInt	ACE, SPEAK	99/ 1 chan WDRC
Ching et al. (2000)	5	Pre	DNS	12 (5;4-17;3)	DNS	1;1 (0;9-1;3)/ >1;1 (0;9-1;3)	Cochlear Nucleus 24	SPrInt	ACE, SPEAK	106/ 1chan WDRC
Dunn et al. (2005)	11	Post	DNS	62;6 (46-82)	5/7	1;7 (0;3-10)/ ≥0;3	Various	Various	ACE, SAS, CIS	DNS/ Various
Holt et al. (2005)	10	Pre	6;8	7;0	DNS	DNS	Various	Various	ACE, SAS, CIS	DNS/ Various
Luntz, et al. (2005)	12	Pre, Post	DNS	25;2 (7-60)	DNS	0;9 (0;1-1;4)/ 0;7 (0;1-1;0)	Various	Various	ACE, SAS, CIS	103/DNS
Morera et al. (2005)	12	Post	11;3 (4-15)	46;2 (23-75)	DNS	0;6/ > 0;6	Cochlear Nucleus 24	DNS	ACE, SPEAK	102/DNS
Tyler et al. (2002b)	3	Post	4;3 (2-7)	50;8 (46;8-53;3)	3/0	7;9 (6-12) > 5;0	Nucleus 22, Clarion	DNS	SPEAK, CIS	87/Variou

Note: Data in table are means with the range in parenthesis. Duration Deaf=duration of deafness prior to implantation; Pre=prelingual; Post=postlingual; DNS=did not specify; CI=cochlear implant; CIS=continuous interleaved sampling; SPEAK=Spectral Peak; ACE=advanced combination encoders; Unaided PTA=pure-tone average of non-implant ear in dB HL; chan=channels in the hearing aid; WDRC=wide dynamic range compression.