Bimodal Devices and Bilateral Cochlear Implants:

A Review of the Literature

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INTRODUCTION

Modern multichannel cochlear implants have proven to be a highly successful intervention for individuals with severe-to-profound hearing loss, producing good open-set speech recognition in quiet for most patients, as well as many other benefits (e.g., see Parkinson *et al.,* 2002). Over the course of the past 30 years, cochlear implant technology has improved dramatically, and along with this has come an expanding patient candidacy criteria and a growing acceptance of the safety and efficacy of this intervention strategy. Although most individuals with bilateral deafness are still only fitted with one cochlear implant, over the past two decades the number of patients fitted with bilateral cochlear implants has been increasing.

There are clear benefits to having bilateral (two-eared) input to the auditory nervous system, and these are well documented in the psychoacoustic literature. The conventional hearing aid literature is also unanimously in support of bilaterally hearing-impaired patients being fitted with hearing aids on both ears. It seems reasonable, then, to conclude that the next logical step is bilateral implantation of cochlear implants for patients in whom both ears meet the criteria for cochlear implants. There are two primary reasons to think that bilateral implantation might provide significant benefit. First, it ensures that the ear with the best postoperative performance will be implanted - - this is particularly important given that research on preoperative indicators to determine the best ear to implant indicates that prediction of postoperative performance is not always strong. Second, it may allow preservation of some of the benefits that persons with normal binaural hearing experience, including localization ability and improved speech understanding in background noise. Early on, there was some concern expressed in the audiological and otologic communities that input from the two ears in bilateral cochlear implantation would not be usable in providing the patient with binaural benefit, or that it even might result in some interference at a higher level of the auditory nervous system. Fortunately, the research to date as reviewed in this paper does not support this concern, and indeed illustrates as a whole that bilateral implantation provides clearly significant benefits to bilaterally deaf patients.

This paper reviews the available literature on this topic as of March 2007. In the first section of the paper, there is a brief summary of the topic of the advantages of two-eared versus one-eared input, and of the literature related to monaural versus binaural hearing aid use. The second section of this paper reviews the cochlear implant literature on the topic of bilateral processing. Data on the related issue of patients who receive bilateral input by wearing a power hearing aid on the opposite ear from their cochlear implant, an approach now commonly called "bimodal listening devices", is first reviewed. Then the published literature on patients who have received bilateral cochlear implants is detailed. Note that only data from published articles in the English language were included and not unpublished data from presentations at conferences.

Terminology

A note is in order on the terminology used in the literature. Some authors use the terms "unilateral" and "monaural", and "bilateral" and "binaural", synonymously, to indicate one-eared and two-eared inputs to the auditory system respectively. Other authors differentiate between these terms by reserving use of the terms "monaural" and "binaural" to those instances where it is known that there is *benefit received* from the device; i.e. that the information from one or both ears is actually used by the auditory system for perception. For instance, consider that a patient could have bilateral cochlear implants, but if that patient was not receiving any benefit from the addition of the second implant, he would not be said to have "binaural processing" by his auditory system. Note also that some researchers use different terms for the same process, such as the synonyms "binaural squelch effect" and "binaural unmasking". An attempt was made herein to mention all the various terms used, but subsequently to use terms reasonably consistently.

BRIEF REVIEW OF BENEFITS OF TWO-EARED INPUT

The Psychoacoustic Literature

There is a fairly voluminous literature in psychoacoustics (hearing science) illustrating the benefits in normal hearing persons of having two-eared rather than one-eared input. When hearing loss disrupts the ability of the brain to process binaural inputs, whether due to large differences in the degree of loss between the ears, or a failure to provide amplification or a cochlear implant to one impaired ear, these benefits can be severely degraded or lost. There are three primary effects ascribed to binaural listening: *the head shadow effect*, *the binaural summation effect*, and *the binaural squelch effect* (e.g. Durlach & Colburn, 1978), producing benefits that range from improved speech recognition in noise, to the ability to localize the direction of a sound, to more “natural” perception. The following briefly describes the key benefits of binaural functioning.

Head Shadow Effect

When speech and noise come from different directions (i.e. are spatially separated, as typically occurs in the real world), there is always a more favorable signal-to-noise ratio (SNR) at one ear than at the other because of the *head shadow effect* and different sound distances to the ears. The head shadow effect is primarily seen in frequencies higher than 1500 Hz (e.g. Shaw, 1974), with the amount of attenuation of sounds from the opposite side of the head dependent on frequency but ranging from about 7 dB in the speech range up to 20 dB or more at the highest frequencies. If both ears are participatory, the ear with the most favorable SNR is always available so that the patient can selectively attend to this ear. This is compared to the unfavorable situation where only the ear with the poorer SNR is functional. Persons with unilateral hearing loss can become very frustrated when people are talking on both sides of them because they must constantly turn their “good ear” to whomever they want to hear best at the time, and then they miss sounds on the deaf ear side.

As will be shown later in this paper, a primary benefit of bilateral cochlear implants appears to be related to the beneficial aspects of hearing from both sides, and always having the ear with the more favorable SNR available. This is generally tested with speech from a frontal speaker and noise from a side speaker - - when the second ear is added that is contralateral to (opposite side of) the noise source, performance benefit comes primarily from the head shadow effect. Note, however, that there is discrepancy across the published studies in how to quantify the head shadow effect, with some researchers merely examining differences in scores with sound ipsilateral versus contralateral to a unilateral ear under test, and others comparing the score for listening with bilateral inputs to that for unilateral listening with the noise presented ipsilateral to the ear under test.

Binaural Summation & Redundancy

Sounds that are presented to both ears rather than just one are perceived as louder due to *binaural summation* of the information received at each ear. In fact, the threshold of hearing is known to improve by about 3 dB for binaural versus monaural presentation to normal ears, resulting in a doubling of perceptual loudness and improved sensitivity to fine differences in the intensity and frequency domains. This latter effect is sometimes referred to as binaural redundancy, and it is believed that it may translate into improved speech perception scores. When listening to speech with only one ear in a difficult listening situation or with one ear with greater sensorineural hearing impairment than the other, there is a loss of the redundancy in cues across the ears that may reduce performance.

The benefit of the *binaural redundancy* aspect of bilateral inputs is typically tested by presenting speech alone or having speech and noise emanate from the same loudspeaker frontally - - when the second ear is added, benefit is possible through redundancies or overlaps in representation at the two ears. In a normal hearing ear, this effect produces about a 1 to 2 dB improvement in SNR (Bronkhorst & Plomp, 1988).   At this time, there is only limited evidence for true binaural redundancy effects on speech perception results in the bilateral cochlear implant literature reviewed herein. This effect is probably not stronger either because such subtle cues are not able to be utilized by ears that have severe to profound hearing loss, or simply because the signal processing available in today's cochlear implants (with two implants processing independently) does not adequately maintain these interaural cues.

Binaural loudness summation has been shown to occur, however, and is a potential confounding factor in comparing across studies. While most researchers have adjusted the loudness of the implant processing for binaural presentation versus monaural presentation (and made sure loudness is reasonably balanced across the ears), some have not. In a clinical bilateral implant fitting, it would generally be presumed that loudness would be adjusted so that the patient's overall loudness comfort level is reasonable, and thus any purely binaural summation effects would be reduced or negated for bilateral listening compared to a previous unilateral implant.

Binaural Squelch/Unmasking

A person with only one functioning ear can usually understand conversation well when listening in a quiet environment, as long as the sounds of speech are made loud enough. However, even a normal hearing person who is listening in high levels of background noise can find speech understanding to be difficult in an adverse listening situation (consider, for example, competing conversations with multiple persons seated at a long table in a very high noise level restaurant). This occurs partly because of direct masking and partly because of upward spread of masking on the basilar membrane of the cochlea (whereby low-frequency sounds have a greater impact on reducing perception of higher-frequency sounds than vice versa). Speech recognition in such noisy environments is even harder for a person with sensorineural hearing loss both because of the inherent distortion and loss of normal nonlinearities introduced by cochlear damage, and because these patients show even greater amounts of upward spread of masking effects than do normal ears.

Fortunately, the auditory nervous system is wired to help in noisy situations as long as there is functional input from both ears - - that is, the auditory system and brain can combine information from both ears so that there is a better central representation than would be had with only information from one ear (e.g. Zurek, 1993). This effect, commonly referred to as *binaural squelch* (but also sometimes called *binaural unmasking*), results from the brainstem nuclei processing timing, amplitude, and spectral differences between the ears to provide a clearer separation of the speech and noise signals. The squelch effect takes advantage of the spatial separation of the signal source and the noise source(s) and the differences in time and intensity that these create at each ear. This is generally tested with speech from a front speaker and noise from a side speaker - - when the second ear is added that is ipsilateral to (same side as) the noise source, any benefit comes from the binaural squelch effect. There is some limited evidence of improved speech understanding in noise in bilateral cochlear implant patients due to binaural squelch effects, although the effect is not seen across all bilateral implant users or studies, and is not as large as the head shadow effect.

Note that binaural summation and squelch are signs of the ability of the auditory nervous system to integrate, fuse, and use information from the two ears. In contrast, the head shadow effect merely results from the physical attenuation of sound across the head and does not require central nervous system integration - - This does not negate the fact, however, that the head shadow effect is a substantial factor in everyday performance for those listeners with unilateral versus bilateral devices.

Localization

Finally, perhaps the most well-known practical binaural benefit is the ability to localize (i.e. determine the direction that a sound is coming from). This function is dependent on auditory system perception of interaural (between ear) differences in time, intensity, and phase (e.g. Yost & Dye, 1997). Localization ability can be a safety consideration. For example, when crossing a busy street, it is important to know the direction that a car is coming from. Persons with significant unilateral hearing impairment can also attest to the frustration of hearing their name spoken but not knowing which direction to turn in order to find the person calling them.

Research to date has focused on localization of sound sources in the horizontal azimuth, but keep in mind that it is also possible for a listener to differentiate sound sources in the vertical plane (by elevation) and in terms of the distance from the listener. It is well known that interaural timing differences provide the information necessary to locate the direction of low frequency sounds - - specifically, those less than about 1500 Hz. For sounds that are higher in frequency, the main cue for horizontal plane localization is the interaural intensity difference that occurs because of the head shadow effect. In addition, head and pinna shadow effects, pinna filtering effects, and torso absorption properties can all contribute to spectral differences that can be particularly helpful in determining elevation of a sound. For a listener with only one functional ear, there are very few cues to assist in sound localization although some rudimentary localization ability can still exist. The literature on bilateral cochlear implants provides significant and substantial evidence that localization abilities are enhanced with the use of both ears versus just one.

Binaural versus Monaural Hearing Aids

Of relevance to the current review is the work that has been accomplished in the hearing aid literature showing benefits of wearing binaural (bilateral) hearing aids versus a monaural (unilateral) hearing aid, when there is hearing loss in both ears. While review of this extensive work would entail a separate paper in itself, the key points are touched on in the following.

One of the strongest arguments that has been used for binaural hearing aid fittings is the impact of “auditory deprivation” on the ability to understand speech. Specifically, it is well known that if only one ear is aided when there is in fact hearing impairment in both ears, speech recognition ability in the unaided ear significantly deteriorates over time (e.g. Silman *et al.*, 1984; Gatehouse, 1992). This effect has also been shown in children with moderate and severe hearing impairments (Gelfand & Silman, 1993; Hattori, 1993). Willot (1996) offers an excellent discussion of what might be happening at the neural level in terms of auditory deprivation and possible secondary CNS plasticity with hearing aid use. In any case, if a patient has hearing loss in both ears, it is important to provide bilateral amplification as soon as possible to retain the ability of the brain to use the input from both ears.

As the importance of bilateral amplification became clearer and the benefits of hearing aids increased with technological advances, bilateral hearing aids became the norm. Bilaterally hearing-impaired people who wear hearing aids in both ears can clearly understand speech better, especially in noise, compared with those who wear a hearing aid in only one ear (e.g. Ross, 1980; Byrne, 1980; Byrne, 1981). They also show improved localization abilities (e.g. Byrne & Dermody, 1975; Byrne, 1980). Ricketts *et al.* (2001) documented the advantages of bilateral hearing aids across a broad variety of conditions. Although some patients do choose to obtain only one hearing aid (generally either because of the cost or cosmetic concerns), patients with bilateral hearing loss are almost always counseled by their otologist and audiologist/hearing aid dispenser that they will likely receive the greatest benefits from binaural hearing aids.

Given the fairly extensive literature in cochlear implants showing that longer duration of hearing loss prior to implantation results in poorer postoperative speech understanding performance, it is reasonable to assume that a similar argument might be made in support of cochlear implantation for bilaterally deaf patients - - That is, if a person is implanted bilaterally early on, then they will likely be able to utilize binaural processing cues for binaural benefit better than if one of their auditory pathways remains unstimulated for long periods of time. This argument may also appear to have a drawback, given that most cochlear implant patients are wearing only one device at this time and thus the other ear has already long remained unstimulated - - some might argue that the unstimulated ear will be unable to take advantage of an additional cochlear implant for binaural processing. However, as will be shown in the literature reviewed herein, even patients with very long durations of hearing loss in the second implanted ear do generally seem to show bilateral cochlear implant benefits, even if sometimes a bit less robust than those implanted bilaterally after shorter durations of deafness.

THE LITERATURE ON COCHLEAR IMPLANTS

There have been an increasing number of articles in the literature in recent years describing the efficacy of bilateral input for cochlear implant patients. However, some of that literature refers to the case where a power hearing aid is on one ear and a cochlear implant on the other ear - - a condition that is now commonly called “bimodal”. The literature on patients with bimodal devices will be reviewed first, followed by a review of the literature where bilaterally severe to profoundly hearing-impaired patients have had cochlear implantation on both ears.

Use of Bimodal Devices: Cochlear Implant with Contralateral Hearing Aid

The first attempts at providing bilateral auditory inputs to bilaterally deafened cochlear implant users involved examining their performance when they wore a power conventional amplifier on the other side from a cochlear implant - - in other words, bimodal hearing devices. This became viable as patients with lesser degrees of hearing loss were implanted with cochlear implants due to increased evidence of greater benefit with a cochlear implant than with a hearing aid. Thus, there was often useable residual hearing on the non-implanted side. An early concern expressed by some in the audiological/otologic communities was that the two forms of energy, one electric (cochlear implant) and one acoustic (hearing aid), would somehow interact in a negative manner so that there would be poorer performance than if a cochlear implant was worn alone - - that is, that some kind of “binaural interference” would occur. It had been previously shown in the hearing aid literature that, while the vast majority of patients performed best with binaural amplification, there were a few patients who showed poorer speech discrimination with two hearing aids compared to one (e.g. Siegenthalar & Craig, 1981; Jerger *et al.*, 1993). It was presumed that these patients did poorly because the signals from the two ears were presenting unusable information to the brain, or information that couldn’t be readily combined, usually because of differing hearing-impairment degrees or types between the ears. Since acoustic and electric inputs are quite different, there was concern that these signals would also not be appropriately combined for binaural benefit in patients wearing a cochlear implant on one ear and a hearing aid on their other ear.

Another area of research that raised concern was psychoacoustic work examining the perception of acoustically versus electrically processed sound. For example, Blamey *et al.*

(1996) demonstrated that different pitches might be elicited when processed by a cochlear implant and a hearing aid in the opposite ear. Further, Blamey *et al.* (2000) showed that the dynamic range and shape of iso-loudness curves between electrical and acoustic hearing in the opposite ears of one patient could differ.

Despite these concerns, however, many patients who had residual hearing in their non-implanted ear clearly preferred to wear a hearing aid on that ear compared with wearing only a unilateral cochlear implant, and subsequent research that specifically examined this issue has indeed demonstrated, almost without fail, greater benefit from wearing both devices than from wearing either one alone. Recently Ching et al. (2005) hypothesized that binaural benefit with bimodal hearing devices may arise from a combination of the head shadow effect, binaural redundancy and squelch effects, and possibly even to “complementary cues” provided by the two different types of hearing prostheses.

Adult Population

In one very early study, Waltzman et al. (1992) demonstrated that eight adults with a unilateral Nucleus cochlear implant perceived speech better, on average, when listening bimodally then with one ear alone. They did note that variables such as auditory thresholds and time of usage of the devices impacted the performance improvement.

That same year, Shallop *et al.* (1992) examined seven adult patients, 6 males and 1 female, aged 39 to 77 (mean = 58.4). These adults had a severe-to-profound hearing loss in the better, unimplanted ear (mean pure-tone average {PTA; for 500, 1000, and 2000 Hz} hearing threshold of 104 dB HL), and a profound hearing loss in the ear implanted with a Cochlear Nucleus 22 device. There was a broad range of ages at hearing loss onset (3 to 67 years) and of duration of hearing loss (5 to 43 years). These subjects were tested wearing only their cochlear implant, only a power hearing aid on the non-implanted ear, and then bimodally with both devices on a variety of speech tests presented at 70 dB SPL at 6 and 12 months postoperatively. Results using binomial tests indicated that at 12 months post-implantation 80% of the subjects scored significantly higher when using the cochlear implant alone compared to the contralateral hearing aid alone on the Iowa Sentences Without Context Test, and the NU-6 word test scored for phonemes. In addition, 60% of the subjects scored significantly higher with the cochlear implant on the Iowa Vowel Test and the NU-6 word test scored for words. There were fewer subjects showing a significant difference between cochlear implant and hearing aid on the Iowa Consonant Test and on CID Sentences of Everyday Speech. For the bimodal condition, performance scores were consistently higher across subjects than for either the contralateral hearing aid only or the implant only listening conditions for all tests expect for NU-6 words. Using binomial tests, 80% of the subjects scored significantly higher in the bimodal condition compared to the contralateral hearing aid only condition for vowel, phoneme, and sentence perception.

The four adults (3 males, 1 female, aged 36 to 79) in a study by Dooley *et al.* (1993) had a mean PTA of 106 dB HL in the non-implanted, better ear. These patients' speech understanding ability was examined both with a conventional hearing aid on the non-implanted ear, and also with a laboratory prototype hearing aid that was controlled by the same processor as the cochlear implant. In this prototype device, a single microphone input was used for both electrical and acoustic outputs. The MPEAK strategy was used for the Cochlear Nucleus 22 implants. Speech tests included BKB Sentences and Boothroyd monosyllabic words scored for vowel and consonant recognition. Bimodal scores under both conditions (with and without the same speech processor controlling both devices) were consistently higher than either unilateral listening condition (hearing aid alone or cochlear implant alone). However, analysis of variance on the arcsine-transformed percent correct scores followed by Tukey post-hoc comparisons indicated significantly higher bimodal performance only for the consonant recognition scores. The authors note that failure to reach significance for the vowel and sentence recognition scores may have been due to a ceiling effect because some of the patients scored more than 80% with the unilateral cochlear implant alone on these tasks.

Blamey *et al.* (1997) reported results from a much larger subject sample. Fifty adult cochlear implant patients were reportedly evaluated and it was found that consistent use of a hearing aid in the non-implant ear provided a significant advantage in speech perception over use of the cochlear implant alone.

Twelve adults were evaluated by Armstrong *et al.* (1997)[1]. Seven of the listeners were Australian (three used the MSP processor and four used the SPECTRA processor with the

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[1] Note that the Shallop *et al.*, Dooley *et al.*, and Blamey *et al.* (1997) studies all used the MSP processor for the Cochlear Nucleus 22-channel cochlear implant.

Cochlear Nucleus implant) and the other five were American (one with the MSP and four with the SPECTRA processor). The Australian group had a mean PTA of 107 dB HL in the non-implanted ear, and the American group had a mean PTA of 100 dB HL in the non-implanted ear. Speech perception at 70 dB SPL was evaluated using CUNY sentences and CNC words (recorded by a native speaker for each group) in quiet and in babble noise at an SNR of 10 dB for implant alone, and implant with a contralateral hearing aid. Repeated-measures analysis of variance indicated a significant bimodal advantage for Australian sentences ($p < .05$), Australian words ($p < .01$), American sentences ($p < .001$) and American words ($p < .001$). Quiet listening produced significantly higher scores than noise listening in all cases ($p < .001$). There was no significant interaction between the conditions for Australian listeners, but for the American listeners, the advantage of bimodal listening was (borderline significance) greater in noise than in quiet ($p = .054$). The word score results from this study are shown in Figure 1. It was noted by the researchers that more of the American patients regularly wore a hearing aid on the non-implant ear. Further, those subjects who regularly wore a hearing aid received greater bimodal benefit than those who only wore the hearing aid part time. It was also anecdotally noted that the subjects reported a more "natural" sound when listening with the hearing aid and cochlear implant binaurally than when listening only with the implant, and some reported their own voice quality was improved with bimodal listening.

Tyler *et al.* (2002a) evaluated three patients who wore a cochlear implant on one ear and a hearing aid on the other ear using word and sentence recognition, and localization tasks. Speech stimuli were presented from the front in quiet and in noise, and noise was presented from the front, right, or left. Localization was tested with noise bursts presented at +/- 45-degree azimuths right or left. Testing was done for unilateral and bilateral listening, and patients were also queried about their perceived ability to integrate information across the ears. Results indicated a bimodal advantage in quiet for only one of the three patients for words and none for sentences. With speech and noise front, two patients showed a bimodal advantage over either unilateral device alone. With noise to the hearing aid side, no bimodal advantage was seen, but with noise to the cochlear implant side, one patient showed a bimodal advantage. Localization ability improved with both devices for two patients (the third patient was able to localize above chance performance with his unilateral cochlear implant alone). The researchers noted that the one patient who did not seem to show a bimodal

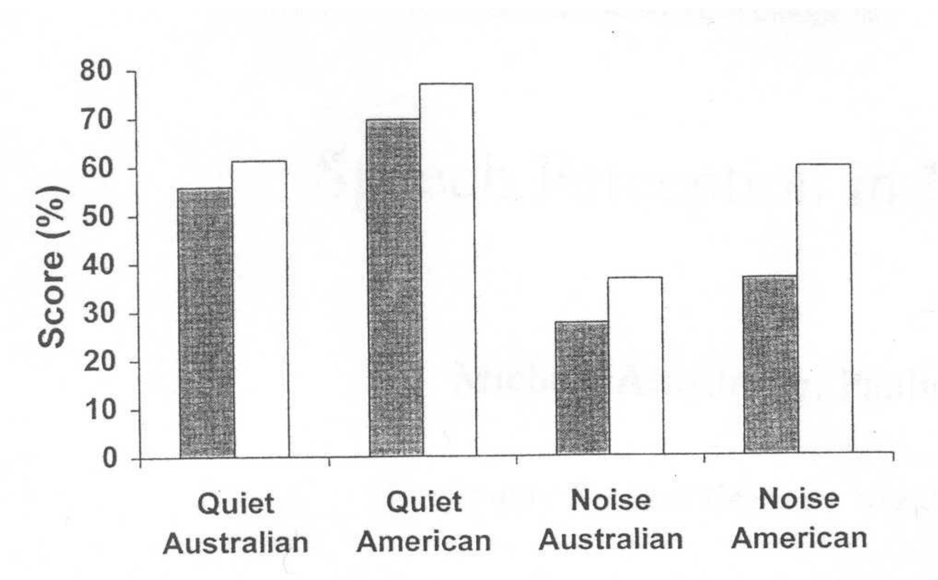

Figure 1.

Mean word scores for CUNY sentences as a function of subject group (Australian or American), presentation condition (quiet or noise), and listening condition (implant alone = shaded bars, or implant plus hearing aid = white bars). (From Armstrong *et al.*, 1997 – Fig. 1).

advantage was the one with the poorest hearing aid alone performance, so that the absolute and relative levels of performance with each ear are probably important in determining the potential for binaural integration.

Hamzavi *et al.* (2004) evaluated data from 7 Austrian adult patients who were bimodal users implanted in their poorer ear. Testing was for the cochlear implant (CI) alone, for the hearing aid (HA) alone, and for the bimodal condition (CI+HA). On the Innsbrucker sentence test, the group mean for speech perception in quiet improved from 47% for CI alone to 96% for CI+HA. On Freiburger monosyllables, the mean scores improved from 15% for CI alone to 52% for CI+HA, and for Freiburger numbers, the mean scores improved from 65% to 98%. The majority of the patients performed better with CI alone than HA alone, and the bimodal condition was superior to either of the monaural conditions.

Iwaki and her colleagues (2004) evaluated six adult bimodal device users with monosyllables in quiet and the Japanese HINT test in both quiet and noise. They also measured P300 cortical potentials using a 1 kHz frequent tone and a 2 kHz target tone for stimuli presented from a frontal loudspeaker. Three individual subjects were found to have a significant bimodal advantage (performance difference greater than chance) on the quiet speech tasks and mean results were better for bimodal than for CI alone. It was noted that the individual subjects showing a significant bimodal advantage had a longer mean hearing aid use time (18.3 years) compared to those who did not (mean 4 years), but differences in other factors such as duration of deafness, hearing thresholds, or age didn't show a difference (possibly due to limited ranges). Latencies of the endogenous P300 were shorter for bimodal listening than for monaural listening, while there was no difference on latency of N1 and P2 of the late potential. The authors noted that the latency of P300 is thought to reflect the time for sound processing in the central auditory nervous system so that it might be used for the objective measurement of expected speech intelligibility in CI users.

Ching *et al.* (2004) provided data from 21 adults (11 female, 10 male) who used either a Nucleus 22 or 24 CI system unilaterally and a hearing aid in the other ear. Twelve of the subjects were experienced bimodal users (mean PTA in non-implant ear = 100 dB HL), while nine of the subjects had not previously tried a hearing aid on the non-implant ear (mean PTA = 98 dB HL). All subjects were fitted with a Bernafon AF120 power single-channel WDRC BTE hearing aid using the NAL-NL1 prescription with individual fine-tuning via paired comparisons tests to determine the frequency response that was best for understanding speech, and loudness balanced with the cochlear implant. The prescribed frequency response was found to work well for bimodal listening, but, on average, the gain needed for binaural loudness balance was 4 dB less than that for prescribed unilateral gain. Performance unilaterally and bimodally was then examined using BKB sentences at 70 dB SPL in noise, both from a single frontal loudspeaker (called "diotic" listening; tested at a +10 dB SNR for both unilateral conditions and bimodal) or with speech from the front and noise from the implant side at 60° (called "dichotic" listening; tested at both +10 and +15 dB SNR; tested only for CI versus bimodal). In addition, a task of horizontal localization was used, with an 11 loudspeaker array and pulsed pink-noise signals presented at about 70 dB SPL. Functional performance was also evaluated by questionnaire results following a real world period of wearing time in each listening condition. Analyses of variance with Tukey's post-hoc comparisons for the diotic condition data indicated significantly better mean speech test scores for bimodal listening than for either unilateral condition, and significantly better performance for new hearing aid users than for the experienced group. In the dichotic listening condition, statistical analyses indicated that bimodal scores were significantly higher than CI alone scores at both SNRs with no significant difference for new versus experienced users. All individual subjects showed similar or better performance for bimodal versus monaural. The means for experienced and new hearing aid users for speech and noise from a frontal location (diotic listening condition) are shown in Figure 2.

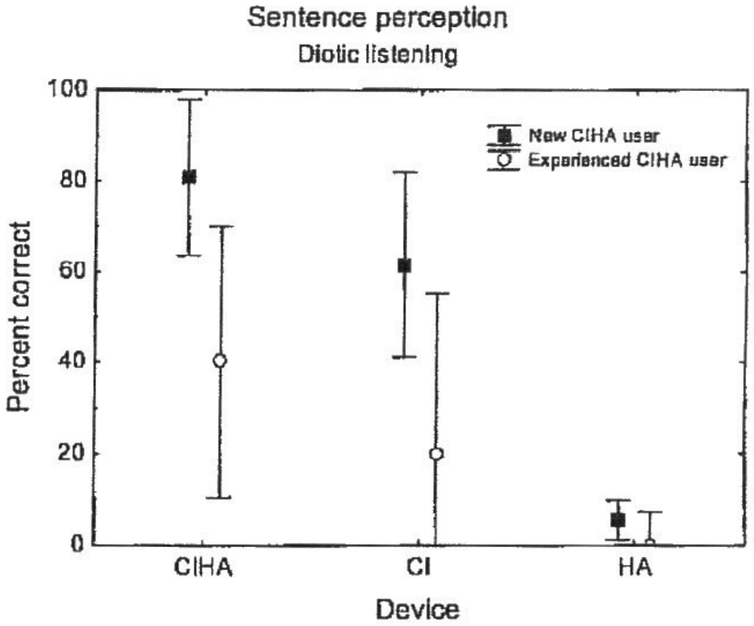

Figure 2.

Mean speech perception scores for BKB sentences in noise for the diotic listening condition as a function of subject group (new or experienced hearing aid users), and listening condition (CI alone, HA alone, and bimodal {CIHA}). (From Ching *et al.*, 2004 – Fig. 3).

In the Ching et al. 2004 study, there was also significantly less localization error for bimodal listening than for either cochlear implant or hearing aid alone. Finally, questionnaire scores were higher bimodally than either unilateral condition. Examination of individual performances revealed that all subjects showed bimodal benefit on at least one performance measure. Subjective comments by the subjects included that bimodal use enabled them to enjoy music more than using the CI alone, made it easier to listen to speech in a noisy environment, and gave them greater confidence in everyday life. Based on these results, the authors recommended a hearing aid always be used on the contralateral ear to a unilateral cochlear implant, provided sufficient residual hearing is present below 1000 Hz.

Seeber *et al.* (2004) compared localization ability of 11 unilateral implant users (aged 23 to 79) who routinely wear a power hearing aid on the contralateral ear (the bimodal patient group), to that of 4 different patients who had bilateral cochlear implants (aged 20 to 65). In the bimodal group, all but one were implanted with the Med-El COMBI 40+ device, and the other patient had a Cochlear Nucleus CI24M. The bilateral implants group all wore Med-El devices. Subjects adjusted the spot of a computer-controlled laser pointer in a completely darkened anechoic chamber to the perceived direction of sound incidence in the frontal horizontal plane by rotating a trackball. The array of loudspeakers presenting the sound were hidden behind a curtain, and included 11 speakers spanning an angle of -50° left to +50° right. Stimuli were wideband noises randomly varied in level between 64 and 76 dB SPL. Regression and correlation analyses were used to examine the subject's overall localization ability. Wilcoxin tests were also used to examine the pooled results for -50° and -40° compared to +50° and +40° as a measure of ability to discriminate sidedness. For the bimodal group: 1) two of the subjects who had substantial residual hearing (PTAs of 73 dB HL and 66 dB HL in the hearing aid ear) showed good localization ability in the bimodal configuration. One of these subjects with the best hearing was also able to discriminate side of origin with either unilateral device alone, 2) five of the subjects with greater hearing loss displayed side discrimination ability with the bimodal configuration, with three of them also able to discriminate side of origin with the cochlear implant alone, and 3) four of the subjects were not able to discriminate side of origin well in either the bimodal or unilateral configuration. For the bilateral cochlear implants group, all 4 subjects had localization ability, although it was fairly limited in three of the subjects.

Morera *et al.* (2005) reported word and sentence perception in quiet and noise for 12 postlingually deafened bimodal-device users from Spain. Six-month postoperative results for CI alone, HA alone, and CI+HA were compared to preoperative results with unilateral or bilateral hearing aids (whichever the users were wearing). In quiet, speech was given at 55 and 70 dB SPL frontally. In noise, speech was at 70 dB SPL and a fixed +10 dB SNR was evaluated with speech frontal and noise either at 0 or +/- 90° azimuth. Group mean results showed significant bimodal advantages compared to CI-alone or HA-alone at either level in quiet (binaural summation), and for disyllabic words in noise with spatially separated speech and noise (binaural squelch). For both speech and noise at 0°, bimodal device use produced a higher mean score than monaural listening but the difference did not reach statistical significance. All subjects showed significantly better postoperative bimodal performance than the best-aided condition preoperatively for one or more of the tests. Examining HA ear preoperative aided scores and the postoperative bimodal advantages found, the data (with some exceptions) suggested that the higher the preoperative contralateral ear aided performance, the higher the resulting postoperative bimodal advantage compared to CI-alone. These authors noted that in some patients there may be a need to wear the CI-alone for a time to produce best performance, before adding the HA back in to a better contralateral ear.

Dunn *et al.* (2005) reported on performance of 12 adults with bimodal devices. Tested were word recognition in quiet with speech from the front (0°), and sentence recognition with speech from the front and noise from either the front or +/- 90° azimuth. The ability to localize everyday sounds was also examined using an 8-speaker array spanning an arc of about 108° frontally. Group mean results showed a statistically significant benefit of adding the hearing aid contralaterally in noise although not all individual subjects showed the advantage across all conditions. For CNCs, four of the 12 subjects showed a binaural summation effect with significantly higher scores (binomial test) for CI+HA than for CI alone, while for CUNY sentences in noise, seven of the 11 subjects tested showed a binaural summation effect for speech and noise from the front. For CUNY sentences in noise, 2 subjects did perform significantly worse when the HA was added. When examining binaural squelch with noise from the side, six of the 10 tested showed a significant benefit bimodally, 3 subjects showed a benefit not reaching significance level (2 having ceiling effects), and one subject showed a decrement bimodally. When examining head shadow effects with noise from the side, eight of 11 subjects tested had a significant bimodal benefit when comparing noise to the HA side versus noise to the CI side listening unilaterally with the CI, and one showed a ceiling effect so could not be tested. Only two of the 12 subjects were able to localize when listening bimodally. One patient with good bimodal speech perception could localize well, and another patient with good bimodal speech perception showed the poorest localization ability.

In a recent study, Mok *et al.* (2006) reported on 14 adults using a Nucleus 24 CI and a hearing aid in the unimplanted ear with hearing loss less than 90 dB HL in the low frequencies of that ear. Three speech tests (open-set CNC words in quiet, CUNY sentences with speech and noise frontally, and closed-set spondees with noise either frontal with the speech or spatially separated) were examined for CI alone, HA alone, and CI+HA conditions. Four of the 14 subjects were unable to complete CUNY sentences and spondees. Six of the subjects had significant bimodal benefit on CNCs and/or CUNY, and five of the subjects had significant benefit on spondees. However, two subjects showed poorer speech results in the CI+HA condition than the CI alone condition on at least one of the tasks. Information transmission analyses were used and indicated that bimodal benefit in quiet arises from better perception of low-frequency speech components. Finally, subjects with poorer aided thresholds in the mid-to-high frequencies were found to have greater bimodal benefit, which the authors suggested might indicate that mid-to-high frequency information provided by the hearing aids may be conflicting with the cochlear implants.

Studies Of or Including Pediatric Subjects

The first study done on a pediatric population had a mixed result. Chmiel *et al.* (1995) tested six children (aged 4 to 13 years old) who continued to wear hearing aids in the non-implanted ear after cochlear implantation of the contralateral ear. The mean PTA hearing threshold for these children was 105 dB HL in the non-implanted ear. Three of the children showed significant benefit from the bimodal listening condition for speech perception scores using a statistical evaluation of differences between treatment conditions for each child carried out by a nonparametric randomization test. The other three children did not show any significant difference in scores between monaural and bimodal listening. None of the children showed a significant difference in speech production testing between the cochlear implant only and the bimodal condition, but it was noted that vocal quality was better in the bimodal condition by informal observation.

In 2000, more favorable results were shown by Ching *et al.* (2000), who demonstrated benefits bimodally for children listening to speech in noise. In 2001, Ching *et al.* examined both the efficacy of bimodal input with a hearing aid and a cochlear implant, and also whether hearing aids for children with cochlear implants needed to be adjusted differently from those for children who use binaural hearing aids. Sixteen congenitally hearing-impaired children (6 boys and 10 girls), aged 6 to 18 years (mean = 11.4 yrs, SD = 3.2) were studied. All the children had received a Nucleus 22 or 24 implant programmed with SPEAK with stable MAPs for 6 months or more. All the children were educated in aural/oral programs or mainstreamed, and wore a power hearing aid in the non-implant ear after implantation. The mean PTA in the non-implanted ear for these children was approximately 104 dB HL. Results of experiments conducted to determine the best settings for the hearing aid revealed that 12 of the 16 children preferred a frequency response within +/- 3 dB/octave of the standard NAL-RP prescription (Byrne & Dillon, 1986). The other children preferred frequency responses with more low-frequency emphasis. The average gain required by the children for loudness balance between the ears was 6 dB more than the prescription (significantly different on a t-test at p = .0004). Arcsine-transformed speech recognition scores were also evaluated on 11 of the children with repeated-measures AOV and post-hoc Tukey tests. Results indicated that the children performed significantly better in the bimodal condition in both quiet and noise (where the hearing aid had been adjusted for best performance) compared to either using the hearing aid alone (p = .0001 for quiet and noise) or the cochlear implant alone (p = .0005 quiet; p = .009 noise) or the bilateral condition before hearing aid adjustment (p = .02 quiet; p = .01 noise) for BKB sentences (key word scoring). For VCV nonsense syllables presented as a closed-set task, there were no significant differences *except* that the hearing aid alone condition was poorer than the CI alone or bilateral conditions (p = .0001). However, the mean score for the nonsense syllables was best for the bimodal listening condition with the hearing aid adjusted. The authors noted that the presentation mode used for the speech and noise (both from a single loudspeaker at 0° azimuth) minimized head diffraction/shadow effects and thus likely underestimated the true binaural advantage. The mean scores for speech testing across conditions are shown in Figure 3.

Ching *et al.* (2001) also obtained objective localization scores on the 11 children. An AOV and post-hoc tests on the horizontal plane error scores indicated a significant improvement in localization ability for the bimodal condition where the hearing aid had been adjusted compared to the hearing aid alone (p = .0004), the cochlear implant alone (p = .0006) or the bimodal condition before hearing aid adjustment (p = .03). Localization with a unilateral cochlear implant did not differ significantly from that with a unilateral hearing aid. Finally, a questionnaire given to the parents about their children's performance with unilateral versus bimodal input conditions illustrated that parents thought the children performed poorer with the hearing aid alone than with any of the cochlear implant conditions (p < .0001). Parents of four of the 11 children perceived significant bimodal benefit compared to performance with the cochlear implant alone, while the remaining parents perceived similar performance with unilateral and bimodal inputs. When individual children were compared across all three

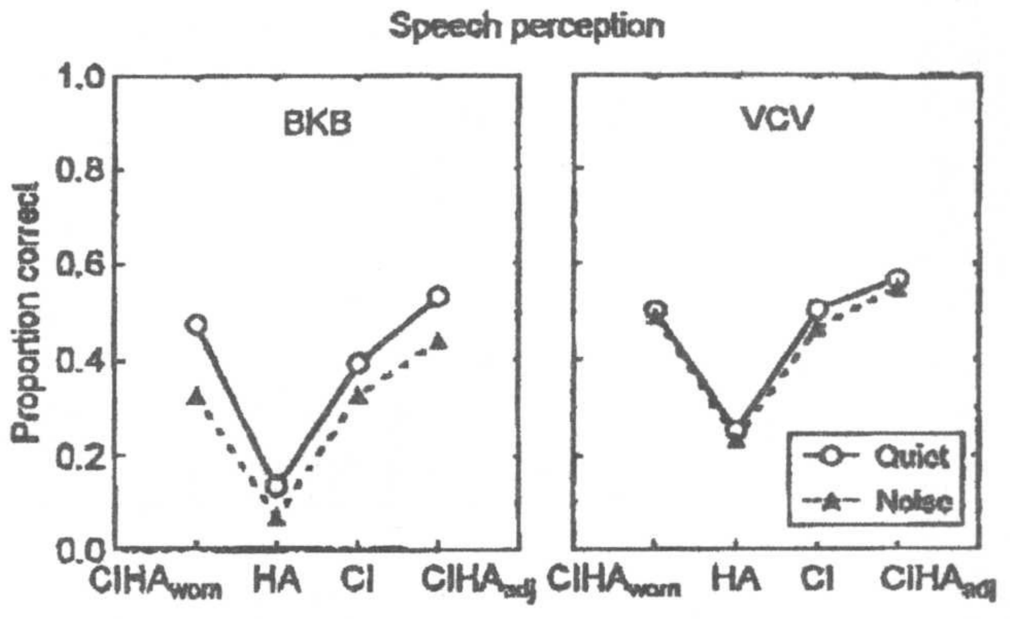

Figure 3.

Mean proportion correct for all children when using a cochlear implant alone (CI), a hearing aid alone (HA), bimodal input from the cochlear implant and the hearing aid set to NAL-RP (CIHAworn), and bimodal input when the hearing aid was adjusted for best performance frequency response and for loudness balance (CIHAadj). Circles represent quiet scores and triangles represent noise scores (From Ching *et al.*, 2001 – Fig. 4).

measures (speech scores, localization scores, and parental perception of benefit), every child received benefit from bimodal input on at least one measure, and no child was disadvantaged by bilateral signal processing.

In 2005, Luntz *et al.* evaluated speech-in-noise performance for 12 patients in Israel implanted with a unilateral CI, who had residual contralateral hearing and used a hearing aid in that ear. Three of the patients were post-lingually impaired adults, and nine were pre-lingually impaired adults and older children (aged 7 to 16). With speech (CUNY sentences, or common-phrase sentences for the prelingually impaired children) presented at 55 dB HL from the same frontal loudspeaker as the noise, and an SNR of +10 dB, subjects were tested after 1 to 6 months of bimodal device use and then again after 7 to 12 months. At 1-6 months, there was no significant difference on a Friedman test between group performance with the CI alone and with the CI+HA (although the bimodal devices mean was higher), but at the second session, there was a significant improvement in both results *and* the CI+HA condition performed significantly better than the CI alone. These group results are shown in Figure 4. No correlation was found at either session between the pre-implantation aided or unaided hearing threshold in the non-implanted ear and a) the performance score obtained in the CI+HA condition, b) the improved performance over time in the bimodal condition, or c) the benefit received with CI+HA compared to CI alone. Evaluation of individual results revealed that seven patients performed better at the second session in CI+HA mode than CI alone, three showed no significant difference (defined as >6%), one could not show benefit from bimodal use because their performance reached the ceiling (98%) with the CI alone on the speech task, and one prelingually impaired child showed poorer speech understanding using both devices than when using the CI alone. The authors reported that the latter child is now being considered for bilateral CIs. Eleven of the subjects, including the prelingually impaired child who performed more poorly bimodally, reported subjective benefits with bimodal use compared to CI alone.

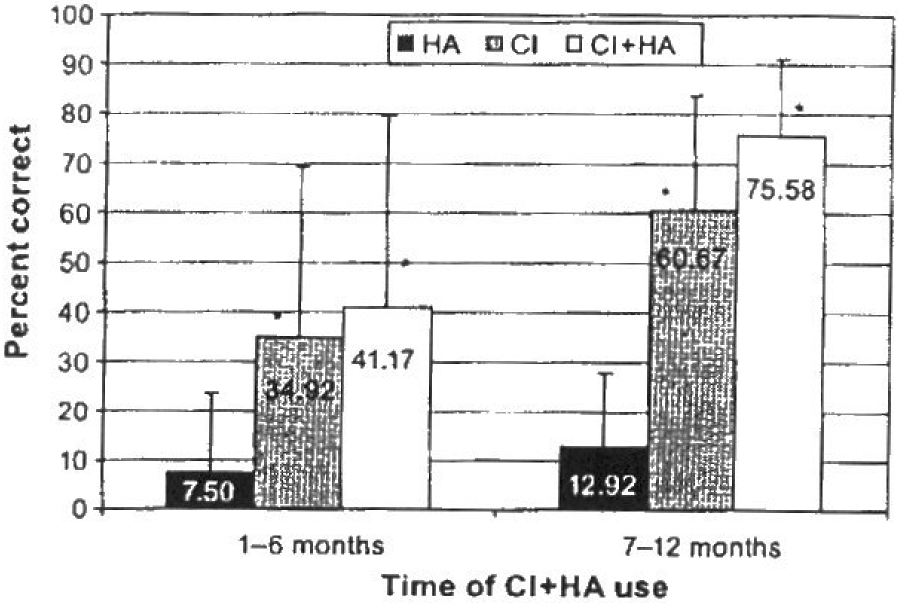

Figure 4.

Group mean results (+/- 1 SD) on sentence recognition in noise after 1-6 months and 7-12 months of CI+HA use in 12 adults and older children. The asterisks indicate significant at $p < .05$ using a Friedman test. (From Luntz *et al.*, 2005 – Fig. 2).

In 2005, Ching *et al.* evaluated binaural redundancy with bimodal devices and the ability to use inter-aural time difference information to improve speech intelligibility in noise via binaural squelch. Data were collected from 14 normal hearing controls (9 adults and 6 children) and 23 hearing-impaired patients. Of the hearing-impaired patients, 14 wore bilateral BTE hearing aids (9 adults and 5 children), and nine wore either a Nucleus CI-22 or CI-24 on one ear with a BTE hearing aid on the contralateral ear (bimodal users; 4 adults and 5 children). Binaural redundancy was assessed by comparing the SNR needed for 50% speech recognition performance for sentences in noise under monaural and bilateral listening conditions. In addition, the subjects' abilities to use inter-aural time difference cues were determined by comparing binaural SNRs obtained with and without a noise delay of 700 usec between ears. This delay represented the approximate human inter-ear delay time for sounds from a lateral incidence. Results showed that the hearing-impaired adults using bimodal hearing devices or bilateral hearing aids, and the hearing-impaired children using bilateral hearing aids did benefit from binaural redundancy cues, while the hearing-impaired children using bimodal hearing devices did not. The authors suggested that this finding might indicate a need for more language experience in order to be able to utilize redundancy cues. For interaural difference cue testing, even though the normal hearing controls and those bilateral hearing aid users with less severe hearing losses (average low-frequency hearing loss < 65 dB HL) used the cues to improve speech perception in noise, none of the bimodal hearing-impaired adults or children were able to, nor those bilateral hearing aid users with greater averaged low-frequency hearing losses. It is of note that the bimodal hearing aid users in this study also all had greater averaged low frequency hearing losses in their non-implant ear. The authors believed that the bimodal users could not utilize interaural difference cues probably because current cochlear implant systems cannot encode inter-aural time delay cues adequately and provide grossly different time delay cues than do hearing aids.

Ching *et al.* (2006a) reviewed a series of their own experiments and data collected on children using bimodal devices. They reported that the children as a whole performed better with bimodal stimulation than with the CI alone on horizontal localization tasks (as shown in Figure 5 for n = 29 children), and could take advantage of head shadow and binaural redundancy effects. However, they also reported that some individual children do not appear to benefit from binaural processing when given bilateral stimulation. For this latter experiment, they compared performance in a reference condition where speech and babble noise were presented from a loudspeaker at 0° azimuth, to performance in a comparison condition where speech was presented at 0° azimuth and noise was presented at +/- 90° simultaneously. The SRT for 50% correct identification of key words in sentences as measured in each condition, with the benefit of spatial separation quantified as the difference in SNR between the two. Comparing 12 normal-hearing children to 5 hearing-impaired children aged 4 to 7, they found that three of the 5 impaired children were unable to take advantage of cues from spatial separation of noise and speech, showing equivalent or increased masking when noise was moved to the sides. They suggest that, in these children, rehabilitation strategies should include efforts to improve SNR with use of directional microphones, and that auditory training may be needed to encourage the enhancement of listening skills.

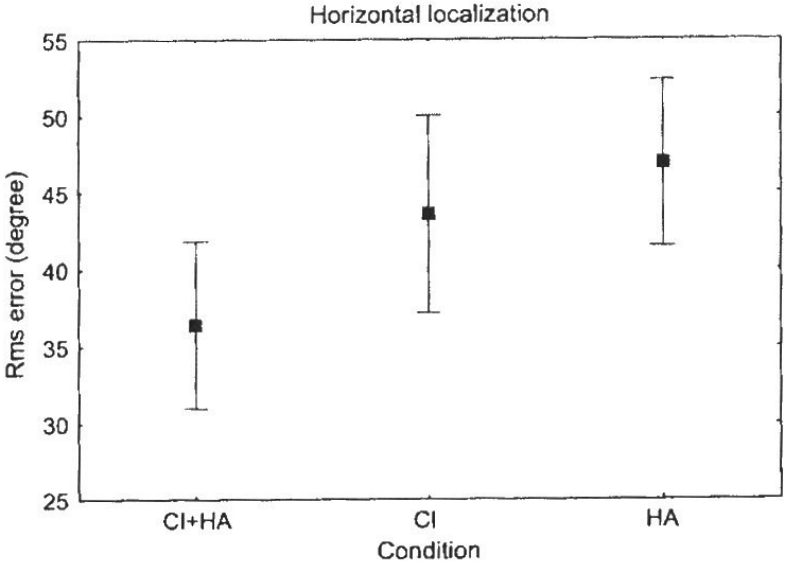

Figure 5.

Mean rms errors (in degrees) of children in a test of horizontal localization when they wore a cochlear implant with a hearing aid (CI+HA), a CI alone, or a hearing aid alone. Note that a *lower* mean error indicates better performance. (From Ching *et al.*, 2006 – Fig. 1).

Litovsky *et al.* (2006a) evaluated performance of 10 prelingually deafened children aged 3 to 14. Half of these children wore bimodal devices (8 of these children had a Nucleus CI and 2 had a Med-El device) and 10 children wore bilateral CIs (9 had bilateral Nucleus CIs, and 1 had bilateral Clarion devices). Evaluated were speech intelligibility (SRTs) using the CRISP spondee closed set test, and localization ability with minimum audible angle (MAA) measurements from a 15-loudspeaker array. Speech test conditions included quiet and 2-talker competing speech from the frontal loudspeaker, or from +/- 90°. Results indicated comparable SRTs for bilateral listening on average across the two groups of children, although there was significant individual variability. When results were compared for listening with only a unilateral implant and listening with bilateral devices, however, some differences were apparent between the bilateral CIs and bimodal devices groups. There were clear and significant improvements in speech results with two-eared listening for the bilateral CIs group across all conditions. In contrast, only some bimodal children showed benefit with addition of the hearing aid and only in some conditions, some bimodal children showed no difference in performance, and some even showed an apparent "bilateral disruption" - i.e. increased (poorer) SRTs with the addition of the hearing aid. Results of MAA measures showed comparable findings - - while both groups benefited from bilateral listening, the benefit was greater for the children with bilateral CIs than for the children with bimodal devices. The amount of bilateral experience was possibly a factor on the MAA task but did not appear to impact the speech task, and, interestingly, performance of children in localization did not appear to have much relationship with their performance on the speech task. The authors did note some caveats in comparisons across the subject groups. First, it was notable that all but one of the bilateral CIs group had not been able to receive any benefit from a hearing aid on their nonimplanted ear prior to a second implantation, and for MAA measures the bimodal group performed slightly better with the unilateral CI, leaving less room for improvement with the addition of the hearing aid.

In another study comparing children using bimodal devices to children using bilateral devices, Litovsky *et al.* (2006b) again evaluated horizontal localization ability using an MAA task. Six children, aged 4 to 14, who wore bimodal devices were compared against 13 children, aged 2 to 16, who were sequentially fitted with bilateral cochlear implants. Most of the children were implanted with Nucleus 24 CIs, but there were also children wearing Clarion and Med-El devices. Stimuli were male-voice spondees presented at a roving level of 4 dB around 60 dB SPL from a series of loudspeakers placed in an arc. Children responded using a 2-alternative forced choice (2AFC) procedure. For the bimodal children, some but not all benefited on the MAA task from addition of the hearing aid to the unimplanted ear. Repeated measures analysis of variance with post-hoc Scheffe's tests indicated that, as a whole, the children with bimodal devices didn't do as well with bilateral input as did those children with bilateral CIs.

This was true even though performance was essentially the same across the groups for the unilateral implant alone. Examination of individual data revealed that two children with bimodal devices did perform as well as the average child with bilateral CIs, one child couldn't do the task, and three children with bimodal devices performed much more poorly than the mean bilateral CI group performance. Audiometric thresholds in the hearing aid ear did not predict which children did well and which did not.

Ching *et al.* (2006b)[2] reported speech perception and sound localization ability with 21 adults and 29 children who had Nucleus CIs on one ear and a hearing aid contralaterally. It was reported that, on average, both groups of subjects showed binaural benefits related to binaural redundancy and head shadow effects for sentence perception in noise. They also localized sounds better with bimodal listening than when using the CI alone. The duration of bimodal devices use and the degree of hearing loss were not found to be related to binaural benefit. Ching *et al.* comment that a contralateral hearing aid may provide "complementary information" from amplification of low frequencies that are not provided by the CI.

Finally, Schafer & Thibodeau (2006) examined speech recognition performance in 22 prelingually deafened children ranging in age from 3 to 12 using Advanced Bionics, Med-El, or Nucleus CIs. Twelve of the children had sequentially implanted bilateral cochlear implants, and 10 of the children had bimodal devices. All were tested in various combinations of unilateral and bilateral inputs, and with FM systems. Speech-in-noise thresholds were obtained using simple phrases and a method of limits procedure, with speech at 0° azimuth and noise at 135° and 225° azimuths to simulate a classroom environment. Group data analyses indicated no significant differences between unilateral CI use and bilateral or bimodal inputs; however, 8 of 12 individual children with bilateral CIs and 2 of 10 children with bimodal devices did do significantly better bilaterally. The authors discuss limitations of the study that may have resulted in less bilateral listening benefits shown than in previous studies. In the FM system conditions, thresholds were up to 20 dB lower (better) relative to other conditions when FM-system input was provided to the first-implanted side or to both sides simultaneously.

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[2] This report presented data drawn from previous Ching *et al.* studies spanning 2001-2004.

Summary

A demographic study by Cowan & Chin-Lenn (2004)[3] indicated that 50% of adults with an unaided threshold of 90 dB HL or better at 500 Hz in the non-implanted ear choose to continue wearing a hearing aid in that contralateral ear for at least 4 hours a day after cochlear implantation. All of the studies that have examined bilateral input obtained with a hearing aid on the opposite ear of a cochlear implant are summarized and contrasted in Table 1 on the next page. It can be seen that, across the studies, there is consistently a binaural advantage for a majority of patients and test conditions, despite the fact that the signals to each ear are different. It is clear that bimodal device use does result in improved performance at least due to head shadow effects, and in some studies there appears to be binaural squelch effects for some, even though it has not been demonstrated that true binaural cues are used by all bimodal listeners.

A few individual subjects in a few studies do show a decrement in performance with the addition of the HA contralaterally but this appears to be the exception rather than the rule, and the factors responsible for this minority group finding are not yet clear. Some of the data collected in children using bimodal devices has shown less positive results than that in adults. It is not clear if the failure to show improvement for a subgroup of the children in a bimodal listening mode is due to their relative lack of experience and learning, to differences in their bilateral processing skills, to sensitivity of the speech testing materials and procedures used, or to some other undefined factor.

The fairly good, albeit not perfect, performance of bimodal devices across the studies begs the question as to whether patients who can receive any benefit from a hearing aid in the non-implant ear should receive bilateral implantation or remain bimodal users. Unfortunately, that question has not yet been clearly answered as there have been very few studies comparing bimodal devices to bilateral cochlear implant use. Ching *et al.* (2006a) stated that, given the proven advantages of an implant and a contralateral hearing aid over a unilateral cochlear implant, the benefits of bilateral implantation would need to be demonstrated for those patients who have residual nonimplant ear hearing and thus can receive benefit from a contralateral hearing aid, because bimodal devices would presumably be more cost-effective.

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[3] As reported in Mok *et al.*, 2006.

Table 1. Overview of Studies On Bilateral Input with a Hearing Aid and a Cochlear Implant

Study	*n, genders & ages*	*Other Patient Characteristics*	*Dependent Variables*	*Design/CI*	*Stimuli Parameters*	*Statistics Used*	*Findings*
Waltzman *et al.*, 1992	8 adults	Unknown[1]	MAC, SPAC, Iowa test battery, ESP, WIPI, GASP	within subject: CI only, power HA only, bilateral with both; CI = Nucleus	Unknown[1]	Unknown[1]	On average, saw better performances bimodally than with either the hearing aid or the CI alone. Variables such as threshold in the non-implanted ear and usage time impacted the outcome.
Shallop *et al.,* 1992	7 adults; (6 males, 1 female; aged 39-77)	Mean PTA non-implant ear (NIE) = 104 dB HL	Vowel & consonant recognition, word & sentence recognition	within subject: CI only, power HA only, bilateral with both; CI = Nucleus 22	In quiet with speech at 70 dB SPL	Binomial comparison tests	Bimodal condition showed consistently best findings, & 60% to 80% of subjects showed significantly better performance bimodal vs. hearing aid alone, for most speech tests
Dooley *et al.,* 1993	4 adults; (3 males, 1 female, aged 36-79)	Mean PTA NIE = 106 dB HL	Vowel & consonant recognition, word & sentence recognition	within subject: CI only, power HA only, bilateral with both (with & without same processor controlling both); CI = Nucleus 22	In quiet with speech at 70 dB SPL	AOV on arcsine-transformed scores & post-hoc Tukey tests	Consistently higher scores in both bimodal conditions compared to any unilateral condition, but only reached statistical significance for consonant recognition
Blamey *et al.,* 1997	50 adults (gender/ages unknown[2])	Unknown[2]	Unknown[2]	within subject: CI only, power HA only, bilateral with both	Unknown[2]	Unknown[2]	Continued use of an implant and contralateral hearing aid can result in a significant advantage in speech perception over use of an implant alone[1]
Armstrong *et al.,* 1997	12 adults (7 Australian & 7 American; age & gender not specified)	Mean PTA NIE = 103.5 dB HL	CNC word & CUNY sentence recognition	within subject: CI only, power HA only, bilateral with both; CI = Nucleus	In quiet, and with babble noise at +5 and +10 SNRs	Two-factor repeated-measures AOV	Significantly better scores in quiet & in noise for bimodal vs. implant alone. For American subjects, bimodal advantage greater in noise than in quiet for sentence stimuli.

Tyler *et al.*, 2002a	111 unilateral implant users surveyed re: hearing aid use; Testing on 3 adults who wore a hearing aid on the other ear from the implant	Details not known[3]	Word and sentence recognition in quiet and noise, & Localization task	within subject: CI only, HA only, bilateral with both; CI = presumed Nucleus devices[3]	Speech in front, Noise in front or to right or left; For localization, noise bursts at +/-45° azimuth	Details not known[3]	Two of the three subjects tested showed bimodal advantages. The third who did not was the poorest scores for the hearing aid alone condition, suggesting that absolute or relative performances across the ears may impact ability to benefit from binaural cues.
Hamzavi *et al.*, 2004	7 bimodal adult users; All were implanted in poorer ear	duration of deafness: 0-20 years; age at implantation: 32 -75; CI experience 1 to 6 years	Freiburger numbers, Freiburger monosyllables, and Innsbrucker sentence test	retrospective cohort study: within subject: CI only, and bimodal Med-El C40 or C40+ (n = 6); Clarion HF2 (n=1)	speech in quiet	Presumed paired t-test, but statistic used not reported	In most patients, the CI alone performed better than the HA alone, and the bimodal condition (CI + HA) was superior to the CI alone. P-values indicate significance of difference monaural CI versus bimodal on all 3 speech tests.
Iwaki *et al.*, 2004	6 postlingual adult bimodal users, aged 48 to 84 (3 female, 3 male)	used bimodal devices for at least 6 months; mean duration of deafness CI ear = 5. 4 yrs	monosyllables in quiet, Japanese (J-) HINT in quiet and noise (in noise, measures SNR for about 50% correct key word recognition) Also P300 late cortical potential to tonal stimuli in noise	within subject: CI only, HA only, bilateral with both; CI = Nucleus 22 or 24	speech at 65 dB (scale not given, but presumed SPL) from a frontal speaker; for J-HINT, noise from 0 or +/-90°	individual significance = better than chance performance difference; group data: paired t-tests and AOVs	3 subjects showed significantly better bimodal than monaural performance on quiet speech tasks, and also had a longer mean duration of hearing aid use than the other 3 subjects. Bimodal was better on all 3 noise positions for J-HINT in noise, but only the frontal position produced statistically significant results. P300 latency significantly shorter for bimodal than monaural CI, but no difference for N1 or P2.

Ching *et al.*, 2004	21 adults aged 25 to 84 (11 female; 10 male); 12 adults were experienced bimodal users; 9 were new HA users in the non-implant ear;	Experienced users mean PTA non-implant ear = 100 dB HL, new users = 98 dB HL. Aids fitted using NAL-NL1 with paired comparisons for frequency response slope preferred, and loudness balanced to the CI.	BKB sentences in noise from a single frontal speaker ("diotic" listening) or with noise to the side of the cochlear implant at 60° ("dichotic" listening); Also, horizontal location and questionnaire results after a period of wearing time under each unilateral condition and bimodal.	within subject: unilateral versus bimodal CI = Nucleus 22 (n = 3) or Nucleus 24 (n=18) users; 10 had SPEAK strategy, 11 had ACE but not with adaptive DR optimization.	Frontal speaker: speech at 70 dB SPL with +10 SNR (compared bimodal, HA alone, CI alone) Noise to side at +10 and +15 dB SNRs (compared bimodal with CI alone)	Arcsine transformed speech scores; Repeated-measures AOV with post-hoc Tukey's tests	Prescribed frequency response generally equaled preferred, but gain needed to be reduced 4 dB on average bimodally. Significantly better speech scores for bimodal than for monaural listening under all conditions and SNRs. For diotic presentation, experienced users performed significantly more poorly than new HA users, but no difference with experience on other tasks. Also significantly less error in localization, and better perceived performance with bimodal devices with than with either unilateral device.
Seeber *et al.*, 2004	n = 11 adults bimodal users (aged 20-79) vs. n = 4 adult bilateral CI users (aged 23-69)	Implant use had been a minimum of 6 months	Localization and sidedness discrimination	Within subject: unilateral implant each ear v. bilateral implants; Most were Med-El, but one had Nucleus CI-24M	Novel method utilizing laser pointer for response	Regression and correlation analyses; Wilcoxin tests	Varying performance across patients. All but 4 of the bimodal subjects were also able to localize with bimodal input. All 4 bilateral implant users showed some localization ability and one performed close to a normal listener. Some patients in both groups could also localize with only a unilateral implant.

Morera *et al.*, 2005	12 post-lingually deafened adults with asymmetric bilateral severe-to-profound loss		Spanish sentence and disyllabic word materials in quiet; words in noise	within subject: preoperative best-aided versus 6-mo post-op CI alone, HA alone, and bimodal CI = Nucleus 24 Contour in 9 Ss and Nucleus 24K in 3 Ss	speech at 70 dB and at 55 dB SPL frontally quiet, 70 in noise; noise at either 0° or +/- 90; SNR = +10 dB		Significantly better bimodally than either monaural condition for speech recognition in quiet (binaural summation; both levels) and for words in noise with spatial separation (binaural squelch). For speech and noise from same speaker, higher but non-significant score bimodally. Better performances bimodally than preoperatively for one or more tests for all subjects. Best predictive factor for bimodal benefit appeared to be preoperative best-aided score in contralateral ear.
Dunn *et al.*, 2005	12 adults with at least 3 months bimodal use	devices loudness matched between ears by changing CI volume	CNC monosyllables and CUNY sentences localization task: 8-loudspeaker array and everyday sounds	within subject: unilateral vs. bimodal 6=Nucleus CI-24R w/ACE, 5=Clarion HFI-CII w/CIS or SAS, 1 = Clarion 1.0 w/CIS	frontal speech at 70 dB C or 60 dB A. Noise from front or +/- 90°. SNR individually set to avoid ceiling/floor effects	binomial tests and repeated-measures AOV rms error for localization	Group mean data supported binomial use, but individual subject data varied across tests and conditions, with an occasional subject doing more poorly with bimodal than CI alone. Only 2 of 12 could localize with bimodal devices.

Mok *et al.,* 2006	14 adult bimodal users	Other ear hearing aid use for at least 75% waking hours after implantation; and/or hearing loss < 90 dB HL in low frequencies in non-implanted ear; Aids fitted by NAL-RP	Open-set CNC words in quiet; CUNY sentences in noise (both at 0° azimuth), Closed-set spondees with noise at 0° and +/- 90° azimuths	within subject: CI alone, HA alone, bimodal CI = Nucleus 24 (n = 8 Contour arrays and n = 6 straight arrays; n = 10 ACE and n = 4 SPEAK strategies)	CNCs at 65 dB SPL; CUNY sentences at 65 dB SPL with 4-talker babble at SNR producing scores between 20% and 80% (often +10); Spondees begun at 75 dB SPL with SNR in broadband noise adjusted for 71% correct recognition.	Arcsine-transformed scores for CNCs/CUNY. AOVs or Kruskall-Wallis nonparametric tests. Information transmission analyses on the CNC results.	4 subjects couldn't complete the sentences or spondee testing; 6 subjects showed significant bimodal benefit on open-set speech perception (4 out of 10 CUNY-noise and 3 out of 10 CNCs-quiet), and 5 on spondees; 2 subjects showed poorer speech results with the addition of the HA on the non-implanted ear compared to the CI alone on at least one test. Information transmission analyses showed that bimodal benefit in quiet is due to low-frequency components of the speech. Subjects with poorer aided thresholds in the mid-to-high frequencies demonstrated greater bimodal benefit, suggesting that mid-to-high frequency amplification from the hearing aid may actually conflict with the CI
<u>*Studies On or Including Pediatric Patients:*</u>							
Chmiel *et al.,* 1995	6 children (females; aged 4 to 13; implanted at ages 3 - 9)	Mean PTA NIE = 105 dB HL;	Age-appropriate speech perception and production tests	within subject: CI only, power HA only, bilateral with both; CI = unknown; not given.	Not given.	Nonparametric randomization test as described by Edgington	Half of the children showed significantly better binaural versus implant only speech understanding scores, and improved (albeit non-significant) vocal quality for the binaural condition
Ching *et al.*, 2000	children; details unknown[4]	Unknown[4]	Unknown[4]	Unknown[4]	Unknown[4]	Unknown[4]	Better performance for speech in noise with bimodal devices

Ching *et al.,* 2001	16 children, aged 6 to 18 (6 boys, 10 girls); Note that speech and localization tests, & questionnaire data only obtained on 11 of the children.	Mean PTA non-implant ear = 104 dB HL	sentence & nonsense syllable recognition, objective localization, parent questionnaire	within subject: CI only, power HA only, bilateral with both (with & without HA adjusted for maximal performance); CI = Nucleus 22 or 24	Speech at 65 dB SPL & with 4-talker babble at +10 SNR; both speech & noise at 0° azimuth	Repeated-measures AOV and post-hoc Tukey	Significant improvement bilaterally for sentences and localization; all individual subjects showed benefit on one of the three measures
Luntz *et al.*, 2005	12 subjects: three postlingual adults, 9 pre-lingual adults and older children	Testing began post-unilateral cochlear implantation with HA use contralaterally in ear with residual hearing	CUNY sentences for adults, pre-lingual children tested with common-phrase test sentences. Subjective judgments of bimodal versus CI alone	within subject: CI only and bimodal. Subjects tested after 1-6 months of bimodal use and then after 7-12 months. CI = 8 Nucleus 24 with ACE, 1 Clarion CI, 1 Clarion CII, & 2 Med-El Combi40 with CIS	speech at 55 dB HL with an SNR of +10 dB; both speech & noise at 0° azimuth	Friedman and Wilcoxin nonparametric tests; Spearman Rho	Benefit obtained with a contralateral HA to a CI improves over time after implantation, at least during the first year post in most patients. One prelingual child showed a decrement with CI+HA at the second test session. 11 of 12 subjects preferred bimodal to CI alone subjectively

Ching *et al.*, 2005	14 normal hearing controls (6 = children) ; 23 hearing-impaired patients - 14 bilateral BTE users (5 = children), and 9 bimodal users (5 = children).	HA = Bernafon AF120 single-channel with wide dynamic range compression, fitted using NAL-RP; loudness balanced with CI	BKB/A sentences in noise presented via direct audio input facilities of the cochlear implant or hearing aid (headphones for normal controls); Noise = speech-shaped	within subject: monaural versus binaural (monaural HA versus binaural HAs; or monaural CI versus bimodal; CI=Nucleus 22 or 24	Speech at 65 dB SPL at output of headphones or hearing aids; CI output for comparable loudness; Evaluated binaural redundancy (monaural vs binaural SNR for SRT) and ability to use inter-aural time difference cues (noise delay of 700 usec).	Analysis of variance with repeated measures; Tukey post-hoc comparisons	Adult bimodal device users or bilateral hearing aid users, and pediatric bilateral hearing aid users could benefit from binaural redundancy cues. Pediatric bimodal device users did not. Only the normal hearing controls and bilateral hearing aid users with less severe hearing losses could use interaural difference cues to improve speech perception in noise. None of the bimodal adult or pediatric users could utilize the cues to advantage.
Ching *et al.,* 2006a	reviewed a series of experiments described on pediatric bimodal users		horizontal localization and speech perception tests	within subject: monaural versus bimodal	Various	Various	Concluded that children listening bimodally can obtain binaural advantages in localization, and take advantage of head shadow and binaural redundancy; however, some hearing-impaired children with binaural processing deficits don’t benefit as much from bilateral stimulation

Litovsky *et al.*, 2006a	20 prelingually deafened children aged 4 to 14 in two groups: 10 bimodal users and 10 bilateral CI users		localization minimum audible angle (MAA speech intelligibility (closed-set, 4AFC, spondee CRISP test: speech level varied in fixed competing speech level to compute SRT for 79.4% correct)	within subject: unilateral implant versus bimodal or bilateral also across groups: bilateral listening benefit in bimodal group (addition of HA) versus in bilateral CI group CIs: most were Nucleus 22 or 24, but also 2 Med-El C40+ in bimodal group and 1 Clarion in bilateral group	Localization setup with 15 loudspeakers in semicircle spanning +/-70° Speech from frontal loudspeaker; 4 conditions: quite, and 2-talker competing speech at 60 dB SPL from front, +90, or -90°	Mixed-design 3-way AOV with group as between subjects variable and listening mode (monaural, bilateral) and listening condition as repeated measures variables. Post-hoc Scheffe's tests.	SRTs were comparable on average for bilateral listening across the two groups. However, for both speech intelligibility and localization, the benefit of binaural relative to unilateral CI listening (binaural advantage) was greater for the bilateral CI group than for the bimodal group. Some in the bimodal group actually did more poorly when the hearing aid was added back in.
Litovsky *et al.*, 2006b	n = 6 children with bimodal devices, aged 4 to 14. n = 13 with bilateral cochlear implants, aged 3 to 16.		Horizontal plane localization acuity (left/right) measured with minimum audible angle (MAA)	Within subject: bimodal or bilateral, versus unilateral CI Bimodal CIs = 4 Nucleus, 1 Clarion, 1 Med-El; Bilateral CIs = Nucleus 24 for 12 children, Clarion Platinum for 1 child	Stimuli were spondees with level roved +_/-4 around 60 dB SPL from an arc of loudspeakers; 2AFC procedure	repeated measures AOV with post-hoc Scheffe tests	Some but not all children benefited on the MAA task from addition of the hearing aid to the nonimplanted ear. As a whole, children with bimodal devices didn't do as well with bilateral input as those with bilateral CIs, even though they performed about the same with the unilateral implant alone. Two children with bimodal devices did perform as well as the average child with bilateral CIs but three children with bimodal devices performed much more poorly than the mean bilateral CI performance.

Ching *et al.,* 2006b	n = 21 adults and 29 children	Review of data condensed across 4 studies 2001 on	Speech recognition and localization task (horizontal plane)	within subject: unilateral implant versus bimodal CIs: Nucleus	BKB sentences in 8-talker babble; speech & noise both frontal, or at +/- 60° at 10 dB SNR. Localization: 11 loudspeakers spanning 180° arc in anechoic chamber	Analysis of variance with post hoc Tukey's; correlation analysis	On average, both adults and children derived binaural advantages from bimodal use related to head shadow and binaural redundancy. Both groups localized sound better bimodally than with the CI alone. Degree of hearing loss and duration of bimodal devices use were not predictive of binaural speech benefit.
Schafer & Thibodeau 2006	Children aged 3-13; n= 12 bilateral CI users n = 10 bimodal users		New test with simple phrases about body parts; Child response was to act out phrase on a doll; Method of limits procedure	Within subject: bilateral condition versus unilateral; various combinations with FM systems CIs: Advanced Bionics, Med-El, Cochlear	Measurement of SRT with adaptive frontal speech level, and classroom noise at 60 dBA from rear speakers	Analysis of variance; 95% confidence levels	No group differences in unilateral versus bilateral performance, but authors concede study design had limitations and 8 of 12 bilateral and 2 of 10 bimodal users showed binaural benefit. FM device on 1st implanted ear or bilateral produced performance improvements

[1] The original report was not located; report is from the abstract from PubMed online.

[2] The original report was not located; this study is reported second-hand by Ching *et al.,* 2001.

[3] The original report was not located; report is from the abstract from PubMed online.

[4] The original report was not located; this study is reported second-hand by Ching *et al.,* 2005.

Use of Bilateral Cochlear Implants

The earliest published report of bilateral cochlear implants was in the late 1980s (Balkany *et al.*, 1988). The primary reason for bilateral implantation in the early days was either that there was need for a technology upgrade (where one ear had a functioning but older single-channel device so the contralateral ear was fitted with a newer, multichannel device) or the device in one ear produced inadequate performance (Green *et al.*, 1992). As reported by Muller *et al.* (2002), in the late 1990s bilateral implants began to be done solely with the hope and intention of providing binaural benefits. Further, there has been a trend toward simultaneous implantation of both ears, rather than sequential implantation (one at a time, with a varying period of time between surgeries). While bilateral implantation has seen a distinct increase in this century, however, it is still relatively rare. Laszig *et al.* (2004) stated, for example, that of the over 50,000 persons who have been implanted with the Nucleus CI worldwide, fewer than 1% had been implanted bilaterally at that time. Ramsden *et al.* (2005) further noted that many of the patients implanted bilaterally are still those who have had medical or technical complications with their first implant.

The literature has shown an increasing number of published research articles examining efficacy of bilateral implantation relative to conventional unilateral implantation. Some studies have examined speech perception issues, some have been controlled laboratory examinations of psychoacoustic performance, and a limited number have offered anecdotal subjective impression or questionnaire data. Although some studies fall across more than one of these categories, they are separately described in the following in order to assist in contrast of the findings within a given class of measurements. In each of the following sections, results are described loosely in chronological order of publications, first for adult patients, and then studies that also involved or were limited to pediatric patients. Following the description of the studies are tables that summarize and contrast the data across the studies for each subcategory (speech perception, psychoacoustic and localization studies, and subjective/questionnaire reports).

Speech Perception

Of primary interest has been determining whether or not bilateral implantation will produce improvements in understanding speech, particularly in background noise, relative to unilateral implantation. For most cochlear implant users speech understanding in noise is relatively poor and they require higher signal-to-noise ratios (SNRs) than do normal-hearing persons (e.g. Hochberg *et al.*, 1992). The combined effect of the head shadow and binaural squelch effects have been reported to be as high as 40% for monosyllabic words for normal listeners (e.g. Brookhurst & Plomp, 1990), but are expected to be less in impaired ears. Cox *et al.* (1981) reported an average of 26% improvement in normal listeners due to binaural squelch effects but only 19% in persons with hearing impairment.

The earliest studies conducted in the 1990s with bilateral versus unilateral cochlear implant listening conditions did not always produce very strong evidence of binaural advantages in terms of speech recognition, perhaps due to the more limited cochlear implant technology of the day or to the choice of patients to receive a second implant (those with limited benefit from the first). In contrast, however, the results of studies done more recently have overall been quite encouraging in this regard.

Adult Population

Balkany *et al.* (1988) appear to have provided the first published report on a patient implanted bilaterally. This patient was a 55-year-old woman deafened simultaneously in both ears (PTA = 100 dB HL bilaterally) due to acute Streptomycin treatment, and who was implanted with a 3M/House device in one ear and a Nucleus device in the other ear (implanted over one year later). Speech discrimination testing (using the Cochlear Corporation/University of Iowa revised cochlear implant test battery at about 72-73 dB SPL) compared her function with each device and with both implants. The multichannel Nucleus provided consistently superior scores to the 3M/House device. In addition, however, there was evidence of a binaural effect, which the authors assumed was due to central integration of the stimuli even though each ear had distinctly different signal processing and unilateral scores. Standardized speech scores were consistently higher binaurally than with either device alone. In contrast, however, the addition of the 3M/House device produced a degradation in performance (relative to the

Nucleus device alone) on certain connected speech tests and this particular patient reported a preference to use only the Nucleus device in her everyday life.

Green *et al.* (1992) examined six adult bilateral cochlear implant recipients (aged 57 to 74 years, mean = 64.5; 2 females and 4 males). Etiology of the patients' deafness and duration of hearing loss prior to implantation varied, but all of the patients had profound bilateral sensorineural hearing loss and had received no benefit from amplification. Four of the patients had a 3M/House implant in one ear and a Nucleus implant in the other ear, one had binaural 3M/House implants, and one had binaural Nucleus implants. Speech perception was evaluated using a variety of auditory-visual (speech reading) tests including speech tracking, Vowel Confusion test, Consonant Confusion test, and CID Everyday Sentences. Auditory-only tests included the closed-set MiniThrift, which is a test of speech pattern contrasts, and the closed-set Word Intelligibility by Picture Identification (WIPI) test. The benefit of adding a second implant was mixed across the patients, and the differences between bilateral and unilateral scores were generally not large. However, all of the patients received some degree of binaural improvement on at least some of the tests, and oddly, the patients with mixed signal processing schemes (different device in each ear) showed slightly greater binaural advantages. Five of the six patients reportedly continued to use both implants after the study completion.

A series of experiments were reported by Lawson *et al.* (1998), on one post-lingually deafened patient who had bilateral Nucleus 22 implants that were controlled experimentally by a single speech processor with a single microphone input. The researchers noted that the potential benefit of such a system would include the possibility that channel interactions could be reduced for the same number of channels, that additional discriminable channels could be added, and that there could be a doubling of the effective stimulation rate limit imposed by the transcutaneous link for a given number of CIS channels. Medial consonant identification scores (auditory only) were obtained for CIS sampling processors using various unilateral and bilateral combinations of electrodes. These researchers reported that they found no evidence that bilateral stimulation degraded speech recognition performance, even when there were arbitrary divisions of information between the ears.

Mawman *et al.* (2000) presented a case report on a 50-year-old male with a 5-year history of progressive bilateral hearing loss thought to be due to auto-immune disorder. He did not receive any benefit from conventional power hearing aids, so was implanted bilaterally with Nucleus CI24M devices in 1998 at the University of Manchester, UK. He was fitted with ESPrit processors with the SPEAK coding strategy. The patient reported that his right implant had a higher pitch and a clearer quality than the left, which was thought by the researchers to possibly be due to a deeper insertion depth on that side. Greater perceptual balance was achieved between ears by changing both the channels activated and the frequency allocation table for the left implant. At 5 months post-implantation, the patient was measured on several tasks including speech-in-noise (auditory only) performance. Both BKB sentences and Arthur-Boothroyd monosyllabic words (open set) were presented at 70 dB SPL in quiet (binaurally only) and in noise at a +5 dB SNR (for both bilateral and each unilateral implant listening condition). Loudspeaker presentation arrangement was not specified in the article. Results revealed higher scores for binaural listening in quiet and in noise than for either unilateral condition. For sentences, the percent correct key word scores were as follows[4]: quiet binaural = 88%, noise binaural = 84%, noise left only = 70%, noise right only = 60%. For monosyllabic words, the scores were: quiet binaural = 86%, noise binaural = 50%, noise left only = 34%, noise right only = 44%.

Results from nine German adults implanted bilaterally with Med-El devices (with standard CIS or CIS+ processing strategies) were described by Muller *et al.* (2002). Three of the subjects were implanted simultaneously and the other six were implanted in sequential operations. Sentence recognition testing was done using the Hochmair/Schulz/Moser (HSM) auditory-only test with speech presented at 65 dB SPL and speech-shaped noise at a +10 dB SNR. Speech was always presented at 0° (frontal) azimuth but noise was presented from either 90° to the right or 90° to the left of midline. Testing was also done in quiet using Freiburg monosyllables. Across both tests and noise conditions, the vast majority of the individual scores, and all the mean scores, showed equal or superior performance for bilateral implants compared to either unilateral condition. The average increase in scores when comparing bilateral implants to unilateral alone are shown in the following:

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[4] Scores were not given numerically in this article, so were visually interpolated from the graphed data.

Mean increase in speech understanding (bilateral implant score minus given unilateral implant score) by test condition for 9 subjects (From Muller *et al.*, 2002).

	Bilateral implants – Left implant alone	*Bilateral implants – Right implant alone*
Sentences, Noise to the right	8.5%	27.4%
Sentences, Noise to the left	34.8%	13.0%
Monosyllables (in quiet)	19.3%	18.0%

It can be seen that the spatial arrangement of the noise source, not surprisingly, impacts performance. The researchers argue that these results show a large head shadow effect, but also a smaller effect that they attributed to binaural squelch effects. Repeated measures analyses of variance (AOVs) and post-hoc Neuman-Keuls on the data revealed that listening with bilateral implants was significantly better than with unilateral implants for sentences in both noise conditions and for monosyllables. Even when the best-ear unilateral score for each subject was compared to the bilateral score, the bilateral scores were significantly higher by 8.8%.

In 2002, Schoen *et al.* reported results from nine postlingually deafened German adult bilateral Med-El implant users who were tested using both implants compared with the better unilateral implant ear (as determined by unilateral monosyllable scores). Three of the subjects received bilateral implants in the same surgery, and the other six subjects had previously been implanted monaurally. Sentences (HSM test) in quiet and noise at various SNRs were presented in a symmetrical set-up using four loudspeakers in an attempt to largely eliminate the head shadow effect (i.e. to present the same SNR to both ears). The goal was to look only at the effects of binaural summation and binaural squelch, since both require binaural processing by the brain. Calculations were made on the test results to determine the gain in SNRs obtained bilaterally versus monaurally at the speech reception threshold (SRT). Results indicated that all subjects had a substantial gain in SNR (mean = 4 dB, SD = 1.9) for bilateral implants compared with unilateral listening, which remained stable over time. A t-test on the group data showed that the gain in SNR was significantly different from 0, and the researchers proposed that a 4 dB gain in SNR could be expected to result in an average improvement in speech reception of 28%. There was no notable difference in performance between those sequentially or simultaneously implanted.

Tyler *et al.* (2002b) reported 3-month postoperative results on nine postlingually deafened adults, aged 35 to 71, who had received bilateral Cochlear CI24M implants simultaneously (with SPrint processors, and either SPEAK, CIS, or ACE strategies). Word (CNC monosyllables) and sentence (CUNY) test materials were presented in quiet at 70 dB SPL and in noise, with the speech at 0° azimuth and the noise from either 0 or 90° to either side. The SNR for testing was set individually (ranging from 0 to +10 dB) in order to avoid ceiling or floor effects but was constant across testing within a patient for unilateral and bilateral implant conditions. Statistical significance for each individual subject's scores was evaluated using binomial testing. Quiet test results indicated a significant advantage for the binaural condition over the better ear unilateral condition in only four of the nine subjects, but the authors noted that binaural benefits in the others may have been masked by ceiling effects (scores over 80% correct). No subjects showed a significant decrease in scores binaurally versus monaurally. With both signal and noise at 0°, a significant binaural advantage was also found for four subjects. For noise to one side of the head, a significant binaural advantage was found for seven of seven tested subjects when the ear opposite the noise source was added to the ear ipsilateral to the noise source - - this would be benefit resulting from the head shadow effect. When the ear ipsilateral to the noise was added to the ear contralateral to the noise, a significant binaural advantage was shown for only one of seven (noise on right) and three of seven (noise on left) tested subjects - - this would be a binaural squelch effect. Sentence recognition results with noise from the side are shown in Figure 6.

Gantz *et al.* (2002) performed simultaneous bilateral implantations on 10 adult patients (aged 35 to 75, gender not specified) with duration of loss ranging from 1 month to 37 years. Note that nine of these 10 subjects had also been used in the Tyler *et al.* (2002b) study. Etiologies included Meniere's disease, autoimmune disorder, progressive noise trauma, and familial/genetic. Speech testing was done bilaterally and unilaterally at 1 year post-surgery. Presented at 70 dB SPL at 0° azimuth were CNC monosyllables, and HINT and CUNY sentence stimuli. For CUNY, testing was also done with babble noise presented from the same speaker, or from a second speaker placed at 45° azimuth to either side. The SNR was 10 dB across patients for frontal azimuth noise, but adjusted as needed depending on a subject's performance level for 45° azimuths to avoid ceiling and floor effects. For quiet testing, no patient performed significantly more poorly with bilateral than unilateral, but bilateral benefits were modest. Only two of the 10 subjects were reported to have "significantly" better

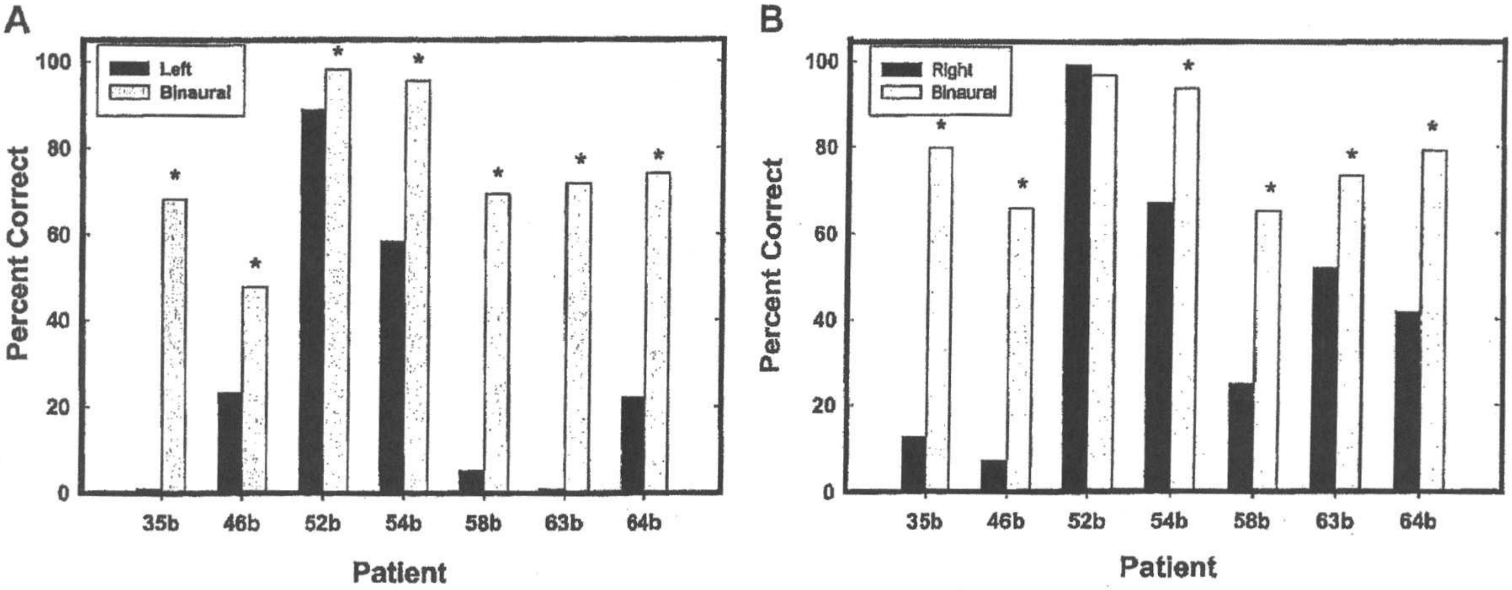

Figure 6.

CUNY sentence recognition with speech from the front and noise from either the right or left for each listening condition and subject. Significantly different scores are indicated by an asterisk. (From Tyler *et al.*, 2002b – Fig. 3).

binaural performance for CNCs (statistic used was not specified but is assumed to be binomial testing as commonly used by these authors), one of the subjects for CUNY sentences (results were limited by a ceiling effect since most patients performed > 90% correct), and five of the subjects for the HINT. For CUNY in noise testing, 4 subjects performed significantly better in the bilateral condition when the noise was added to the frontal speaker. When the noise was added at 45° azimuth to the ipsilateral (same) side as the unilateral implant under test, all subjects showed improved bilateral performance, with 8 subjects showing a significant improvement - - this is due directly to the head shadow effect, since the ear with the more favorable SNR had been added. The individual improvements were substantial in this condition, some as large as 50%. When the noise at 45° was added on the contralateral side to the unilateral implant, 3 subjects showed significant bilateral benefit (1 subject could not show improvement due to a ceiling effect) - - improvement in this condition is due to binaural squelch. Gantz *et al.* hypothesized that this latter binaural benefit might require more listening experience or some kind of coordinated processing, but they also noted that a factor may be that subjects in their study were intentionally chosen to have differences in durations and degrees of loss between ears.

In a 2003 study, Au *et al.* examined the performance of Cantonese speakers in Hong Kong, a language that depends on tonal aspects of speech. Four post-lingually deaf adult patients (2 females and 2 males, aged 23 to 38) were evaluated, who had bilateral Med-El Tempo+ CIs programmed with a CIS strategy. Duration of deafness ranged from 12 to 20 years and the second implant was placed either simultaneously (n = 1) or up to 7 months after the first implant (n = 3). Speech scores on a Cantonese lexical tone discrimination task were compared when listening with both implants or only with one implant (reported unilateral scores were averaged across the right and left implants) as shown in Figure 7. Speech was presented at a 0° azimuth at 65 dB SPL, and in background noise at SNRs of +15, +10, +5, 0, -5, -10, and –15 dB. Results indicated higher mean scores in quiet and in noise at all SNRs for bilateral implants than for unilateral listening, but the differences were not significant on Wilcoxin tests for quiet, +15, +10, and +5 SNRs (other SNRs were not tested because binomial analysis indicated the scores were not different from chance. Binomial analysis indicated that in the bilateral mode subjects could achieve scores comparable to those they obtained in quiet at SNRs of +5 or better. In contrast, in the unilateral mode, the SNR had to be +10 or better for noise scores to be comparable to quiet.

Also in 2003, van Hoesel and Tyler evaluated speech perception performance in four adult bilateral Nucleus CI-24M cochlear implant users (a fifth user could not perform the task reliably). For this testing, the patients wore a research SPEAR processor, which was programmed with a strategy called “peak derived timing” intended to provide binaural processing cues and in which loudness was adjusted to account for binaural summation effects. Measured were SRTs (for 50% correct) for BKB sentences at 65 dB SPL that were presented from the front, and in speech noise that was presented either from the front or 90° to either side, in an adaptive SRT paradigm. When both speech and noise were from the front, there was no significant difference between binaural and unilateral performance (mean difference = 0 dB). Due to head shadow effects, there was a significant SRT improvement ($p < .001$ using AOV with post-hoc Tukey tests) when noise was contralateral to a unilateral implant compared to when noise was on the same side. There was also a significant, albeit

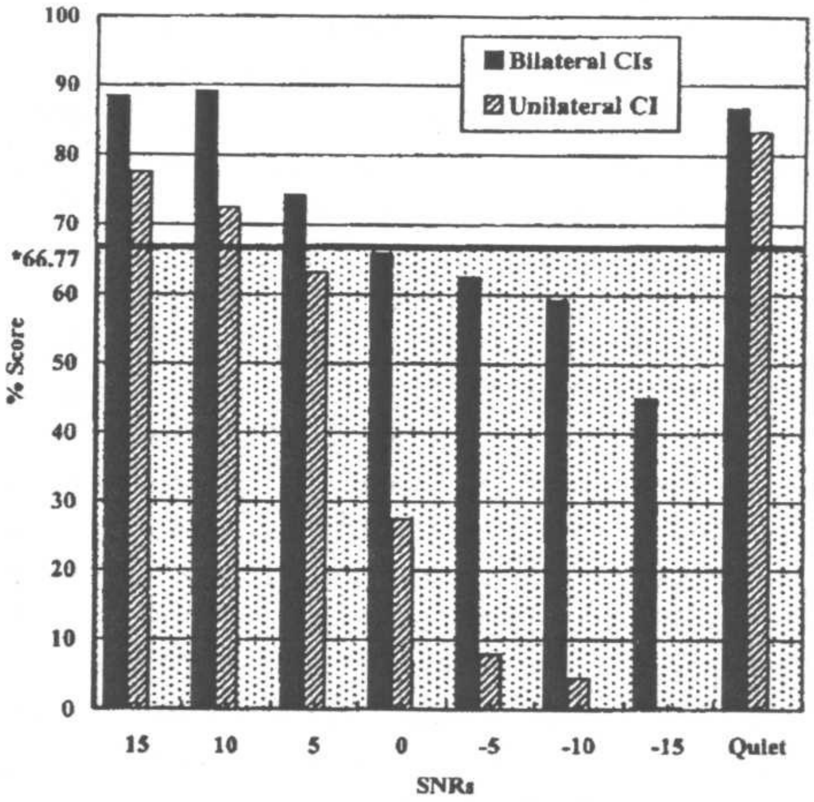

Figure 7.
Mean percent correct Cantonese lexical tones discrimination scores from 4 subjects at various SNRs and quiet (unilateral scores averaged across ears). (From Au *et al.*, 2003, Fig. 1).

smaller, binaural benefit due to binaural squelch (p = .04) of about 1 or 2 dB compared to when noise was presented ipsilateral to a unilateral implant. The researchers concluded that (in addition to localization benefits described in the next section), bilateral implants do offer important advantages to patients.

Litovsky *et al.* (2004) reported on 17 adults (8 males and 9 females with an average age of 52.7) who had undergone simultaneous implantation with Nucleus CI24R (CS) bilateral implants. Fourteen were postlingually deaf with 15 or less years of deafness and the other three were either deaf from infancy or congenital losses. Fourteen of the adults were evaluated with BKB sentences presented adaptively in competing babble noise with SNR varied from a starting point of +21 dB to an ending point of 0 or –6 dB. The percent correct scores were used to estimate SRTs as the SNR for 50% correct. Speech was presented at 0° azimuth and noise at either 0° or 90° to either side. Results indicated a binaural advantage over listening with either unilateral implant when the noise was at the poorer of the two ears, but there was no apparent advantage when noise was at the better ear. It is possible that results might have been better with longer testing intervals; in this study, testing was at 3 months postactivation.

Dorman and Dahlstrom (2004) reported two case studies (1 male aged 31, and 1 female aged 71) in which one ear had been implanted first with a Med-El CIS-Link processor with an Ineraid electrode array and subsequently the second ear was implanted with a Clarion 8-electrode Hi-Focus device. These patients were considered particularly of interest because it was likely that the two implanted cochleae presented different representations of the signals to the brain. Both subjects were postlingually deafened, the male by childhood meningitis and the female progressively of unknown etiology. The patients were tested unilaterally and bilaterally with CNCs and HINT sentences presented at 0° azimuth at 70 dB SPL. The male patient was tested with HINT in noise at +5, but the female patient was tested in quiet due to poorer (only chance) performance when tested in noise. The male patient was also tested using synthetic vowels presented in a /bVt/ environment. For the male patient, results indicated no difference in performance between the best unilateral implant and bilateral stimulation for CNCs; However, there was a marginally significant binaural benefit for vowels (86% vs. 76%, t = 2.00; p = .0509) and a large significant binaural benefit for HINT sentences in noise (94% vs. 60%; binomial expansion test, p < .05). For the female patient, there were significant binaural benefits for both CNCs (34% vs. 14%; p < .05) and HINT (61% vs. 29%, p < .05).

Schleich *et al.* (2004) conducted a study on 21 German-speaking users (10 females, 11 males, ages 17.5 to 66.5 years {mean = 44}) of Med-El COMBI 40/40+ implants in which SRTs (50% correct) were measured using the Oldenburg sentence test. Twenty subjects were postlingually deafened and one prelingually, and duration of deafness ranged from 0.6 to 47.8 years (mean = 12.9). Etiologies were also quite varied. Speech was presented from the front, with noise either from the front, the right side or the left side (at +/- 90°), and performance was measured both unilaterally and bilaterally using an adaptive SNR procedure. Data from the 18 subjects who could accomplish the task showed a significant head shadow effect (using Wilcoxin signed-ranks tests at p < .05; calculated as unilateral ear SRT with noise to ipsilateral side minus score with noise to contralateral side). There was also a significant binaural summation effect (calculated as SRT with unilateral implant when noise and speech front minus binaural SRT). A binaural squelch effect (calculated as SRT when listening unlaterally with contralateral noise minus score when listening binaurally) was only significant for noise from the left. There was a mean 6.8 dB improvement binaurally due to the head shadow effect, 0.9 dB for the binaural squelch effect, and 2.1 dB for the binaural summation effect. There was no significant correlation between effect sizes and duration of deafness.

Laszig *et al.* (2004) conducted a multicenter, longitudinal study across German-speaking clinics in Germany and Switzerland on 37 profoundly impaired adults, 22 of whom had received simultaneous bilateral cochlear implantation, and 15 of whom had been sequentially implanted. All patients had Nucleus 24 implants with either SPrint or ESPrit 3G processors. Most used an ACE speech coding strategy. Assessments were made of unilateral and bilateral listening conditions for speech perception in quiet at 0° azimuth, and in background noise with 3 loudspeaker setups: 1) the signal and noise both from 0°, 2) the speech at +45 and the noise at -45°, and 3) the speech at -45 and the noise at +45°. The latter setup was chosen instead of speech at 0° and noise at +/-90° because it was believed that it would better measure binaural squelch effects. Speech materials included Freiburger monosyllabic words at 70 dB SPL in quiet, Oldenburger (OLSA) sentences at 70 dB SPL in quiet or in 65 dB SPL noise with sentence level varied to determine SNR for 50% correct performance, and Hochmair-Schulz-Moser (HSM) sentences in quiet at 70 dB SPL or in noise with a +10 dB SNR. Repeat testing was done at 1-, 3- and 6-months after bilateral implantation. Using t-tests, the authors reported a significant binaural redundancy effect for the Freiburger monosyllables in quiet compared with the poorer ear alone scores across time intervals, but no difference from the better ear at 6 months. There was also a bilateral benefit for the OLSA sentences in quiet at 6 months compared to either ear (although some subjects had unilateral score ceiling effects that precluded showing bilateral benefit). With spatially separated speech and noise, there were large head shadow effects (mean improvement of 10 to 11.4 dB in the SNR for 50% correct performance on the OLSA sentences, and 42% to 55% mean improvements for the HSM sentences) for the ear farthest away from the noise source compared to the ear closest to the noise source, and small binaural squelch effects for about half of the subjects (with a mean 8% improvement bilaterally compared with the better ear on the HSM sentences).

Ramsden *et al.* (2005) presented data on 27 British adult CI users, aged 29 to 82 (mean = 57 years) who were sequentially implanted with a second Nucleus 24 CI24M or CI24R(ST) after 1 to 7 years of unilateral CI use (mean = 3 years). One additional subject dropped out at 1-week postactivation because he reportedly "could not integrate the separate signals from each ear" so chose not to use the second implant. Another subject developed significant tinnitus in the second implanted ear which precluded full testing but he subsequently became a successful bilateral user. Measured at 70 dB SPL were monosyllabic CNC words in quiet, and CUNY sentence scores in quiet or in 8-talker babble under two conditions: 1) both speech and noise from a single frontal loudspeaker, and 2) with the noise spatially separated at +/- 90° (90° and 270° azimuths). Noise level was set individually to avoid ceiling or floor effects, with SNRs ranging from +5 to +15 dB. Group data were analyzed using either analyses of variance with post-hoc Tukey's or paired t-tests. Results indicated that for speech in both quiet and noise, mean performance for the second implanted ear was significantly worse than for the first implanted ear (although not for all individual subjects). For speech in quiet, there was no significant bilateral advantage at 9 months postactivation. For CUNY sentences in noise frontally, however, there was reported a small (mean 5.4% at 9 months) but significant bilateral advantage compared to the first ear implanted ($p < .001$). When noise was presented ipsilaterally to the first implanted ear, there was a large (mean 21% at 9 months) and significant bilateral advantage over that ear listening monaurally ($p < .001$), as well as a smaller benefit (mean 11.7% at 9 months) over the second implanted ear listening monaurally ($p < .001$). When the noise was presented to the second implanted ear, there was a large and significant bilateral benefit compared to monaural performance in that ear (mean 49.8% improvement at 9 months bilaterally; $p < .001$), but no bilateral benefit compared to monaural listening with the first implanted ear. However, using binomial tests, 6 of 18 subjects evaluated did demonstrate a significant binaural squelch benefit at 9 months postactivation under the latter condition. The authors also tested what they called the "dual microphone"[5] option for unilateral cochlear implants, and found it did not produce performance advantages. Finally, it is of note that there was also no apparent group mean improvement in scores for the second implanted ear from 3 months to 9 months postactivation across the measures. In their discussion, the authors note that they could not have predicted postoperative best ear performance based on preoperative classifications of better and poorer ear. Further, they suggested that the poorer performances in the second implanted ears may have been due to longer durations without stimulation. Finally, they postulated that it might have been helpful to

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[5] Since there is no dual microphone option for the processors used in that study, it is assumed that the authors were actually referring to the "dual-port" microphone option rather than to two microphones *per se*.

require the subjects to use the second implanted CI alone for a period of time to allow that ear to improve in perception before bilateral CIs were worn.

A study was conducted by van Hoesel and colleagues (2005) to examine the effects of amplitude-mapping adjustments on speech intelligibility of Oldenburg sentences with bilateral versus unilateral CI use. The motivation for the study was concern that if no adjustments are made to a standard monaural amplitude mapping function for bilateral implant fittings, then sounds may become too loud due to bilateral loudness summation and thus impact speech intelligibility. Eight adult bilateral Nucleus 24 CI users in Hannover, Germany, were tested across four different maps. Each map was worn 1 week bilaterally, and then tested under both unilateral and bilateral conditions using an adaptive speech-in-noise test with a single frontal loudspeaker, and bilaterally for low-level speech in quiet. One of the maps was a standard clinical map, fitted to each ear as it would have been if only one CI was to be used. The other three maps used stimulation levels that were reduced: 1) near maximal stimulation levels, 2) near thresholds, or 3) by a similar amount over the entire dynamic range. The resulting data revealed a modest but statistically significant decrease in speech recognition performance when stimulation levels were lowered for both quiet and noise listening. For level reductions that corresponded to binaural loudness summation, the performance decrease was about 1 to 2 dB. Altering the slope of the map did not change performance much. With the same map, there was a modest but significant improvement in bilateral listening compared to unilateral listening. Thus, the authors concluded that using higher stimulation levels in amplitude-mapping functions can improve both monaural and binaural speech performance. When no adjustments are made in the bilateral condition for loudness summation, an average SNR bilateral benefit of 1.4 dB relative to monaural can be found. Even though binaural performance may decrease slightly if levels are reduced to compensate for loudness summation, however, the binaural advantage for frontal speech and noise presentation over the better ear performance will offset the decrease.

Senn *et al.* (2005) evaluated two prelingually deafened teenage girls and three postlingually deafened male adults who wore sequentially implanted Med-El C40/40+ CIs bilaterally with Tempo speech processors and a CIS strategy. Speech intelligibility using the German HSM sentence test in quiet from the front or in CCITT noise from the side (+/- 90° azimuth) was measured. Speech was presented at 70 dB SPL and individual SNRs used in an attempt (not completely successful) to avoid ceiling or floor effects. Results indicated significantly higher scores for bilateral CIs (mean 33% and 56% across the monaural ears) as opposed to listening with a unilateral CI when the unilateral CI tested was ipsilateral to the noise source (head shadow effect benefits; $p = .03$). There was no significant group mean bilateral benefit when noise was contralateral to the unilateral CI under test, but several individual subjects did appear to show a binaural squelch effect. After $\geq$1.5 years of bilateral CI use, the 2nd implanted ear still did not perform as well as the first implanted, although all subjects felt they performed substantially better with bilateral implants.

In a recent study, Dunn *et al.* (2006) evaluated 7 adult bilateral Clarion CII cochlear implant recipients who had been implanted simultaneously, and who had used a CIS processing strategy (which produces temporal information up to 400 Hz) for at least 18 months. The purpose of the study was to determine the effect of converting them to a processing strategy with increased rate and number of channels (HiResolution, up to 2,800 Hz). The hypothesis was that because the higher rate strategy produces greater representation of temporal fluctuations, the increased fine timing cues provided would produce better speech perception. CUNY sentence recognition scores in multitalker babble from a loudspeaker in the front were collected using the CIS strategy (8-channel, 813 pps), and then after programming with HiResolution Paired (HiResP, 16 channel, 5,100 pps, and HiResolution Sequential (HiResS, 16-channel, 2,900 pps). Subjects wore each HiRes strategy alternating in an ABAB design, with testing repeated over time. Results showed that 5 subjects performed better immediately with the HiRes strategies, and after 1 month of wearing alternating strategies, two subjects improved by 60%, two subjects by 40%, and two subjects by 30% over the CIS strategy. Similar results were obtained at 3 months post-HiRes programming. There were no significant differences between the two HighRes strategies. The authors noted that further work is needed to determine the independent effects of rate versus number of channels.

Ricketts *et al.* (2006) examined speech recognition in noise ability of 22 postlingually deafened adult bilateral Med-El C40+ CI users (sequentially implanted) when they were listening with both implants or with only one implant. Six of the subjects were not able to perform the task due to poor speech recognition ability, so results were reported on the remaining 16. After 4-7 months of bilateral CI use, speech recognition was evaluated in the presence of five spatially-separated uncorrelated noise sources (ranging from 30° to 330° azimuth) at a fixed

+10 dB SNR. Results indicated a significant 9% mean improvement bilaterally compared to unilaterally, and a 3.3 dB mean bilateral advantage using a modified adaptive SNR method with HINT sentences. Ten of the subjects were brought back for retesting at 12-17 months post activation of the second implant, and showed improvements in both unilateral and bilateral performance but no change in the bilateral advantage. Finally, six subjects were evaluated in quiet and in varying SNRs (+5 to +20). The largest bilateral advantage was seen with the poorest SNR (+5), and performance in quiet was better than that in even the most advantageous SNR (+20). The authors note that the impact of head shadow effect was negligible with their speaker setup and thus they attribute the bilateral advantage shown in this study to a combination of binaural squelch effects and diotic summation.

Finally, Litovsky *et al.* (2006c[6]) performed a multisite prospective study of 37 postlingually deafened adults who had been simultaneously bilaterally implanted with Cochlear Nucleus devices. Speech recognition performance using CNCs and HINT sentences in quiet, and BKB-SIN tests in noise, was compared for bilateral implants and for listening with each CI alone. Testing was done over time with both speech and noise from a frontal (0° azimuth) speaker to examine binaural redundancy, and with speech from 0° but noise from +90 or -90° azimuths to examine head shadow and binaural squelch effects. By 6-months postactivation, a significant bilateral advantage was found over either unilateral condition for listening to speech in quiet. For speech in noise, a large and significant bilateral benefit was found when subjects were able to take advantage of the head shadow effect (i.e. when ear opposite to the noise was added for bilateral listening, significant improvement over unilateral listening). A few subjects also showed evidence of binaural squelch effects (i.e. when the ear at the noise side was added for bilateral listening, there were significant improvements over unilateral listening), and binaural redundancy effects (i.e. when the speech and noise were both frontal, bilateral performed better than unilateral). Because some subjects had asymmetric performance between ears, while others had more symmetrical interaural performances, these subgroups of subjects were examined separately. This sub-analysis revealed similar performances across the groups overall.

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[6] The author of this review was a co-author on this study.

Studies Of or Including Pediatric Subjects

Fewer published articles were located that addressed speech recognition for bilateral cochlear implantation specifically in a pediatric population. Vermiere *et al.* (2002) gave a case report on a female child who was aged 4.8 at the time of testing. This child had been congenitally deafened due to hyperbilirubinism and was reportedly suspected of having auditory neuropathy. She was implanted on the right side with a Nucleus 24 at the age of 2.5 years, and on the left side with a Nucleus Contour at age 4.4 years. The child's speech and language development upon testing was found to be comparable to a same-age normal-hearing child. Results of age-appropriate speech identification and recognition tests in the Dutch language revealed higher performance with bilateral implants compared to either unilateral implant used alone.

Kuhn-Inacker *et al* (2004) reported bilateral implantation on 39 German children who had a fairly broad age range at 1st and 2nd implants (1st implants ranged from 8 months to 16 years 4 months; 2nd implants ranged from 1 yr 7 months to 16 years 4 months), time lag between implants (range from 0 years {simultaneous} to 4 years 9 months). All but four of the children had a prelingual onset of deafness, and the other four had onset peri-lingually. Speech discrimination in noise tests were done on 18 of the children (11 males and 7 females; aged 2 years and 11 months to 9 years and 1 month) using bisyllabic words in an open-set format in all but the youngest child (who was tested closed-set). Speech was delivered at most comfortable loudness level (MCL) with speech-type noise fixed at a 15 dB SNR. The test setup used 2 loudspeakers for speech and 2 more loudspeakers for noise with an arrangement that was intended to minimize head shadow effects and thus look only at true binaural processing effects. The interval between bilateral implantation and speech testing ranged from 6 to 24 months. Results indicated that all children did better with bilateral implants than in unilateral conditions, and the mean results were significantly different at $p < .0001$ on a paired t-test. Open-set speech discrimination scores ranged from 46% to 100% correct in the bilateral condition and from 21% to 78% correct in the unilateral condition, as shown in Figure 8. The mean difference between bilateral and unilateral scores was 18.4% (+/- 8.2%). Although linear regression analysis showed that neither age at first implantation nor interval between implant surgeries significantly influenced the results, there was observed a trend toward faster, better performance with a second implant when the intersurgery lag time was shorter. The authors recommended that intensive rehabilitation be used to obtain optimal performance in children.

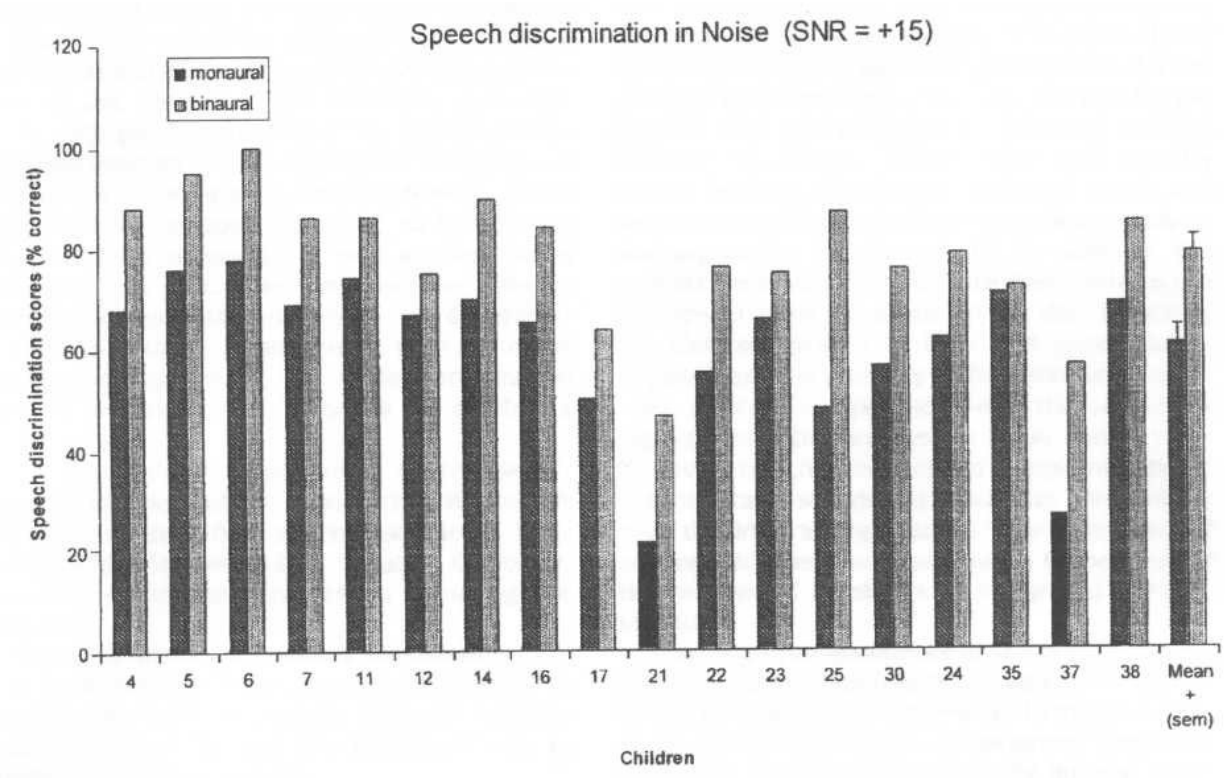

Figure 8.
Monaural and binaural speech discrimination scores in noise (percent correct) for each child as well as the mean scores (+standard error of the mean). (From Kuhn-Inacker *et al.*, 2004, Fig. 4).

In the Litovsky *et al.* (2004) study, three children (aged 8, 8, and 12 years old) were also evaluated who received bilateral implants in sequential implantations 3 to 8 years apart. The CRISP (Children's Realistic Index of Speech Perception) test was used 3 months after the children received the second implant. In this test, there is a closed set of familiarized target spondee words (male voice) with 4AFC picture identification. The spondees were presented from 0° azimuth. Competing female voice sentences were presented from 0° and also from 90° to the right or left, at a fixed 60 dB SPL. An adaptive tracking method was used to determine SRT for the target words and the data were analyzed using a method of parameter estimation that yielded an SRT corresponding to approximately 79.4% correct performance. Results were mixed across subjects and conditions. For two of the three children, bilateral performance was better than unilateral when noise was near the side that was implanted first, but the third child did not receive bilateral benefit. The authors suggested that the children may have needed more time with the second implant to realize maximum binaural benefit.

A comparison study for a group of 20 prelingually deafened children aged 3 to 14 was done by Litovsky *et al.* (2006a), as previously described in the section on bimodal devices. Ten children wore bimodal devices and 10 children wore bilateral CIs (9 Nucleus, and 1 Clarion) that were received in sequential implantation surgeries at least 1 year apart. Evaluated was speech intelligibility (CRISP test). Test conditions included quiet and 2-talker competing speech from the frontal loudspeaker, or from +/- 90°. Results indicated clear and significant improvements in speech results with two-eared versus one-eared listening for the bilateral CI group across all conditions, with results somewhat less compelling for the bimodal users. The amount of bilateral experience did not appear to impact the speech task. The authors did note that there were differences between the groups that might somewhat limit conclusions from the comparison in terms of bimodal versus bilateral CIs.

As previously described in the bimodal devices section, Schafer & Thibodeau (2006) evaluated children wearing either bilateral CIs or bimodal devices using an SRT task in classroom-simulated noise. Although the authors themselves note limitations in the design of the study may have resulted in their failure to show significant bilateral versus unilateral group mean performance improvement, individual data showed that more bilateral CI users had a significant binaural advantage than bimodal users. They also demonstrated advantages of using FM systems with cochlear implants or hearing aids.

Law & So (2006) examined speech production (as opposed to perception) of prelingual profoundly hearing-impaired Cantonese speaking children in Hong Kong. There were two groups: those who used bilateral cochlear implants (n=7) and those who used bilateral hearing aids (n=7). Ages ranged from 5 to 6 in each group. Results indicated that the CI users had a significantly higher percentage correct score for consonant production than did the HA users.

Summary

Table 2 summarizes the studies on bilateral implantees that have examined speech perception in quiet and/or in noise. Across the studies it can be seen that patients perform the same or (often) better in the bilateral condition than in either unilateral condition, with almost no reports of patients performing worse with bilateral implants than with a unilateral implant. Substantial and significant improvement is seen across studies with binaural implant use due to the head shadow effect, and typically lesser but sometimes significant improvements in some studies due to binaural squelch and/or binaural redundancy effects.

One of the problems in comparing across studies is that some have used a fixed SNR that has resulted in ceiling effects (patients performing so well with their unilateral implant that there is no room for significant improvement with the bilateral implant), but when the SNR is appropriately set to avoid this problem, bilateral listening has shown consistent improvements over unilateral in a vast majority of patients. A second issue in comparisons has been the use of different test materials in different languages, which precludes direct comparison of the numbers, and design issues such as time given for acclimatization (adjustment) to unilateral and bilateral implants, whether compensation for binaural loudness summation was used or not, the azimuths of presentation of the speech and noise, and whether or not processing is done with clinical devices or experimental binaural laboratory processors. Finally, there are potential confounds across studies in duration of deafness of the patients prior to implantation, whether they previously wore hearing aids binaurally or not, differences in duration or degree of losses between the ears of a patient, and so on. The striking finding, however, is that, across speech materials, countries and languages, research designs and different patient populations, the results have consistently and strongly supported binaural benefit for speech recognition, particularly in noise with spatially separated speech and noise sources as are likely to occur in the "”real” world. The data collected on pediatric patients has been sparser to date and not quite as clear-cut as the adult data, but still supports bilateral implantation.

Table 2. Overview of Studies On Bilateral Cochlear Implants: *Speech Perception Studies*

Study	*Sample Size (n), age, and gender of subjects*	*Other Patient Characteristics*	*Dependent Variables*	*Design/ CI*	*Stimuli Parameters*	*Statistics Used*	*Findings*
Studies On Adult Patients:							
Balkany *et al.*, 1988	n = 1 female age 55	Deafened bilaterally simultaneously by Streptomycin	Cochlear Corporation/ University of Iowa revised Cochlear Implant Test Battery	Within-subject unilateral implant each ear v. bilateral implants; 3M/House one ear, Nucleus other ear	Speech at 72-73 dB SPL	N/A	Better performance binaurally than unilateral on standardized word tests, but poorer on some connected speech tests when 3M added to Nucleus
Green *et al.*, 1992	n = 6 (4 male, 2 female); aged 57-74	Varying etiology & duration of deafness (including Meniere's, otosclerosis, chronic otitis media & meningitis)	Variety of auditory-visual and auditory only including speech tracking, V & C confusions, sentences, WIPI and speech pattern contrasts (MiniThrift)	Within-subject unilateral implant each ear v. bilateral implants; 3M/House and Nucleus in various combinations	Speech at 70 dB SPL; MiniThrift recorded but all other tests presented live voice	None; only individual results presented	Differences were small but each patient showed a binaural advantage on at least one of the tests
Lawson *et al.*, 1998	n = 1 female adult; (age not specified)	Postlingual deafness due to Listeraia rhomboencephalitis as a young adult; implants obtained 5 months apart	Medial consonant identification task	Within-subject unilateral implant each ear v. bilateral implants; Nucleus 22 implants controlled by a single experimental processor (CIS)	Details of stimuli and stimulus presentation were not provided	N/A	No evidence that bilateral stimulation degraded performance, even for arbitrary divisions of information between the ears

Mawman *et al.*, 2000	n = 1 male age 50	Post-lingually deaf, progressive auto-immune over 5 years; Simultaneous bilateral implantation	BKB sentences, AB monosyllables (open set) in quiet & noise	Within subject: unilateral implant each ear v. bilateral implants; Nucleus CI24M with SPEAK strategy (ESPRIT)	Speech level not reported; SNR = +5 dB	N/A	Higher percent correct scores for binaural quiet or noise than with either unilateral implant
Muller *et al.*, 2002	n = 9 adults (gender and ages not specified)	Post-lingually deaf, varying etiologies and loss durations across ears	German HSM sentences in noise and Freiburg monosyllables in quiet	Within subject: unilateral implant each ear v. bilateral implants; Med-El Combi-40 or Combi 40+	Speech at 65 dB SPL at 0° azimuth; SNR at +10 dB speech-shaped noise; noise at either 90° or 270°	Repeated-analysis AOV and post-hoc Neumann-Keuls	Consistent, significant advantage for bilateral implants versus unilateral in all tests and conditions
Schoen *et al.*, 2002	n = 9 adults (gender not specified), ages 22-68 at time of implantation	Post-lingually deaf, varying etiologies and loss durations across ears Some sequentially implanted, some simultaneously	German HSM sentences in quiet and in noise	Within subject: best unilateral implant v. bilateral implants; Med-El Combi-40 or Combi 40+ (with CIS strategy)	Speech at 70 dB SPL & SNRs from 0 to 20 dB; 4 loudspeakers at 45, 135, 225, & 315° to produce the same SNRs across ears (attempt to reduce head shadow effect)	Calculations of best-fit curves, and t-test	Significant bilateral benefit compared to the best unilateral ear score; Stable mean 4 dB improvement in SNR, presumably due to binaural redundancy.
Tyler *et al.*, 2002b	n = 9 adults (gender not specified), ages 36-71	Post-lingually deaf, varying etiologies and loss durations across ears	CNC monosyllables & CUNY sentences in quiet and in noise at 3 months postactivation	Within subject: unilateral implant each ear v. bilateral implants; Nucleus CI24M with SPEAK (n = 6), ACE (n = 2), CIS (n = 1)	Speech at 70 dB SPL at 0° azimuth; SNRs from 0 to +10 depending on the patient. Noise in front or at 90° to either side	Binomial tests	A significant binaural advantage was found for: 4 of 9 subjects in quiet, 4 of 9 with speech & noise from the front, 7 of 7 tested when the ear contralateral to the noise was added, & 1 or 3 (noise right & left respectively) of 7 when ear ipsilateral to the noise was added

Gantz *et al.*, 2002	n = 10 (gender not specified), ages 36-75 (9 of these are same as Tyler *et al.*, 2002b)	Post-lingually deaf; varying etiologies and loss durations across ears simultaneous implantation	CNC monosyllables & HINT sentences in quiet, CUNY sentences in quiet and in multitalker babble; Given at 3 months & 1 year postoperatively	Within subject: unilateral implant each ear v. bilateral implants; Nucleus CI24M with SPEAK (n = 6), ACE (n = 3), CIS (n = 1)	Speech at 70 dB SPL at 0° azimuth; SNR fixed at +10 dB with noise at either 0°, or at 45° to either side	Statistical test used was not reported	Depending on test, from 2 to 8 of the 10 subjects performed significantly better with bilateral implants than either unilateral; None did more poorly with bilateral implants. Concluded that even those with long durations of deafness benefit from bilateral.
Au *et al.,* 2003	n = 4 (2 male, 2 female) ages 23-38	Post-lingually deafened Chinese Cantonese-language speakers (Hong Kong)	Cantonese lexical tone discrimination (speech) scores in quiet & noise	Within subject: unilateral implant (average across ears) v. bilateral implants; Med-El with CIS strategy	Speech at 65 dB SPL at 0° azimuth; SNRs of +15, +10, +5, 0, -5, -10, & -15	Wilcoxin Matched-Pairs (quiet scores); Binomial Test (noise scores)	Mean quiet scores higher for bilateral but non-significant difference; In noise, needed more favorable SNRs with unilateral than bilateral to perform same as in quiet
van Hoesel & Tyler, 2003	n = 4 adults (a 5th adult could not perform the task); gender not specified, ages 36-71	Post-lingually deafened with etiologies including Meniere's & autoimmune	BKB sentences presented adaptively in speech-weighted noise	Within subject: unilateral implant each ear v. bilateral implants; Nucleus CI-24M, with SPEAR to provide binaural cues; loudness adjusted for binaural summation.	Speech at 65 dB SPL at 0° azimuth; SNR varied for 50% correct SRT and noise at either 0-+90 or –90° azimuths	Analysis of Variance with Tukey Post-Hoc tests	No binaural benefit with speech and noise at 0°, but significant improvement binaurally compared to when noise presented to ipsilateral ear (due to head shadow effects)

Dorman & Dahlstrom, 2004	n = 2 adults (1 male, 1 female) ages 31 & 71	both postlingually deafened; male due to childhood meningitis, & female progressive of unknown etiology	CNC words, and HINT sentences. Male only also tested with synthetic vowels in /bVt/ environment.	Within subject: best unilateral implant v. bilateral implants; Each had Med-El CIS-Link processor & Ineraid electrode array on one ear, & Clarion 8-electrode Hi-Focus array on the other.	Speech at 70 dB SPL at 0° azimuth. For male subject, HINT tested in noise at +5 SNR (female subject only tested in quiet due to poor performance)	t-test, binomial expansion	Male showed a smaller binaural benefit (vs best unilateral ear) for vowels, & a large and significant benefit for sentences in noise. Female showed significantly better binaural performance for CNCs and HINT in quiet.
Schleich *et al.,* 2004	n = 21 adults (11 males, 10 females); aged 17.5-66.5 years (mean = 44); Speech data on only 18 Ss as the other 3 could not perform the task	20 were post-lingually deafened, 1 pre-lingually; native-German speakers (Austrian study) Sequential surgeries Duration of deafness 0.6 to 47.8 years	Oldenburg Sentences in noise	Within subject: unilateral implant each ear vs. bilateral implants with calculations of various binaural effects Med-El Combi 40+ implants	Adaptive speech signal level and noise fixed at 60 dB SPL to determine SNR for 50% correct	Wilcoxin signed-ranks tests	Significant large effect due to head shadow (mean improvement = 6.8 dB), significant smaller effect due to binaural summation (mean = 2.1 dB), and small but significant effect from one side only due to binaural squelch (mean = 0.9 dB). No significant correlation between any factors found (duration of deafness, age, etc)

Laszig *et al.*, 2004	n = 37 adults at multiple sites aged 18-67 Note: not all subjects at all sites tested on all tasks.	postlingually deafened severe to profound hearing loss native-German speakers 22 subjects simultaneously implanted, and 15 subjects sequentially implanted	Freiburger monosyllables in quiet Oldenburger sentences (OLSA) in quiet, and in speech-shaped noise at 65 dB SPL with speech level varied to determine SNR. Hochmair-Schulz-Moser (HSM) sentences in quiet, and in speech-shaped noise at fixed +10 dB SNR	Within subject: unilateral implant each ear vs. bilateral implants CIs = Nucleus 24 with either SPrint of ESPrit 3G speech processors; Most used ACE strategy	For quiet & noise tests: single frontal speaker with speech at 70 dB SPL For noise: also from speakers placed at +/- 45° azimuths (S+45/N-45, and N+45/S-45)	Paired student t-tests	Significant binaural redundancy effect for monosyllables in quiet compared with the poorer ear alone scores, but no difference from the better ear at 6 months. Bilateral benefit for OLSA sentences in quiet at 6 months compared to either ear. Large head shadow effects for OLSA or HSM sentences. Smaller binaural squelch effects shown for about half of the subjects.

Ramsden *et al.*, 2005	n = 30 adults, (aged 29 to 82 years old); but data reported on only 27 Ss (one rejected second implant after 1 week; one had intractable tinnitus early in study that later resolved; one apparently had no data collected)	Sequential surgeries after 1 to 7 years unilateral CI use; Duration of deafness ≤ 15 years in both ears	Monosyllabic CNC words in quiet; CUNY sentences in quiet and in noise. Testing at 1-week, 3 months, and 9-months postactivation.	Within subject: unilateral implants vs. bilateral implants Cochlear Nucleus CI24M or CI24R(ST);	Speech at 70 dB SPL from a frontal speaker; Noise at individually selected SNR from front, or +/- 90°	Group data: AOVwith Tukey post-hoc or paired t-tests; Individual data: binomial tests	Ears implanted 2nd performed worse than 1st implanted ears, with no improvement in 2nd ear scores over time. For speech in quiet, no significant bilateral advantage, but significant bilateral advantage for speech & noise from front compared to the 1st ear. When noise at 1st ear, significant bilateral advantage over both monaural ears, but not when noise contralateral to that ear. However, 6 of 18 Ss did show significant binaural squelch benefit. When noise at 2nd ear, significant bilateral advantage over that ear alone, but not over the 1st implanted ear alone.

van Hoesel *et al.*, 2005	n = 8 adults, aged 30 to 69	Simultaneous implantation; at least 2 years of bilateral experience with ESPrit processors	Compared speech recognition (Oldenburg Sentences) across 4 maps (each worn 1 week): 1) clinical map for unilateral fittings; 2) decreasing C-levels; 3) decreasing T-levels; 4) decreasing T- and C-levels. Reductions were 12% of dynamic range, and loudness balanced between ears	Within subject: unilateral versus bilateral CIs Nucleus 24 with ACE strategy	Speech at 65 dB SPL, with noise level varied using an adaptive procedure to determine SNR; Both speech and noise from single frontal loudspeaker	AOVs	Modest but significantly decreased speech recognition when stimulation levels were lowered for both quiet and noise. For level reductions corresponding to binaural loudness summation, SNR decreased 1-2 dB. Little effect of altering slope of the map. Within a map, modest but significantly improved performance bilateral CIs compared to unilateral. The authors concluded that even if levels are reduced to compensate for loudness summation, the binaural advantage over the better ear performance will offset the decrease.
Senn *et al.*, 2005	n = 2 prelingually deafened teen girls and 3 postlingually deafened adult males	Sequential implantation	German HSM sentence intelligibility in quiet or CCITT noise	Within subject: unilateral versus bilateral CIs Med-El Combi 40/40+ with Temp+ speech processors and CIS strategy	Speech at 70 dB SPL from a frontal speaker, noise from speakers at +/- 90° azimuth; SNRs of 15 dB for teens, 5 dB for adults	Nonparametric Wald test	Substantially better performance bilaterally than unilateral CI with noise ipsilateral to that side (due to head shadow effects). Non-significant difference when noise contralateral to unilateral CI ear tested, but some individual subjects showed significant binaural squelch effects.

Dunn *et al.*, 2006	n = 7 adults, aged 28 to 79, wearing bilateral CIs and using CIS strategy for at least 18 months	Simultaneous bilateral implantation Purpose of study was to examine performance under a strategy with increased rate and number of channels	CUNY sentence recognition in multitalker babble after ABAB 1-month periods of wearing two different HiRes strategies; Tests at 1-, 3-, and 6-months post-HiRes programming	Within subject: CIS vs HiResolution Paired vs HiResolution Sequential (Note: No comparison to unilateral listening in this study) Advanced Bionics CII High Focus CIs	Single frontal loudspeaker for speech and noise; SNR set individually to avoid ceiling or floor effects, with speech at 70 dB SPL	Binomial model and paired t-tests	Dramatic improvements (30-60%) in speech perception in noise for many of the subjects at 1-month after switch to HiRes strategies. No differences between the two HiRes strategies. After 6 months of use, 80% of Ss continued to perform better with a HiRes strategy than with CIS.
Ricketts *et al.*, 2006	N = 22 adult bilateral CI users (but 6 could not perform the task due to poor speech recognition ability)	Sequential bilateral implantation	Series of experiments: n=16 in fixed SNR, n=10 over time with fixed SNR, n= 6 with varying SNR.	Within subject: unilateral implants vs. bilateral implants; Med-El C40+	In quiet and in SNRs from +5 to +20; HINT sentences and adaptive HINT sentences 5 uncorrelated noise sources from 30° to 330°	Repeated-measures AOV; arcsine-transformed %	Significant 9% (3.3 dB SNR) bilateral benefit vs. unilateral listening; no significant change over time in bilateral benefit. Greatest benefit at poorest listening SNR.
Litovsky *et al.*, 2006c	n = 37 adult bilateral CI users, aged 26 to 86. prospective multisite study	Simultaneous bilateral implantation Postlinguistic onset of severe to profound bilateral hearing loss;	Speech in quiet: CNC monosyllables and HINT sentences Speech in noise: BKB-SIN test - adaptive procedure to determine SNR for 50% correct. Loudness balanced across CIs Testing preoperatively with hearing aids, and at 1-, 3-, and 6-months postactivation of CIs	Within subject: unilateral implant each ear alone vs. bilateral implants; Nucleus 24 Contour CIs; SPrint or ESPrit processors with either SPEAK, ACE, or CIS strategies.	In quiet: speech from single frontal speaker at 65 dB SPL. In noise, either both from frontal loudspeaker or speech at 0° and noise at +/- 90°; Speech at 65 dB SPL and noise level varied.	Arcsine-transformed %-correct scores; Repeated-measures AOVs with post-hoc paired-samples t-tests; Binomial tests for individual comparisons	By 6-months postactivation, significant bilateral listening vs. unilateral CI advantage in quiet. For testing in noise, large and robust bilateral benefit when head shadow effect utilized, and a few subjects also showed binaural redundancy or binaural squelch benefits.

Studies On or Including Pediatric Patients:							
Vermiere *et al.,* 2002	n = 1 female, age 4.8 at time of testing	Etiology of deafness: congenital, hyperbilirubinemia (& possible auditory neuropathy); 2.5 at 1st implant & 4.4 at 2nd implant	Sentence ID (Tyler-Holstad); sentence recognition (EARS); language development (standardized Dutch battery)	Within subject: unilateral implant each ear vs. bilateral implants; Nucleus CI24 1st ear and Nucleus 24-CONTOUR 2nd ear, both with SPEAK	Presentation level not reported	N/A	Better speech recognition performance with bilateral implants than with a unilateral implant; Also, speech & language development comparable to normal-hearing child
Litovsky *et al.,* 2004	n = 17 adults (8 male, 9 female) ages; only 14 adults had speech tests Also, *Pediatric:* n = 3; age 8, 8, and 12	14 were postlingually deaf, 3 deaf in infancy or congenitally; All adults received both implants at the same time Children were prelingually deafened, and had sequential surgeries 3-8 yrs apart.	BKB sentences presented adaptively in multitalker babble For children, CRISP: spondee words presented with competing sentences	Within subject: unilateral implant each ear vs. bilateral implants; Nucleus CI24R (CS), except one child who had a CI22 in one ear.	Adaptive SNR; Formula to estimate SRT for 50% correct For children, adaptive with competing stimuli at 60 dB SPL; Method to estimate SRT for 79.4% correct For both, speech in front, noise in front or at 90° either side	None used; only individual results presented	Bilateral advantage when noise at the poorer ear but minimal when noise at better ear. For children, 2 of 3 showed binaural advantage with noise near the side that was implanted first.

Kuhn-Inacker *et al.,* 2004	n = 39 children (but speech in noise tests obtained on only 18)	Broad range of ages at 1st & 2nd implantation (ages 8 mo to 16 yr 4 mo); all but 4 were prelingually deafened. For children receiving speech testing, ages ranged from 2 yr 11 mo to 9 yr 1 mo	Bisyllabic words in speech-type noise in an open-set format for all except the youngest child	Within subject: unilateral implant v. bilateral implants; Med-El 40 or 40+	Speech at most comfortable level, noise at +15 SNR. Four loudspeakers delivered speech & noise in order to minimize head shadow effects	Paired t-tests; linear regression analysis	Significantly higher word scores for bilateral vs best unilateral implants; All individual scores showed higher scores binaurally. Regression analysis showed that neither age at 1st implant nor interval between surgeries impacted the results significantly, but observation suggested that shorter inter-implant interval facilitates performance. Intensive rehabilitation training recommended.
Litovsky *et al.*, 2006a	20 prelingually deafened children aged 4 to 14 in two groups: 10 bimodal users and 10 bilateral CI users	Sequential bilateral implants, with inter-implant interval at least 1 year	localization minimum audible angle (MAA speech intelligibility (closed-set, 4AFC, spondee CRISP test: speech level varied in fixed competing speech level to compute SRT for 79.4% correct)	within subject: unilateral implant versus bimodal or bilateral also across groups: bilateral listening benefit in bimodal group (addition of HA) versus in bilateral CI group CIs: most were Nucleus 22 or 24, but also 2 Med-El C40+ in bimodal group and 1 Clarion in bilateral group	Localization setup with 15 loudspeakers in semicircle spanning +/- 70° speech from frontal loudspeaker; 4 conditions: quite, and 2-talker competing speech at 60 dB SPL from front, +90, or -90°	Mixed-design 3-way AOV with group as between subjects variable and listening mode (monaural, bilateral) and listening condition as repeated measures variables. Post-hoc Scheffe's tests.	SRTs were comparable on average for bilateral listening across the two groups. However, for both speech intelligibility and localization, the benefit of binaural relative to unilateral CI listening (binaural advantage) was greater for the bilateral CI group than for the bimodal group. Some in the bimodal group actually did more poorly when the hearing aid was added back in.

Schafer & Thibodeau 2006	Children aged 3-13; n= 12 bilateral CI users n = 10 bimodal users		New test with simple phrases about body parts; Child response was to act out phrase on a doll; Method of limits procedure	Within subject: bilateral condition versus unilateral; various combinations with FM systems CIs: Advanced Bionics, Med-El, Cochlear	Measurement of SRT with adaptive frontal speech level, and classroom noise at 60 dBA from rear speakers	Analysis of variance; 95% confidence levels	No group differences in unilateral versus bilateral performance, but authors concede study design had limitations. 8 of 12 bilateral and 2 of 10 bimodal users showed binaural benefit. FM device on 1st implanted ear or bilateral produced performance improvements
Law & So, 2006	n = 7 children with bilateral CIs n = 7 children with bilateral HAs	Children from Hong Kong Congenital, bilateral profound losses; Both groups aged 5-6	Cantonese speech	Between group comparison CIs: Med-El Combi 40+ with TEMPO+ speech processor	Single word and spontaneous speech elicited; test of speech production (not perception)	Phonological analysis	All except 1 child had incomplete phonetic repertories, and all had incomplete vowel and tone inventories. Children with CIs had better consonant production than children with HAs

Psychoacoustic and Other Studies, and Localization

Recall that the largest and most significant benefits in terms of speech intelligibility improvements with two implants were due to head shadow effects, which are due to interaural level (or amplitude) differences (ILDs), while the effects of binaural squelch/unmasking, which are related to ILDs but also to interaural time and phase differences (ITDs), were smaller when present. As noted by van Hoesel (2004), in order for bilateral implant users to obtain the same advantages as normal listeners for binaural versus monaural processing, it would seem that sound-processing strategies of cochlear implants would need to preserve the appropriate ILD and ITD cues. In fact, according to van Hoesel, most current cochlear implants preserve envelope timing cues (envelope ITDs) but not fine timing cues. Even if those cues were made available, however, van Hoesel argued that it might be that the hearing-impaired ear would be unable to utilize the cues effectively; i.e. there might be a lack of sensitivity to these small differences between the ears.

To examine the contributions of these factors, a number of researchers have directly examined performance of bilateral cochlear implant users with psychoacoustic studies of sensitivity (Just Noticeable Differences, or "jnds") to ILDs and ITDs, or other measures. Further, some have examined issues related to pitch or loudness perception across bilaterally implanted ears. Recently, there has been some work evaluating electrophysiological responses in terms of evoked potentials. Finally, there are a number of studies that have examined localization abilities of bilateral versus unilateral cochlear implant conditions. When localization is in the horizontal plane (which all studies to date have examined), determining source laterality is dependent on both ILD and ITD information. The following provides a brief overview of the results from some of the available psychoacoustic studies of bilateral cochlear implant users.

Adult Population

From 1993 to 1997, van Hoesel and colleagues accomplished a series of experiments that examined psychoacoustic and localization abilities in two adults who were using bilateral cochlear implants. The first was a male adult, who van Hoesel states was the first bilateral cochlear implant patient in Australia, with a longstanding bilateral profound hearing loss resulting from head trauma. He was fitted with a second Nucleus 22 device on his contralateral ear five years after his first surgery. The second experimental subject was another male adult who had profound bilateral hearing loss resulting from Meniere's disease, with an intersurgical interval for the Nucleus implants of 8 years. Across these studies (van Hoesel *et al.* 1993[7], 1995[8], van Hoesel & Clark, 1997), it was found that both bilateral implant users could effectively fuse information across the implants. Lateralization experiments (determining perception of right/left shifts with changes in stimulation to electrode pairs, one in each ear) showed good sensitivity to ILDs. These subjects showed, however, very large jnds in ITDs relative to normal ears. These implant subject's jnds were on the order of 0.5 to 1 msec. There were also noted to be strong effects on ITDs of varying the electrical stimulation level between a patient's two implants.

In the 1997 study, van Hoesel & Clark further examined jnds in ITDs for these two patients with rate and place of stimulation varied. Results also showed that jnds in ITDs were large compared to normal ears, even when place of stimulation on each side was carefully matched. Values were similar for stimulation rates from 50 to 200 pulses per second (pps), but increased at 300 pulses per second. Examination of rate difference limens showed similar results for diotic stimulation (bilateral stimulation with rates on both sides varied together) and unilateral stimulation, but showed improved jnds for dichotic stimulation (rate on one side fixed and rate on other side varied around this value) at rates below about 150 to 200 pps. Binaural loudness summation was present when electrical pulse trains were applied to single electrode pairs across the ears, for matched as well as unmatched place conditions. When loudness in each ear was similar, binaural loudness was about twice as large. Finally, central masking effects were found (thresholds increased) but were not place dependent as is the case for normal ears. Using the second of the two bilateral implant patients, van Hoesel & Clark (1999)[9] illustrated that the good sensitivity of the one patient to ILDs did indeed translate to binaural speech intelligibility benefits from head shadow effects for spatially separated speech and noise.

In the case report presented by Lawson *et al.* (1998) on a patient with bilateral Nucleus 22 implants controlled by a single processor, pitch matching and ranking studies were done using

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[7] As reported in van Hoesel, 2004.
[8] As reported in van Hoesel, 2004.
[9] As reported in van Hoesel *et al.*, 2002.

all available stimulation sites in both ears to determine bilateral pairs with comparable pitch. Using those pairs, the subject's ability to lateralize sound was studied as a function of ITD and ILD. Results indicated that, for loudness-matched stimulus pulses, the subject was able to identify the ear receiving the earlier onset for interaural delays as brief as 150 usec (microseconds). For simultaneous stimulation, the subject could identify the ear receiving the louder signal for the smallest deviations from loudness-matched amplitudes available from the implanted electrodes. The authors argued that these results support further work on coordinating binaural stimulation to improve speech understanding in noise scores in bilateral implant patients.

In the Mawman *et al.* (2000) case report, the patient with bilateral cochlear implants was given a localization test for monaural left versus binaural conditions. Both 500 and 3000 Hz narrow band noises were presented at 70 dB SPL from 7 azimuth angles for a duration of 4 seconds. For both frequencies, results indicated improved identification with bilateral implants, with slightly better low-frequency localization. Specifically, for 500 Hz, correct performance increased from 17% to 40%, and for 3000 Hz, from 14% to 34%.

In 2002, van Hoesel *et al.* looked at sensitivity to ITDs, and lateralization, in another adult bilateral implant user. This patient was a 51-year-old male who was implanted bilaterally with Cochlear CI24M devices. It was hypothesized that he would show better sensitivity to ITDs than the previous two subjects studied by this research group because he had much shorter duration of deafness due to a progressive hearing loss that was probably of autoimmune etiology. The patient was examined using both his two independent ESPrit processors, and with custom laboratory software that allowed bilateral processing, a higher stimulation rate, and no automatic gain controls (AGCs). For the lateralization task, pink noise bursts were presented using an 11-loudspeaker array spanning a frontal 180-degree arc in an anechoic (echo-free) room. No training or feedback were given, and the patient indicated which speaker he believed produced the sound. Results with the clinical processors indicated substantial improvement in mean errors for bilateral versus unilateral listening at 70 dB SPL (mean absolute errors of 80° and 73° for left and right ears {average SD across speakers of 10 and 17, respectively} versus only 16° for bilateral {SD =18}). Even greater improvement was seen at a level of 60 dB SPL that avoided activating the AGCs. The custom processor produced comparable results. For measurement of jnds in ITDs using a 3AFC task targeting 70%

correct performance, the stimuli included simple low-rate electrical pulse trains and high-rate pulse trains modulated at 100 Hz. The jnds were about 400 micosec for rates between 50 and 200 pps for simple stimuli, which is substantially better than the previous bilateral implant subjects they tested, albeit still poorer than normal ears. Open-set sentence recognition in babble noise was also measured at 70 dB SPL frontally with the processors set to compensate for binaural loudness summation. Babble noise was presented either from the front or 90° to either side at 5 dB SNR. Using AOV with Tukey post-hoc tests, results indicated no significant binaural advantage when the noise was from the front. When the noise was from the right side, binaural and left side scores were significantly superior to right side scores ($p < .0001$), but did not differ from each other. The opposite pattern was seen when the noise was from the left side. Binaural listening always benefited from the noise moving away from the frontal position, but for monaural listening this was only the case when the noise was contralateral to the ear being tested. The results indicate primarily head shadow effects then, rather than binaural squelch effects.

In the Tyler *et al.* (2002b) study previously described, limited localization data were also collected using a simple right-left localization task to evaluate 7 of the 9 patients in their study who had been simultaneously implanted with bilateral devices. Loudspeakers were placed at 45-degree angles to the right and left of frontal midline and the patient was asked to identify which loudspeaker produced a series of 3 pulses of speech-weighted noise (200 ms on, 200 ms off). One hundred presentations were made for each listening condition. Results revealed that most subjects had significantly better left-right discrimination using bilateral implants compared to using just one, as shown in Figure 9. This study was followed up on a year later by another one using the same subjects plus one additional subject, and the same methods (Gantz *et al.*, 2002). Results again indicated significantly higher performance for binaural listening than for either ear alone. In fact, localization performance with a unilateral implant was essentially chance for most subjects, while bilateral performance ranged from 95% to 100% correct.

Long and colleagues (Long *et al.*, 2003) reported a case study of a single bilateral user with psychoacoustic experiments using a laboratory processor that carefully controlled bilateral stimulation. The subject, a 72-year old female, had first noticed hearing loss at age 25 and

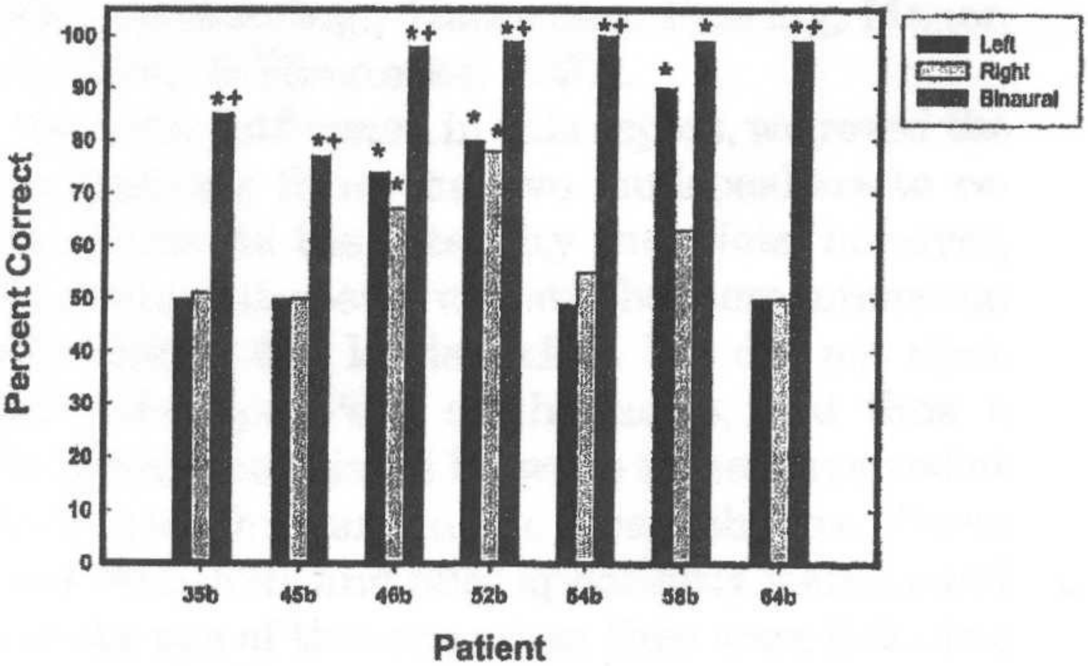


Figure 9.
Left-right localization ability measured in the horizontal plane with two loudspeakers at 45-degree azimuths. Scores better than chance performance (50%) are indicated by an asterisk, and binaural performance significantly better than monaural is indicated by a plus (using binomial tests). (From Tyler *et al.*, 2002b, Fig. 5).

was profoundly deaf bilaterally by age 44. At age 59, she received a 6-electrode Ineraid but did not receive much benefit from it (single-syllable word score = 10%). At age 70, she received an 8-electrode pair Clarion implant in the other ear with the hope that the newer technology would improve her performance, but unfortunately her single-syllable word score with this implant was below 10%. For this series of experiments, stimulation of single, bilateral electrode pairs was accomplished using fixed-amplitude 100-pps trains of biphasic pulses in lateralization tasks. The subject was found to be sensitive to ITDs as small as 300 usec (moving the perceived auditory image from left to right), although sensitivity varied across interaural electrode pairs tested. When pitch matching was used to select electrode pairs with similar pitches, ITDs tended to be better. Sensitivity to ILDs was greatest with electrodes that showed significant ITD sensitivity. The researchers note that these findings offer hope that normal binaural advantages could be provided for bilateral implant users with binaural processing, because this patient was able to experience fused and lateralized sensations despite her poor performance with her implants and long duration of deafness.

In the 2003 van Hoesel and Tyler study that was first described in the speech perception section of this paper, the five simultaneously implanted Nucleus bilateral cochlear implant patients were also subjected to localization studies in which pink noise bursts were presented from an 8-speaker array in a frontal 108-degree arc. Results indicated typical rms averaged errors across the speakers of about 10° for listening with bilateral implants, but 20- to 60° errors for either unilateral implant alone. All five subjects showed a bilateral implant advantage as illustrated in Figure 10. Use of a research processor that enhanced interaural timing cues (instead of the clinical processors) did not help much with localization. Additional lateralization studies indicated good sensitivity to ILDs down to 0.17 dB for some subjects, and moderate sensitivity to ITDs on the order of 100 usec. ITD sensitivity deteriorated when stimulation rates for unmodulated pulse trains increased above a few hundred Hertz, but at 800 pps showed sensitivity comparable to 50 pps when a 50-Hz modulation was applied.

Laback *et al.* (2004) assessed the sensitivity of two bilateral Med-El implant users to ILDs and ITDs for various signals presented through the auxiliary inputs of clinical sound processors. These processors used a CIS strategy, which preserves envelope cues but not fine timing information, and were configured to achieve equal loudness sensations at the two ears for diotic input signals. For the experiment the stimuli were fed into the auxiliary inputs rather than presented through the head-mounted microphones. Subject #1 was a postmeningitic 18 year old implanted bilaterally during her 14th year (sequential surgeries performed close together in time). Her duration of deafness was less than 6 months bilaterally at implantation. Subject #2 was a 56 year old (gender not given) who was implanted in one ear when he/she was 48 years old and in the other when he was 54. The first implanted ear had 25 years duration of deafness at implantation and the 2nd had 21 years duration. In a lateralization experiment, jnds measured using a 2AFC method for ILDs indicated high sensitivity for both patients for the broadband stimuli used, with values approaching those of normal hearing controls who listened to the same stimuli through headphones. Pitch-matched single electrode pairs showed significantly lower jnds in ILDs than those for pairs of electrodes that were mismatched in pitch. The jnds in envelope ITDs were higher than those of the normal controls

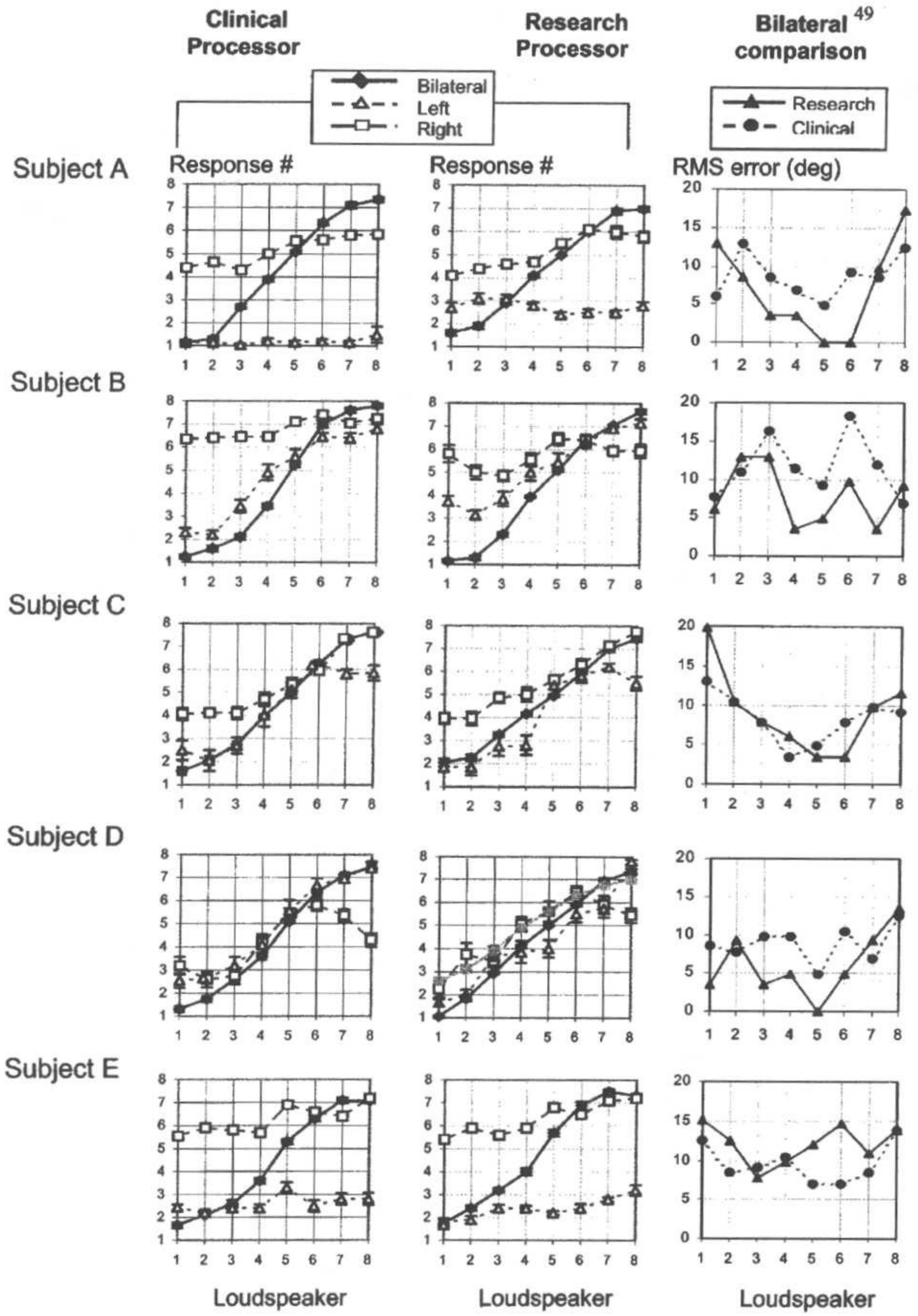
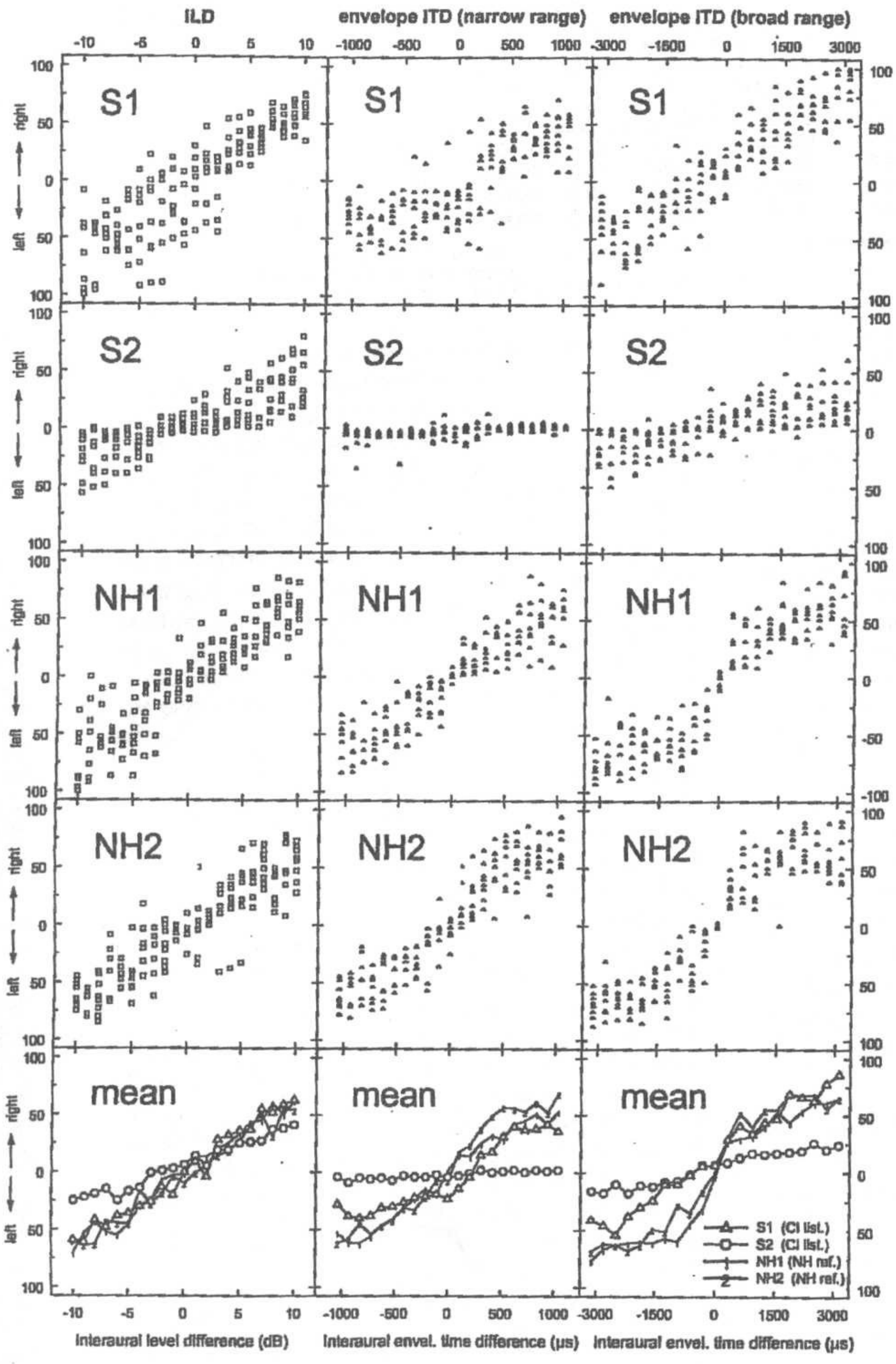


Figure 10.
Localization data (means and SEs) for five subjects for clinical and research processors with 20 presentations from each of 8 loudspeakers. Column 3 shows rms errors in degrees for bilateral device use. Gray symbols for subject D indicate additional data with speakers behind the subject. (From van Hoesel & Tyler, 2003, Fig. 2).

and more variable on test-retest. The envelope ITD jnds for these two patients for click trains were lower than for a speech token or noise burst stimulus. The best envelope ITD jnd found was 259 usec for the click train at 100 Hz for Subject #2. Lateralization results for the two hearing impaired subjects and two normal-hearing controls are shown in Figure 11.

Nopp *et al.* (2004) also evaluated bilateral users of Med-El COMBI 40/40+ implants, with standard TEMPO+ speech processing using the CIS+ strategy. For 20 adult subjects (10 males, 10 females, age 17 to 67 years old {mean = 45.1) implanted in adolescence or later, sound localization was tested unilaterally and bilaterally. Duration of deafness across ears ranged from 3 to 48 years, and subjects had at least 1 month of experience with their second implant prior to testing. Nine speakers equally spaced in a frontal arc between +/- 90° azimuths were used, and stimuli were speech-shaped noise bursts presented at randomized levels. Friedman nonparametric repeated-measures AOV and post-hoc Tukey tests revealed a substantial and significant benefit of bilateral listening over unilateral listening with either ear. With the second implant added, accuracy of localization increased by an average of 30% and variability in response was reduced substantially. Examination of individual data showed that, with two exceptions, all subjects had substantial improvement in localization ability using two implants compared to using only one. The two subjects who failed to show bilateral benefit were both deafened bilaterally at earlier ages than any of the other subjects (in infancy and prior to age 4 respectively). When duration of deafness was calculated as a fraction of the patient's current age, there was a positive correlation (Pearson) for the group as a whole with localization performance as calculated as a mean deviation between judged and actual azimuths (1st deafened ear: $r = 0.684$, $p < .001$; 2nd deafened ear: $r = 0.690$, $p < .001$); However, when the two subjects who had no bilateral benefit were excluded, the correlation was no longer significant. The researchers hypothesize that there may be a critical period for fully learning to process binaural cues, but that once binaural processing is acquired it does not deteriorate significantly over even longer duration of deafness.



<u>Figure 11.</u>
Lateralization judgments on ILDs (left column) and envelope ITDs within +/- 1042 usec (middle column) and within +/- 3125 usec (right column) for two bilateral cochlear implant users (S1, S2) and two normal-hearing controls (N1, N2). Bottom row summarizes the mean judgments for each listener. (From Laback *et al.*, 2004, Fig. 5).

As previously described in the bimodal section, Seeber *et al.* (2004) compared localization ability of 11 bimodal device users to that of 4 bilateral CI users. Most were wearing Med-El Combi 40+ devices. A frontal horizontal plane localization task was completed for an array of 11 loudspeakers spanning an angle of minus 50° left to +50° right. For the bimodal group, all but 4 subjects showed bilateral input localization ability. For the bilateral implants group: 1) one subject showed localization accuracy close to that of normal-hearing subjects. This subject was also able to discriminate the side of sound origin using the first implanted device alone, and 2) the other three subjects showed more limited but significant localization ability using both implants, and one of these subjects was also able to side-discriminate using only the first implanted device.

van Hoesel (2004) accomplished a series of psychoacoustic tests on a few patients in Melbourne who had bilateral Cochlear CI24M implants. First, using a 2AFC paradigm and constant-amplitude pulse trains at 50 pps, ITD jnds were determined in one patient as a function of place of stimulation in one ear with place held fixed in the other ear. The best jnds were around 150 usec for matched-pitch bilateral electrode pairs. Place offsets of 3 bands or more were needed before ITD sensitivity degraded to the point of doubling. Second, loudness summation for broadband pink-noise burst stimuli was examined. It was found that binaural listening resulted in an average loudness that was about 1.8 times greater than either ear alone. Third, binaural masking level differences (BMLDs) were examined using 500 Hz pure tones in narrowband noise, both presented directly in to the stereo audio input connector of the experimental SPEAR processor with the PDT strategy, which preserves fine-timing cues rather than just envelope ITDs. For the two patients tested, BMLDs were 2 dB and 1.5 dB, measured as the difference between the averaged thresholds for in-phase and out-of-phase tones. This is less than the 10 to 15 dB expected in normal hearing persons, and was taken by van Hoesel to indicate that very little binaural unmasking would be expected for speech-in-noise listening unless BMLD effects could result from low-rate envelope rather than fine-timing fluctuations. Fourth, localization studies were completed on two patients to examine the effects of total array span, signal characteristics, and sound-processing strategy. Two speaker arrays were compared: 1) spanning +/- 65° so that for the implant microphones and signals used there would be no ILD ambiguities and low-rate ILD cues would likely have little effect, and 2) spanning 180° where there would be regions where broadband ILDs are not monotonically related to source azimuth and low-rate ILD cues might improve localization. For one subject with the 180-degree span, there was better localization with the 50-Hz click trains than with pink noise for both commercial high-rate envelope extracting strategies and with the SPEAR PDT strategy. This agrees with the psychophysical result that sensitivity to ITD is reduced at higher rates. Both subjects showed much better performance with click trains than pink noise on a lateralization task, providing further evidence that ITDs can be of benefit when signals contain low-rate cues.

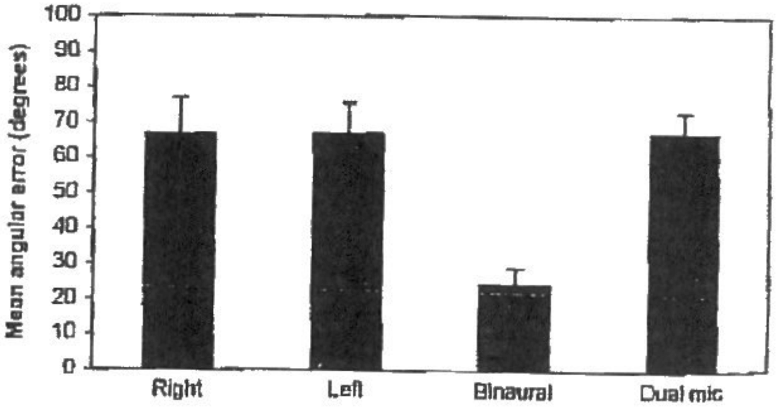
Litovsky *et al.* (2004) also evaluated localization abilities in the 17 simultaneously bilaterally implanted adults in their study. A localization task was used in which 8 matched loudspeakers were positioned in a semicircle in front of the subjects at 20-degree intervals. Stimuli were four bursts of 170-msec pink noise at an average level of 65 dB SPL with 10 msec rise/fall times and a 50-msec ISI. Stimuli were presented 20 times at each speaker location in random order. Subjects were asked to hold their heads still during presentations and to indicate the speaker of origin. Results indicated that for most of the subjects localization was better under bilateral conditions than unilateral. Examination of individual factors that might have impacted performance showed that the strongest predictor of binaural benefit in the localization task was duration of bilateral hearing aid use before implantation. Subjects who had previously worn bilateral hearing aids for more than 10 years showed the best localization performance with bilateral implants, presumably because their auditory pathways had not been deprived of stimulation. Interestingly, duration of deafness itself was not a strong predictor.

In the Laszig *et al.* (2004) study previously described in the section on speech perception, horizontal plane localization measurements were also completed on 16 of the 37 subjects, at one test site. Using a 12-loudspeaker setup, 30° apart, shortened HSM sentences were presented at a level individually selected between 55 and 70 dB SPL to assess directionality abilities. For 15 of the 16 subjects, and the group mean, performance was significantly better when listening bilaterally than when using either CI alone. The root-mean-squared (rms) degrees of error were reduced by 38° for bilateral listening compared to listening with a unilateral CI.

Senn *et al.* (2005) in the study described in the previous section also tested horizontal plane localization (MAA measurements) in the 2 teenage and 3 adult sequentially implanted bilateral Med-El CI users with a CIS strategy. White noise bursts of 1000 ms duration were presented from a loudspeaker mounted on a rotating boom and compared with the MAAs of age-matched normal control subjects. Spatial discrimination was found to be good in the front and the back of the head with near-normal values (hearing-impaired patients: 3 to 8°, normal controls: 1 to 4°), but poor performance was found from the sides relative to normal (patients: 30 to 45°, normals: 7 to 10°). Bilateral CIs produced significantly better performance than unilateral CI conditions. Just noticeable differences (jnds) in interaural intensity and time were also assessed in this study, using white noise bursts, click trains (40 us clicks, 50 Hz), and noise bursts in which either only the envelope or only the fine structure was shifted in time. The bilateral CI users showed near-normal interaural intensity jnds, but substantially poorer interaural time jnds than the normal controls, with some variation depending on the type of stimulus. Envelope onset/offset cues could be perceived by these CI users but not interaural fine structure time differences.

Schoen *et al.* (2005) performed a series of three experiments on 12 subjects who were postlingually deafened adult bilateral users of Med-El Combi 40/40+ CIs. All had been sequentially implanted and had listened bilaterally for at least 3 months. In an anechoic test chamber, localization testing was done using CCITT noise (500 ms at 70, 75, and 80 dB SPL) and a 7-loudspeaker array between +/- 90° in a horizontal frontal plane. Results indicated that all 11 subjects tested were able to localize well using their bilateral implants. In addition, ILD sensitivity was measured in 4 subjects using localization tests with loudness of the two processors unbalanced to various degrees. This was found to produce a bias in azimuth toward the processor with the louder setting. Finally, ITD sensitivity was measured via lateralization as a function of the time difference between pulses directed to one of the two speech processor microphones. Six of 7 subjects tested on this task showed a significant sensitivity to ITDs with a mean time difference of 1200 us required for lateralization. The authors concluded that the results across the experiments indicated: 1) bilateral CI users can regain the ability to localize, 2) they may be able to translate interaural level difference into a lateral spatial shift with the rate of shift corresponding to what has been found in normal hearing subjects, and 3) they may be sensitive to interaural time differences, with the differences for complete laterality being similar to normal hearing subjects.

Verschuur and colleagues (2005) examined localization ability in the horizontal plane of 20 adult bilateral cochlear implant users (sequentially implanted after less than or equal to 15 years duration of deafness, and with at least 9 months bilateral experience). Cochlear implants were all Nucleus 24. Testing was accomplished at between 3 and 9 months after initial activation of the second implant. Five stimuli were used (speech, tones, noise, transients, and reverberant speech), with an 11-loudspeaker array with other stimuli roving in +/- 5 dB steps around 60 dB SPL and pink noise at 60 and 70 dB SPL (to activate the AGC). Analysis of variance with post-hoc t-tests indicated a significantly lower mean localization error with bilateral listening (24°) than with unilateral (67°, with chance performance at 65°) or with use of a unilateral CI with the "dual-microphone" option[10]. Mean results are shown in Figure 12. It was noted that this performance was still poorer that of normal controls in a previous study (who averaged 2 to 3° localization error) or of bilateral hearing aid users (10° error). The authors hypothesized that this was due to the absence for the CI users of temporal fine-structure cues, limitations associated with absolute level judgments due to amplitude quantization in the CIs, or ability to compare the amplitude spectrum between the ears limiting ILD perception. There were no large differences found in performance across stimulus types or locations for bilateral listening



<u>Figure 12.</u>
Mean angular error on a localization task as a function of listening condition: unilateral use of each cochlear implant, bilateral cochlear implants, and unilateral condition with the "dual" (port) microphone. (From Vershuur *et al.*, 2005, Fig. 2).

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[10] Presumably this actually refers to the "dual-port" microphone.

Long *et al.* (2006) conducted a study in which four adult CI users, who had not had bilateral input for 8 to 13 years, were examined for their ability to use binaural cues for binaural unmasking after bilateral implantation. Specifically, binaural masking level differences (BMLDs) were measured for a 125-Hz pure tone that was masked by a 50-Hz-wide narrowband noise centered at that frequency. These signals were processed in a manner that was reportedly similar to that of CIS speech processing strategies; Specifically, the signals were half-wave rectified, low-pass filtered, used to modulate a 1000 pps biphasic phase train presented synchronously to a single electrode in each ear in MP1+2 mode (custom software with the SPEAR2 experimental processor). A 3AFC task was used with a fixed SNR per block of 72 trials and feedback was provided. All subjects showed thresholds of <500 usec for detecting interaural time differences (ITDs), and all were found to have significantly better signal detection when the signal was presented out of phase at the two ears than when it was in phase. The average BMLD was large, at 29 dB. When the BMLD was measured with an interaural time delay of 600 us instead of phase inversion at one ear (a more "real world" condition), the BMLD was still fairly large, at 15 dB for the three subjects tested. A second experiment was performed in which additional processing of the stimuli was used to simulate compression used in CIs, and this resulted in a reduced but still statistically significant mean BMLD of 9 dB. Finally, more processing was used to remove more slowly varying interaural cues, and when fluctuations slower than 50 Hz were equated between the ears, the BMLD was reduced to a nonsignificant average of 1.3 dB. However, when only the fluctuations slower than 10 Hz were removed, the BMLD remained at 7.4 dB (larger but statistically nonsignificant). The authors concluded that the findings in this study contradict the notion that only waveform fine structure dominates binaural processing because the bilateral CI users were able to perform well even though they were only receiving information about the slowly varying envelope-based interaural differences. Thus, they argue it may be possible to improve real life performance with bilateral cochlear implants with multichannel processors using an envelope-based speech-processing strategy. They also note that these adult patients were able to perform well binaurally even though they had relatively long periods of auditory deprivation in one ear.

Neumann *et al.* (2007) compared the accuracy of sound-direction identification in the horizontal plane by 8 adult bilateral Nucleus 24 Contour CI users (simultaneously implanted; ACE speech coding strategy with a pulsatile stimulation rate of 900 Hz and loudness balancing between ears). Localization was measured by pink noise and with speech stimuli in a large classroom with average reverberation time of about 0.4 sec. A nine-loudspeaker array was used with azimuths from -90° to +90°, and performance was measured with each unilateral implant used alone and the bilateral condition. Results indicated that sound-direction identification accuracy was significantly better bilaterally than unilaterally, with a mean rms error of 29° for bilateral, 54° for left unilateral and 46.5° for right unilateral. There were similar performances for the noise or speech stimuli.

Recently, Smith & Delgutte (2007) used evoked potential measurements to try to match interaural electrode pairs with bilateral cochlear implants. These researchers proposed that it is important to match the cochlear positions of stimulation channels in each ear for most successful bilateral use. Using an animal (cat) model with 8-electrode arrays implanted in each cochlea, they developed and tested a noninvasive method for matching interaural electrodes based on electrically evoked auditory brainstem responses (EABRs). The binaural interaction component (BIC) of the EABRs was found to peak for interaural electrode pairs at the same relative cochlear position and to drop with increasing cochlear separation in either direction. They also used 16-channel recording probes and determined the spatial pattern of inferior colliculus (IC) activation for each stimulating electrode, and found that the interaural electrode pairings that produced the best aligned IC activation patterns were also those that yielded maximum BIC amplitude. The researchers proposed that EABR measurements may provide a method for assigning frequency-channel mappings in bilateral implant recipients such as pediatric patients, for whom psychophysical measures of pitch ranking or binaural fusion are not available.

Studies of or Including Pediatric Subjects

In addition to the adults tested, Litovsky *et al.* (2004) also evaluated localization abilities in three children who had worn bilateral implants for 3 months, after sequential implantation. Localization and right/left tasks were used with a computer game setup to maintain the children's attention to the task, and feedback given after each trial. Results indicated that localization was only slightly better under bilateral conditions than unilateral, with performance just above chance for bilateral listening and below chance for monaural. Right-left discrimination was also slightly better for bilateral listening in the pediatric subjects. Across both tasks, however, the differences were not statistically significant. The researchers suggested that perhaps a more prolonged period of adjustment and learning with the bilateral implants was needed than the 3 months these children experienced, in order to obtain maximum binaural advantage.

In 2006(b), Litovsky *et al.* extended their 2004 study to a larger pediatric group of bilateral CI users (13 children, aged 3 to 16) and also with comparison to a group of six children (aged 4 to 14) using bimodal devices (this study was previously described in the bimodal section). All but one of the children had severe prelingual hearing loss. Horizontal localization ability was measured using a Minimum Audible Angle (MAA) task. All but one of the bilaterally implanted children had Nucleus 24 CIs, but one child wore Clarion Platinum devices. Stimuli were male-voice spondees presented at a roving level of 4 dB around 60 dB SPL from a series of loudspeakers placed in a frontal arc. Children responded using a 2AFC procedure. Statistical analyses indicated that, as a whole, the children with bimodal devices didn’t do as well with bilateral input as did those children with bilateral CIs. For the children with bilateral CIs, about 70% discriminated right/left for source separations of < 20°, and, of those, 77% performed better when listening bilaterally than when using either cochlear implant alone (although a few subjects could perform the task when listening with one CI alone). MAA thresholds were better for the first CI implanted than for the second device implanted for nearly all of the subjects. Repeat testing was done for some subjects over a 2-year period and suggested that large improvements in performance occurred with increasing experience - particularly for the second cochlear implant received. Litovsky *et al* also noted that one subject had a 12-year history of having no binaural hearing, yet was able to localize after 23 months of using bilateral cochlear implants, suggesting that bilateral benefit may extend beyond children who are implanted immediately after the onset of deafness and that plasticity for developing binaural hearing may extend into middle to late childhood.

Bauer *et al.* (2006) retrospectively examined data from 4 children who had received bilateral CIs prior to the age of 2, two of whom had been sequentially implanted and two of whom had received simultaneous bilateral cochlear implants. Cortical evoked potentials were measured. For the 2 subjects who had received sequential implants, P1 latencies recorded from the first implanted ear were within normal limits for age after 3 to 6 months of implant use. In contrast, P1 latencies from the second implanted ear reached normal limits as early as 1 month after implant use. In the 2 subjects who had received simultaneous CIs, P1 latencies in both ears were within normal limits by 1 month poststimulation with the implants. These data thus suggest a high degree of plasticity of the central auditory pathways when early cochlear implantation is done.

Summary

Table 3 summarizes the key psychoacoustic and localization studies on bilateral implantees. Overall, there is the fairly consistent finding that adult bilateral cochlear implant patients have much better sensitivity to differences in level between the ears (ILDs) than to differences in timing (ITDs), with the possibility that individual performance differences may be impacted by age at which deafness occurred or duration of deafness. This is consistent with the speech tests which show a greater effect of head shadow (which is more dependent on ILDs) than of binaural squelch (which is also dependent on ITDs). There are also differences across stimulation rates, with sensitivity to fine-timing ITDs very poor in cochlear implant patients for rates beyond about a few hundred Hertz. Binaural summation and central masking effects have been found, again showing that fusion and use of information across bilateral implants does occur. Perhaps the most striking and practical results, however, are from the localization task studies. In those studies, data provide strong evidence that localization is significantly enhanced with two implants compared to with one implant, consistent with findings in the binaural amplification literature. In the Litovsky studies that accomplished localization testing in pediatric patients, the binaural advantage appeared to be not quite as strong or significant in children as shown in adults, but it was still present. The suggestion is that children may need more training or experience with bilateral implants to show maximal benefit.

Table 3. Overview of Studies On Bilateral Cochlear Implants: *Localization and Other Studies*

Study	*Sample Size (n), age, and gender of subjects*	*Other Patient Characteristics*	*Dependent Variables*	*Design/CI*	*Stimuli Parameters*	*Statistics Used*	*Findings*
			Studies On Adult Patients:				
van Hoesel *et al.*, 1993, 1995; van Hoesel & Clark, 1997	n = 2 adults (males)	Post-lingually deaf with etiologies of head trauma and Meniere's and fairly long duration of deafness prior to implantation	Lateralization studies with measurements of ILDs & ITDs, and evaluations of binaural summation and central masking	Bilateral processing case studies; Cochlear Nucleus devices	Electrical stimulation with biphasic current pulses on bipolar electrode pairs (See text and articles for more stimuli details across the various measurements)	None; individual results reported	Good sensitivity to ILDs, but large jnds for ITDs re: normal ears. Binaural summation present when electrical pulse trains applied to single electrode pairs across ears. Central masking effects found. Results indicated fusion of information across the two implants.
Lawson *et al.*, 1998	n = 1 female adult; (age not specified)	Postlingual deafness due to Listeraia rhomboencephalitis as a young adult; implants obtained 5 months apart	Lateralization as a function of ITD and ILD	Bilateral processing case study; Nucleus 22 implants controlled by a single experimental processor (CIS)	Loudness matched stimuli composed of 50-msec bursts of 80-usec/phase pulses at 480 pulses/sec.	N/A	Subject could identify ear receiving earlier onset for ITDs down to 150 usec for 3 pitch-matched electrode pairs. For similar simultaneous stimuli, subject could identify ear receiving louder stimuli for the smallest deviations from loudness-matched amplitudes available.
Mawman *et al.*, 2000	n = 1 (male, age 50)	Post-lingually deaf, progressive auto-immune over 5 years; Simultaneous bilateral implantation	Horizontal plane localization	Within subject: unilateral implant (left only) v. bilateral implants	500 and 3000 Hz NBNs at 70 dB SPL, 7 speaker azimuths	N/A	Higher percent correct scores for binaural than with left unilateral implant

van Hoesel *et al.*, 2002	n = 1 (male, age 51)	Post-lingually deaf, progressive bilateral hearing loss over 5 years probably due to auto-immune illness	Horizontal plane localization, direct measurements of jnds in ITDs	Within subject: unilateral implant v. bilateral implants; Nucleus with ESPrit processors programmed with SPEAK, and with a custom research processor	Array of 11 speakers frontal at 18° intervals; sequence of 170-msec pink-noise bursts with 10 msec rise/fall and 50 msec interstimulus interval at nominal 60 and 70 dB SPL. For jnds, 3AFC paradigm for 70.7% on psychometric function	N/A	Localization possible with bilateral implants but not unilateral Measured ITD jnds using simple pulse trains were about 400 usec for rates between 50 and 200 pps, which is better than their previous work with subjects having longer duration of deafness.
Tyler *et al.*, 2002b	n = 9 adults (gender not specified), ages 36-71; localization test performed on 7 of the subjects	Post-lingually deaf, varying etiologies and loss durations across ears	Left-right horizontal plane localization Given at 3 months postoperatively	Within subject: unilateral implant each ear v. bilateral implants; Nucleus CI24M with SPEAK (n = 6), ACE (n = 2), CIS (n = 1)	Pulses of speech noise (200 ms on/off); 100 presentations/condition. Loudspeakers placed at 45° to the left and right of midline; patient required to face forward and not move head	Binomial tests	All 7 subjects performed better binaurally than either monaural condition, and the difference was significant for 6 of the 7.
Gantz *et al.*, 2002	n = 10 (gender not specified), ages 36-75 (9 of these are same as Tyler *et al.*, 2002b)	Post-lingually deaf; varying etiologies and loss durations across ears	Left-right horizontal plane localization Given at 1 year postoperatively	Within subject: unilateral implant each ear v. bilateral implants; Nucleus CI24M with SPEAK (n = 6), ACE (n = 3), CIS (n = 1)	Pulses of speech noise (200 ms on/off); 100 presentations/condition. speakers placed at 45° to the left and right of midline	Statistical test used was not reported but presumably binomial tests	All 10 subjects performed significantly better in binaural condition than in either unilateral condition
Long *et al.*, 2003	n = 1 adult (female); age 72	First hearing loss noticed at age 25 progressed to profound bilateral deafness at age 44; First implant at 59, other ear at 70	Lateralization testing with bilateral pairs of electrodes to determine ITD and ILD sensitivity	Bilateral processing case study; 1st implant = 6-electrode Ineraid; 2nd = 8-electrode pair Clarion	Fixed-amplitude biphasic current pulses (76.9-usec/phase, 300-ms train duration) with 100 pps repetition rate	N/A	Despite poor implant performance & long duration deafness, subject could fuse binaural signals effectively.

van Hoesel & Tyler, 2003	n = 5 adults, (gender not specified) ages 36-71	Post-lingually deafened with etiologies including Meniere's & autoimmune	Localization testing and Lateralization tasks to examine ILD and ITD sensitivity	Within subject: unilateral implant each ear v. bilateral implants; Nucleus CI-24M, with SPEAR to provide binaural cues; loudness adjusted for binaural summation.	8-speaker array frontal spanning 108° arc, and pink noise bursts nominally at 65 dB SPL	Analysis of Variance with Tukey Post-Hoc tests	Bilateral performance on localization better than monaural better ear. Lateralization studies showed good sensitivity to ILDs. Effects of ITDs weaker than ILDs, with ILD improvement depending on low-rate information below a few hundred Hz.
Laback *et al.*, 2004	n = 2 adults (aged 18 & 56) n = 2 normal hearing controls listening through earphones	Younger subject implanted bilaterally (sequentially) at 14 after < 6 months deafness from meningitis; Older subject implanted at age 48 & 54 after 21/25 years deafness due to head trauma/unknown etiology	Lateralization experiment to measure jnds for ILDs and envelope ITDs with direct delivery of electrical stimuli to bilateral electrode pairs	Bilateral processing case study; Med-El implants with CIS strategy	Adaptive 2AFC method with varying stimuli including click trains at different rep rates, a speech fragment, and noise bursts.	AOV and Tukey post-hoc tests	ILD jnds showed high sensitivity to broadband stimuli, with values close to normal ears; Pitch-matched electrode pairs showed lower ILD jnds than mismatched; ITD jnds were higher than normal & more variable, and were lower for click trains than broadband stimuli.
Nopp *et al.*, 2004	n = 20 adults (10 male, 10 female; aged 17 to 87)	All implanted at adolescence or later; varying duration of deafness, previous hearing aid usage, & etiologies; 19 were postlingually deafened	Frontal plane localization task	Within subject: unilateral implant each ear v. bilateral implants; Med-El COMBI 40/40+ implants	9-speaker array and speech-shaped noise bursts at randomized levels	Friedman non-parametric repeated-measures AOV & Tukey post-hoc tests	Substantial and significant binaural benefit for all but 2 subjects; The two not showing benefit were deafened at the earliest age (infancy & prior to age 4) and had long durations of deafness.

Seeber *et al.*, 2004	n = 11 adults bimodal users (aged 20-79) vs. n = 4 adult bilateral CI users (aged 23-69)	Implant use had been a minimum of 6 months	Localization and sidedness discrimination	Within subject: unilateral implant each ear v. bilateral implants; Most were Med-El, but one had Nucleus CI-24M	Novel method utilizing laser pointer for response	Regression and correlation analyses; Wilcoxin tests	Varying performance across patients, but all bilateral implant users showed some localization ability and one performed close to a normal listener. All but 4 of the bimodal subjects were also able to localize. Some patients in both groups could also localize with only a unilateral implant.
van Hoesel, 2004	n = 2 adults	Details not provided in this article	Examination of ITD sensitivity, binaural loudness summation, binaural masking level differences (BMLDs), & localization	Bilateral processing case study; Nucleus CI-24M implants with SPEAR and PDT strategy	See article text for details of stimuli and procedures across tasks	N/A	ITD most sensitive with pitch-matched electrode pairs; binaural loudness summation to broadband stimuli is similar to narrow-band; small BMLDs are measurable but small; speaker locations & signal characteristics impact localization ability
Laszig *et al.*, 2004	n = 37 adults at multiple sites in study, aged 18-67, but only 16 completed localization task at one site	postlingually deafened severe to profound hearing loss native-German speakers 22 subjects simultaneously implanted, and 15 subjects sequentially implanted	Horizontal plane localization with 12 speaker locations 30° apart Stimuli = shortened sentences from the Hochmair-Schulz-Moser sentences	Within subject: unilateral implant each ear vs. bilateral implants CIs = Nucleus 24 with either SPrint of ESPrit 3G speech processors; Most used ACE strategy	Presentation levels between 55 and 70 dB SPL individually selected for each subject.	Student paired t-tests	Bilateral stimulation produced significant improvements in localization ability over either monaural CI alone. rms degrees of error reduced 38° for bilateral compared to unilateral listening.

Senn *et al.*, 2005	n = 2 teen girls & 3 adult males with bilateral CIs; compared to 5 nearly-age-matched normal hearing controls	teens were prelingually deafened; adults postlingually deafened	Minimum audible angle (MAA) measurements of horizontal plane localization Just noticeable differences (jnds) for interaural level and time differences (2AFC adaptive procedure)	Within subject: unilateral implant each ear vs. bilateral implants. CIs = Med-El C40/40+	For localization, white noise bursts For jnds, white noise bursts (1000 ms duration), click trains (800 ms duration, 40 us clicks, 50 Hz), and noise bursts with either only the envelope or only the fine structure shifted in time.	Nonparametric Wald analysis of variance and Wilcoxin matched-pairs tests (one-tailed)	Bilateral CI patients had good spatial discrimination frontally and behind the head (near-normal values), but poorer performance from the sides. jnds for interaural intensity were close to normal, but were poorer for time cues. Envelope onset/offset cues were perceived by the patients, but not fine structure time differences.
Schoen *et al.*, 2005	n = 12 subjects - n = 11 tested on localization, n = 4 for ILD tests, n = 7 for ITD tests.	at least 3 months experience with bilateral CIs Postlingually deaf and sequentially implanted	Localization testing; ILD sensitivity measured by doing localization tests with loudness of the 2 processors unbalanced to various degrees; ITD sensitivity measured via lateralization as a function of the time difference between pulses directed to one of the speech processor microphones	Anechoic chamber testing CIs = Med-El Combi 40/40+ with CIS or CIS+ strategy	Localization: CCITT noise (500 ms, original and HRTF-filtered, 70/75/80 db SPL), 7 loudspeakers between +/- 90° azimuth.	Pearson correlation coefficients to determine localization ability & examination of response consistency; repeated measures AOVs	All subjects could localize well. Unbalanced loudness of the speech processors produced an azimuthal bias toward the processor with the louder setting. 6 of 7 subjects showed a significant sensitivity to ITDs with a mean time difference of 1200 us required for lateralization.

Verschuur *et al.*, 2005	n = 20 adults tested	Sequential implantation. All subjects had at least 9 months experience with their bilateral CIs; Duration of deafness ≤ 15 years in either ear; minimal benefit from hearing aid in 2nd implanted ear	Horizontal plane localization with 5 stimuli: speech, tones, noise, transients, and reverberant speech; 11 loudspeaker array in a 180° horizontal arc	Within-subject: unilateral versus bilateral; also with dual-microphones (sound combined to the Sprint processor) CIs = Nucleus 24M or 24K (with either SPEAK or ACE, but same strategy used both ears and loudness balanced)	Stimuli presented at 60 dB SPL except pink noise also given at 70 dB SPL to activate AGC. Roving over +/- 5 dB range.	Calculation of mean localization error; repeated measures AOV with post-hoc t-tests.	Bilateral performance significantly better than unilateral for all subjects across stimulus types and sound sources. Differences in performance across stimulus types were small. Performance poorer than normal controls or hearing aid users from previous studies.
Long *et al.*, 2006	n = 4 adults	Sequential implantation: All had worn a unilateral implant only for 8 to 13 years before receiving bilateral CIs	Examination of ITD sensitivity and BMLDs	Bilateral processing study; Nucleus CI 24s with SPEAR3 experimental processor with custom software	Narrowband noise masker with tonal stimuli at 125 Hz processed to simulate CIS strategy, compression, and then to reduce slowly varying fluctuations. See article text for more details of stimuli processing and procedures across the experiments	Psychometric functions for detection of signal; comparison across conditions but statistic used not reported (presumably paired t-tests)	Large significant BMLDs obtained; slightly less with time delay compared to phase inversion. Advantage occurred even though subjects only received information about the slowly varying sound envelope, and even with having had significant auditory deprivation of 2nd implanted ear
Neuman *et al.*, 2007	N = 8 adults	Simultaneous implantation; loudness balanced between ears	Examination of horizontal plane localization in large semi-reverberant classroom	Within-subject: unilateral versus bilateral performance; CIs: Nucleus 24 Contour with ACE	9-loudspeaker array; 2 stimuli: speech (single sentence by male voice) and pink noise bursts (2 500 ms; 50 ms rise/fall, 300 ms ISI)	Repeated-measures AOV with Tukey post-hoc tests	Bilateral performance significantly better than unilateral either ear; no difference between the stimulus types

Smith & Delgutte, 2007	Animal model (cats);	Animals deafened via ototoxic drug prior to cochlear implantation bilaterally with 8-channel array	Electrically evoked ABRs (EABRs) evaluated; Also used 16 channel recording probes to measure neural activity along the inferior colliculus				Maximizing binaural interaction component of the EABR proposed to be useful in assigning frequency channel mappings for pediatric patients
<u>*Studies On or Including Pediatric Patients:*</u>							
Litovsky *et al.*, 2004	n = 17 adults (8 male, 9 female) ages; only 14 adults had speech tests Also, <u>*Pediatric:*</u> n = 3; age 8, 8, and 12	14 were postlingually deaf, 3 deaf in infancy or congenitally; All adults received both implants at the same time Children were prelingually deafened, and had sequential surgeries 3-8 yrs apart.	Horizontal plane localization task For children, localization and right/left discrimination tasks	Within subject: unilateral implant each ear v. bilateral implants; Nucleus CI24R (CS), except one child who had a CI22 in one ear.	8 matched speakers at 20° intervals, 4 bursts of 170-msec pink noise with 10 msec rise/fall times and 50-msec interstimulus interval (ISI) at a nominal 65 dB; 20 trials per speaker In children, 15 speakers at 10° intervals, 10 bursts of 25-msec pink noise with 5 msec rise/fall and 250 msec ISI at a nominal 60 dB; 10 trials per speaker	Analysis of variance and post-hoc t-tests on adult data	Significant binaural advantage for localization; strongest predictor of performance was preoperative bilateral hearing aid use For children, weaker bilateral advantage. Researchers suggested may need more than the 3 months bilateral implant use to show maximum benefit.

Litovsky *et al.*, 2006b	n = 13 with bilateral cochlear implants, aged 3 to 16. n = 6 with bimodal devices, aged 4 to 14.	Sequential bilateral implantation; prelingual deafness Extends 2004 study to a larger n (but also includes the same 3 Ss from that study)	Horizontal plane localization acuity (left/right) measured with minimum audible angle (MAA)	Within subject: bilateral CIs or bimodal, versus unilateral implant Bilateral CIs = Nucleus 24 for 12 children, Clarion Platinum for 1 child; Bimodal = 4 Nucleus, 1 Clarion, 1 Med-El	Stimuli were spondees with level roved +_/-4 around 60 dB SPL from an arc of loudspeakers; 2AFC procedure	repeated measures AOV with post-hoc Scheffe tests	7 of the 9 children (77% of 13) with bilateral CIs who could discriminate left/right for source separations ≤ 20° did better bilateral than monaural, but there was individual variability. MAAs were generally better for the 1st CI implanted than the 2nd. Repeated testing over 2 years of some children showed improvement with experience. Children with bimodal devices didn't do as well with bilateral input as those with bilateral CIs, even though they performed as well with the unilateral implant alone.
Bauer *et al.*, 2006	n = 4 bilateral CI recipients	2 = Sequential implants; 2 = Simultaneous; all CIs implanted at less than 2 years old	P1 latency of the Cortical Evoked Potential (electrophysiological study)	Between group comparison	Synthesized speech stimulus /ba/ presented via loudspeaker to side of implant ear at 45°	Retrospective case study descriptions	Patients simultaneously implanted have much shorter time course to P1 latency maturation than those implanted sequentially; For sequential, 2nd ear implanted matures faster than first ear

Subjective and Questionnaire Data

There have been only a few studies that have included or focused on subjective data in evaluation of bilateral cochlear implant recipients. Some of these have been merely observational notes by the researchers or anecdotal comments by the subjects, with some limited questionnaire data collected to date.

Adult Population

Green *et al.* (1992) did not formally evaluate subjective comments, but noted in their report that patients stated that using two devices, rather than one, offered more "volume" with greater "wholeness" of sounds. All but one of the 6 patients reported that they subjectively felt their speech understanding was improved with binaural listening compared to listening with only one implant.

In the Mawman *et al.* (2000) case report, the patient with bilateral cochlear implants was given a 20-item questionnaire to assess expectations from the cochlear implants. Details of the questionnaire are lacking in the publication, but responses reportedly indicated that this patient's expectations from the implants were met or exceeded in all cases. The patient also said his quality of life was improved and he chose to consistently wear both cochlear implants daily.

Gantz *et al.* (2002) noted that during programming of the processors at the initial fitting of the 10 subjects who simultaneously were bilaterally implanted, all subjects immediately commented on the improved quality of sound with the addition of the second ear. Most patients noted a qualitative difference between ears with one ear sounding more "hollow" or "mechanical" than the other, yet all still reported that they preferred bilateral over listening with either side alone.

In the 2005 Ramsden *et al.* study, it was noted that 27 of the 30 adult sequentially implanted bilateral CI users preferred the sound quality of bilateral implants compared with unilateral CI use, and that all 27 continued to use the bilateral implants daily. One subject dropped from the study at 1 week post-implantation because he believed he performed more poorly with both implants in use so chose to become a unilateral user again, and one subject had tinnitus problems with the second implant for a period of time but eventually became a successful bilateral user.

In the Senn *et al.* (2005) study previously described, limited subjective questionnaire data were reported. Subjects (2 prelingually impaired teen girls, 3 postlingually impaired adult males) were asked how much benefit they received from the second implant after bilateral sequential surgeries in terms of speech intelligibility in quiet, in noise, and localization ability. An analog visual scale from 0 to 10 was used for responses, and all responses ranged from 7 to 10 (10 indicating the most positive response for bilateral versus unilateral implant use).

In 2006, the first study intended to directly investigate perceived benefit from bilateral cochlear implants was done by Summerfield *et al.* These researchers recruited 28 postlingually deafened adults from seven British hospitals who had worn unilateral Nucleus 24 implants for 1 to 6 years and were seeking a contralateral ear implant to improve performance (all were successful unilateral users). Half were randomly assigned to receive a second implant immediately, while the other half were required to wait 12 months before receiving it. Two subjects in each group didn't complete the study, so that there was data for a total of 12 subjects in each group. Questionnaires used included three condition-specific measures from the SSQ Questionnaire, and also the Glasgow Health Status Inventory, The Health Utilities Index (HUI) Mark III, the Overall Quality of Life (visual-analogue scale), and the EuroQol EQ-5D. Results indicated self-reported improved abilities for bilateral implants compared to unilateral in spatial hearing, quality of hearing, and hearing for speech. Results were overall nonsignificant for quality of life measures. Multivariate analyses showed positive changes in quality of life from improved hearing but this was offset by negative changes associated with worsening tinnitus over time with bilateral implants.

In the previously described Litovsky *et al.* (2006c) multicenter study of 37 simultaneously implanted adult users of Nucleus 24 CIs, APHAB questionnaire data were also collected on 30 of the patients after a 3-week period during which the bilateral CI users only wore a unilateral implant on their best or selected ear. Then the APHAB data were re-collected after a period of using the bilateral implants again. The results indicated that the bilateral users perceived their performance with the bilateral implants as significantly better than with a unilateral implant on the best-performing ear on the Ease of Communication (EC), Background Noise (BN), and

Reverberation (RV) subscales of the APHAB. There was no significant difference on the Aversiveness of Sounds (AV) subscale. The mean results are shown in Figure 13. It was also anecdotally noted that many of the subjects were quite reluctant to be without their second implant during the “deprivation” period of three weeks, because they believed they performed so much better with both implants.

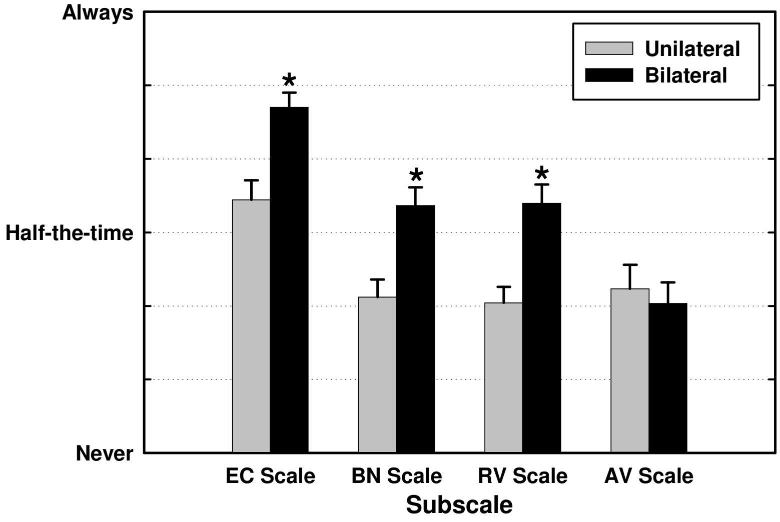

Figure 13.
Mean (+/- 1 standard error) scores from the 4 subscales of the APHAB questionnaire for 30 subjects wearing only their best unilateral cochlear implant versus wearing bilateral cochlear implants. A higher value indicates better perceived performance. (From Litovsky *et al.*, 2006c - Fig. 9).

Studies of or Including Pediatric Subjects

The child in the Vermiere *et al.* (2002) study was noted anecdotally by the mother and school teacher to have a “better sense of rhythm” with bilateral implants, and that she didn’t seem to depend on lip-reading as much as before when she was only unilaterally implanted. While with a unilateral implant the child had to look directly at the person talking in order to understand them, after bilateral implantation she reportedly seemed to respond appropriately even when the talker stood behind her.

Helms *et al.* (2004) reported that they had bilaterally implanted 75 patients at their Wuerzburg, Germany clinic who were under the age of 16. They gave parents of these bilaterally implanted children a scaling questionnaire (0 = no effect, to 50 = optimal effect) describing the behavior of the child in various everyday life situations with one implant compared to how he/she subsequently did with two implants. Although no further details of the questionnaire were given, these researchers reported that statistical analysis (test not reported) showed significant perceived improvement with two implants compared to one. They also noted that the children with bilateral implants were all mainstreamed in school and doing well. They stated that these children are able to listen longer and that listening was less stressful to them than when they had only one implant.

Observations and qualitative behavior descriptions were also given by Kuhn-Inacker *et al.* (2004) on 39 of the Wuerzburg children. The researchers reported that these observations clearly showed that bilateral cochlear implants improve communication, especially in more complex listening situations. Improvements were observed in speech understanding (for instance, they reacted faster to their names in groups and appeared to lip-read less in conversation), directional hearing and speech articulation, ability to relax while conversing, and enjoyment of music. The authors noted, however, that an intensive rehabilitation program was needed for optimal benefit with the second processor and that it should be fitted with the first processor turned on. Finally, they noted that they believed the rehabilitation program should include appropriate expectation counseling for older children.

Summary

Table 4 on the next page summarizes the studies on bilateral implantees that have examined questionnaire or other subjective data, or reported qualitative comments by the bilateral implant users. Across the studies, subjective reports are favorable. In addition, continued binaural use in the real world by a vast majority of patients in recent studies indicates that any added cosmetic and practical hindrance is overcome by the patient’s perception that they are receiving binaural benefit in their ability to function in the real world. Overall, however, subjective and questionnaire data are still relatively sparse in the published bilateral cochlear implant literature to date.

Table 4. Overview of Studies On Bilateral Cochlear Implants: *Subjective Data*

Study	*Sample Size (n), age, and gender of subjects*	*Other Patient Characteristics*	*Dependent Variables*	*Design*	*Stimuli Parameters*	*Statistics Used*	*Findings*
Studies On Adult Patients:							
Green *et al.*, 1992	n = 6 (4 male, 2 female); aged 57-74	varying etiology & duration of deafness (including Meniere's, otosclerosis, chronic otitis media & meningitis)	Qualitative comments by patients during the study	Within-subject unilateral implant each ear v. bilateral implants; 3M/House and Nucleus in various combinations	N/.A	None; only individual results presented	Patients stated that two devices offered more "volume" with greater "wholeness" to sounds than one device. All but one patient felt their speech understanding was better with two devices.
Mawman *et al.*, 2000	n = 1 (male, age 50)	post-lingually deaf, progressive auto-immune over 5 years; Simultaneous bilateral implantation	Questionnaire regarding how the implants lived up to the patient's expectations	Within subject: unilateral implant v. bilateral implants	20 questions from a scale of +100% (greatly exceeded expectations) to -100% (fallen a long way short of expectation)	N/A	All scores were between expectations having been met or exceeded. Patient also reports improvement in quality of life and wears both devices consistently.
Gantz *et al.*, 2002	n = 10 (gender not specified), ages 35-75	post-lingually deaf; varying etiologies and loss durations across ears	Qualitative comments by patients during programming	Within subject: unilateral implant each ear v. bilateral implants; Nucleus CI24M with SPEAK (n = 6), ACE (n = 3), CIS (n = 1)	N/A	N/A	All 10 patients noted improved quality of sound with the addition of the 2nd ear during programming. Most patients found one ear to have poorer quality than the other, but there was still a consistent preference for bilateral.

Ramsden *et al.*, 2005	n = 30 adults, (aged 29 to 82 years old);	Sequential surgeries after 1 to 7 years unilateral CI use; Duration of deafness ≤ 15 years in both ears	Anecdotal report of preference	Within subject: unilateral implants vs. bilateral implants Cochlear Nucleus CI24M or CI24R(ST);	N/A	N/A	In this study that evaluated speech perception, it was noted that 27 of the 30 subjects preferred the sound quality of wearing bilateral CIs to wearing a unilateral CI, and continued to use them both daily.
Senn *et al.*, 2005	n = 2 teenage girls, prelingually deafened, and 3 adult males, postlingually deafened	Sequentially implanted	Limited subjective questionnaire data' patients responded on a visual analog scale	Within subject: unilateral vs. bilateral Med-El C40/40+ CIs	N/A	N/A	All patients reported perceiving substantial advantages for bilateral CI use versus unilateral CI use for speech intelligibility in quiet and noise, and for localization.
Summerfield *et al.*, 2006	n = 28 postlingual adults who were unilateral CI users requesting bilateral implantation (24 subjects completed the study; 12 in each group). Aged 29-82.	1 to 6 years unilateral CI use.	Questionnaire self-report data: 1. three condition-specific measures from the SSQ Questionnaire 2. Glasgow Health Status Inventory, 3. Health Utilities Index (HUI) Mark III, 4. Overall Quality of Life (visual-analogue scale), 5. EuroQol EQ-5D.	12 subjects in two groups: 1) those receiving requested contralateral/second implant right away; 2) those delayed by 12 months to receive sequential surgery. Measurements made across time compared across groups and to previous unilateral implant user data CIs = Nucleus CI24 with SPEAK strategy	N/A	Multiple approaches: descriptive, confidence intervals, regression lines, group comparisons, t-tests, multivariate analyses	Perceived improved abilities for bilateral implants compared to unilateral in spatial hearing, quality of hearing, and hearing for speech. But overall nonsignificant differences for quality of life measures. Multivariate analyses showed positive changes in quality of life from improved hearing were offset by negative changes associated with worsening tinnitus over time for some patients.

Litovsky *et al.*, 2006c	n = 30 of 37 adults in multicenter study with complete subjective data	Simultaneously implanted bilateral CI users	APHAB Questionnaire given after 3-week deprivation period in which the better ear (or selected ear if equal) was worn; Then given again after another period of bilateral CI use	Within-subject comparison of bilateral use versus unilateral CI use CIs = Nucleus 24	Bilateral CIs result “anchored” to unilateral CI result by providing subject with their previous answers when questionnaire given again.	nonparametric Wilcoxin signed-ranks test for matched pairs (2 tailed)	Results indicated significantly better perceived performance on the EC, BN, and RV subscales of the APHAB (no difference on the AV subscale).
Studies On or Including Pediatric Patients:							
Vermiere *et al.*, 2002	n = 1 female, age 4.8 at time of testing	Etiology of deafness: congenital, hyperbilirubinemia (& possible auditory neuropathy); 2.5 at 1st implant & 4.4 at 2nd implant	Anecdotal report from mother and teacher	Within subject: unilateral implant each ear v. bilateral implants; Nucleus CI24 1st ear and Nucleus 24-CONTOUR 2nd ear, both with SPEAK	N/A	N/A	Bilateral implants provided a better sense of rhythm, and less dependence on speech-reading to assist auditory input, relative to previous performance with unilateral implant
Helms *et al.*, 2004	n = 75 German patients aged 16 or younger at implantation	Prelingually deaf children	Anecdotal reports, and a “standardized audio-psychologic test” in which parents described the behavior of their child with one versus two implants	Within subject: unilateral implant each ear v. bilateral implants; Med-El implants	Questionnaire scaled between 0 (no effect) and 50 (optimal effect) but no other details supplied	Statistical analysis of the questionnaire was reportedly done, but no details given.	The progress of children implanted bilaterally was faster with two implants than one; a highly significant perceived binaural benefit found with the questionnaire
Kuhn-Inacker *et al.*, 2004	n = 36 of the German children	Prelingually deaf children	Observations of the children’s communication behaviors	Within subject: unilateral implant each ear v. bilateral implants; Med-El implants	N/A	None	Bilateral cochlear implants improved speech understanding, directional hearing and speech articulation, ability to relax while conversing, and enjoyment of music.

Other Related Topics

Surgical and Programming Considerations

Some of the published literature has addressed surgical and programming issues when fitting a patient with bilateral implants. For example, Gantz *et al.* (2003), who performed simultaneous bilateral implantations on 10 subjects noted that bilateral implantation presents certain challenges from a surgical perspective. These include the fact that use of monopolar cautery must be discontinued once an implant is in place, monitoring of the facial nerve must be done bilaterally, and draping and preparation of surgical sites must be done in an expeditious manner. Gantz *et al.* offered suggestions for revised surgical steps in order to accommodate the use of monopolar cautery to assist in creation of the skin flaps and achieving hemostasis (page 172), and commented that simultaneous bilateral implantation adds approximately 1.5 hours to the surgery but that it can still be performed as an outpatient procedure (As reported in Das and Buchman, 2005, their average operating time for simultaneous bilateral implantation is about 4 hours and 16 minutes). All the patients in that study experienced no unusual intraoperative challenges and had a routine postoperative course of recovery.

The first bilateral patient in the Gantz *et al.* (2003) study was programmed using pitch-matching across channels with dual computers and interfaces, but the resulting MAPs for this patient did not produce higher scores than those obtained with conventional procedures applied to each ear. Subsequently, these researchers used monaural programming methods for each device separately, but with the addition of time afterward for adjustment for comfort and balance between the implants. In the 10 subjects in that study, C-levels were adjusted in some patients to account for loudness summation. Finally, Gantz *et al.* commented that the procedure did add some significant time to the programming session, but that an advantage was the ability to give verbal instructions to the patient in one ear while programming the other.

New Tests for Measurement of Bilateral Benefit

Tyler *et al.* (2006) report on one unilateral cochlear implant user who was able to perform on a localization task as well as a typical bilateral user. They commented that the reason for this ‘star’ patient’s good performance may be that he is using spectral changes from head movements, or knowledge that louder sounds are more likely from the implant side and sounds with less high frequency energy are likely from the non-implant side. Using previously collected data on 30 subjects, these researchers also calculated the difference between bilateral performance and unilateral performance in the ear with the better SNR for each subject as an indication of binaural squelch for CUNY sentences. For collection of that data, speech was presented from the front and noise from +/- 90°. They compared this to localization data collected on the same subjects using a Spearman test and found no significant correlation ($r = .25$; $p > .05$). In their discussion, these authors argue that new research approaches may be needed to capture some of the more challenging aspects of bilateral listening. Specifically, they propose several possible new measures.

The first new measure suggested by Tyler *et al.* (2006) combines localization and recognition by cueing the location of talkers. Using an 8-loudspeaker array, the listener receives an auditory cue from one loudspeaker as to where the voice is coming from, and then must re-orient to that speaker to better hear the target spondee word against babble that comes from a spatially separate speaker. The spondee word recognition task uses an adaptive level approach. Thus, listeners more accurate in localizing the source will better optimize the SNR for the target. Other new measures suggested by Tyler *et al.* are a localization testing with lateral movement perception for speech babble moving through an arc of speakers, and an adaptive spondee female speech word recognition test with multiple “jammers” (single male and female voices located at either side). Finally, they suggest consideration of a localization task allowing head movement, so that bilateral CI patients may then show even more of an advantage over unilateral CI users.

The Binaural Digisonic Cochlear Implant

Truy *et al.* (2002) pointed to economic concerns regarding bilateral implantation with two devices (where unilateral implantation is rationed) and thus worked with the MXM Company (Vallauris, France) to develop a unique cochlear implant called The Binaural Digisonic. This multichannel implant is able to stimulate both cochleae with a single external transmitter/processor. The external device transmits the processed signal via electromagnetic coupling to a single receptor/stimulator implanted under the skin behind the ear, which is in turn connected to two electrode arrays in the homolateral (same side) cochlea and the contralateral (other side) cochlea via the vertex. The array on one side has 8 active electrodes and the array on the other side has 7 active electrodes and the researchers argue that by increasing the geometric distance between electrodes, there is less chance of electrical interaction between activated electrodes reducing frequency discrimination[11]. It was reported that this device is intended to be introduced commercially after a multicenter study is completed.

The surgical technique for the Binaural Digisonic is described in this team's 2002 publication including details of how instruments used for endoscopic face-lifting procedures are utilized to connect the implanted receptor/stimulator to the contralateral cochlea. In addition, speech recognition for disyllabic words (French standardized Lafon's test) presented auditory-only in both unilateral and binaural activation conditions were presented for two patients implanted. These preliminary findings are shown below:

Speech Discrimination Scores in Patients Wearing the Binaural Digisonic cochlear implant after 12 months use: From Truy *et al.*, 2002

	Speech score right ear	*Speech score left ear*	*Speech score both ears*
Patient *1 (Duration of Deafness R = 40 yrs, L = 7 years)*	7%	18%	19%
Patient 2 (Duration of Deafness R = 25 years, L = 15 years)	5%	39%	41%

Truy *et al.* (2002) claim that these results are at the bottom end of other published data on the Digisonic presented by Furminieux *et al.* (2001), but since that article was published only in French, it was not possible to report those findings for this review. They argue that one reason these results are poor may be because both of these patients had longer durations of deafness than previous reported subjects. Further they argued that the device they used did not have enough active electrodes per ear, and claimed that a new device that provides 12 electrodes per ear would next be evaluated. In any case, these results appear fairly dismal since binaural performance is no better than the better ear unilateral performance, and the speech scores are very low overall. No more recent publications about this device were found for this review.

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[11] Recall that this idea was first introduced by Lawson *et al.* (1998) with an experimental unit that stimulated two Nucleus electrode arrays in one case-study patient.

Thai-Van *et al.* (2002) reported electrophysiological studies using electrically-evoked auditory brainstem responses (EABRs) on two patients (52 and 35 year old males) who had been implanted with the MXM Binaural Digisonic Convex system and thus received simultaneous bilateral stimulation. In both of the patients, duration of deafness differed across the two ears; Specifically, the first patient had been deafened in one ear at age 12 and the other at age 45 from progressive hearing loss, and the second patient had lost his hearing on one side at age 10 due to meningitis and on the other at age 20 with unknown etiology several years post-cholesteatoma surgery. Results obtained after 6 months implant use indicated that the EABRs from the ears with longer deafness duration showed delays in wave V latency relative to the other ear, and in one patient a lack of a replicable wave III as well, suggesting that neural responsivity was impacted by years of deafness. The authors argued that electrophysiological studies might be useful in determining appropriate candidates for bilateral cochlear implantation.

DISCUSSION AND CONCLUSIONS

As noted by Tyler *et al.* (2003), there are several problems with trying to give more normal binaural hearing with cochlear implants. The first problem is that precise timing of intra-aural electrical stimulation is not yet possible with two independently functioning cochlear implants. This doesn't mean that bilateral coordination of pulsed signals is impossible, but it does mean that delay cues on a pulse-by-pulse basis may need to be retained with some form of new signal processing if patients are to receive full benefit. A second problem is that, because binaural advantages depend on relative level information between ears, any cochlear implant processing system that modifies intensities and timing (such as AGC) might distort the cues. For example, when one processor goes into compression for a very loud sound that is coming closer, the brain might inadvertently perceive the drop in loudness as the sound moving away. A third problem is that since CI patients have substantial numbers of missing hair cells and nerve fibers bilaterally, they may have developed abnormal binaural brain maps. Further, the pattern or duration of loss may differ vastly on each side. Litovsky *et al.* (2006) also note limitations in current clinical fitting approaches, and to the fact that electrode placements and thus the number of electrodes distributed along the cochlea can vary dramatically across users and place constraints on how well the information in binaural fitting strategies can be matched across ears.

Tyler *et al.* (2003) also note that learning may influence the ability to use binaural cues, so study designs must consider this possibility. There are two potential problems here: 1) a patient implanted simultaneously with two implants may need to experience for a period of time listening through only one device in order to make the unilateral comparison fair, and 2) there may be a need to acclimatize to bilateral cochlear implants after sequential implantation, in order to ensure maximum binaural benefit and make the bilateral comparison fair. van Hoesel (2004) notes the variability across published studies in terms of the amount of benefit derived from binaural processing with implants, and states that this is perhaps due to experimental confounds related to listening experience, bias, or loudness effects when comparing bilateral to unilateral inputs. Nevertheless, Tyler *et al.* (2003) in their review of the literature generally concluded that there are benefits to bilateral implantation, as long as the costs and risks are considered, and indeed most authors/researchers have been uniformly positive about the binaural benefits seen in studies to date.

In a 2004 review, van Hoesel notes that most of the research seems to suggest that the binaural benefit of using two cochlear implants is primarily from the effects of level variations at the two ears due to overcoming the head shadow, while benefit from interaural time differences (ITDs) appears to be smaller than in normal hearing listeners. He suggests, however, that even if signal processing schemes were developed to improve the contribution of timing information at the two ears, CI patients might well not be able to hear or utilize these cues anyway due to poor sensitivity to small ITDs. Further, Wilson *et al.* (2003) in their review of the literature and report on some studies done at the Research Triangle Institute noted that results to date suggest that strict coordination of the carrier pulses across the two sides may not be either important or necessary; i.e. lateralization is not impaired by different carrier rates on the two sides. What these researchers believe appears to be important is preservation of the relative timing and amplitudes of the envelopes across the two sides, so long as carrier rates are relatively high.

In conclusion, despite some caveats and individual performance variability, the overall evidence is very compelling that, as has been demonstrated in the hearing aid field, adult patients with bilateral deafness do best with bilateral rather than unilateral cochlear implants. This is true even when there is a difference in duration of deafness and differing etiologies between ears. Given the still relatively small number of bilateral cochlear implant recipients, there are a surprising number of publications available on the topic to date and a notable increase in recent publications and numbers of subjects included in some recent studies. Benefit has been seen across Cochlear, Advanced Bionics, and Med-El cochlear implants and sometimes even when a patient has two very different types of implants in each ear.

There is a great deal of discussion in the literature regarding whether the benefit relates to some form of integration by the brain in the form of binaural squelch or binaural redundancy effect, or is merely due to the physical advantage of overcoming the head shadow - - Frankly, in some sense this is only an academic argument in terms of patient benefit, since it won't matter to the user the source of the advantage, but only that his/her performance in real world environments (where the head shadow effect is significant) is better with two implants than with one. That said, there is increasing evidence that true binaural signal processing can also be seen in a number of patients, albeit sometimes only as a small effect. Some factors that may predict binaural processing benefit are very long durations of deafness or age at which deafened, or previous bilateral hearing aid use, but the degree of importance of these is not yet clear and more research is needed to predict which patients will receive the most benefit from bilateral implantation. Given the strength and growing depth of the data and the fact that nearly all patients do benefit in one manner or another, it would be difficult to argue that bilateral implants should *not* be supplied to those adults who desire them and who meet implant criteria in both ears.

One issue that has still not been adequately addressed is whether the bilateral benefit obtained from bimodal device use (the less costly and non-surgical alternative) is good enough for patients with residual contralateral ear hearing sensitivity who obtain some hearing aid benefit, or whether bilateral cochlear implants would actually provide a significantly greater performance advantage for these patients. Seeber *et al.* (2004) did a between group analysis of bimodal versus bilateral CI users, but subjects were not matched and thus the comparison was not a particularly strong one. Litovsky *et al.* (2006a) also did a comparison between groups of children with bimodal and bilateral CI use, and concluded that bilateral CI users do somewhat better on localization and speech intelligibility, but these researchers also admitted that there were some differences between the two subject groups that limited the strength of that comparison as well. A within-subject repeated-measures study could conceivably be designed in which hearing aid use on the contralateral ear to an implant was evaluated in the binaural condition prior to sequential 2nd implant surgery, and then post-surgical measurement was made of performance with the two implants after a period of acclimatization. The problem with this approach of course is that it requires subsequent implantation on the hearing aid ear, and thus would more likely only be used in patients who are performing relatively poorly with the hearing aid in a bimodal condition. Thus, this may be one area that could cause problems in seeking reimbursement for bilateral implantation for those adult patients who have residual contralateral hearing sensitivity and thus who could be fitted with a power hearing aid on the contralateral ear. However, given the extensive literature showing that even patients with residual hearing do better with a unilateral cochlear implant than with a hearing aid, it might still be arguable that they can be expected to do better with bilateral cochlear implants than with a hearing aid on the contralateral ear providing less effective and a different form of stimulation. In contrast, for adult patients who have marginal or no ability to benefit from an acoustic hearing aid, the data now available seem more than adequate for seeking reimbursement for either sequential or simultaneous implantation.

Another controversial area is the use of bilateral cochlear implants in the pediatric population. Fewer studies to date have addressed bilateral implants in children than in adults. Some of these studies have shown more limited benefits from bilateral implants for prelingually impaired children than for postlingually impaired adults, although studies do show many children receiving significant benefit from bilateral implantation. Litovsky and colleagues (2004) mention gene therapy, hair-cell regeneration and other potential future treatments for hearing loss as reasons some might question bilateral implantation in children. The argument here is that one cochlea should remain intact so that should some of these therapies become available and viable in the child's lifetime, he/she could benefit from them - - as opposed to damaging both cochleae with implantation. This argument is stronger for those children who can use a power hearing aid to benefit in the ear contralateral to the implant, because they will still receive binaural benefit and binaural development of the auditory nervous system. However, for those children with profound bilateral hearing loss who receive little or no benefit from amplification in either ear, an alternative argument is that bilateral implantation is needed in order to provide development of both auditory system pathways during a critical period in childhood in order to provide good performance for the child in future. In 2006, Litovsky *et al.* mentioned the additional consideration in children that to gain full bilateral advantage it may be important to implant them as young as possible. These researchers noted that the sample size to date is too small to make a general recommendation regarding age, but that results so far indicate that bilateral benefits are not restricted to a certain age in the pediatric population. Finally, with newer and hybrid implants and surgical techniques that produce less cochlear damage and potentially could leave some residual hearing, the argument that one ear needs to be left alone to wait for future possibilities may prove less effective.

In 2005, Offeciers *et al.* published a consensus on both bimodal stimulation and bilateral cochlear implants that summarized recommendations most often seen in the literature to date. For bimodal stimulation, these researchers concluded the following:

1. The advantages of bimodal stimulation for patients who have good residual hearing for use of a hearing aid in the unimplanted ear include stimulating both ears, providing binaural advantages, not requiring surgery on the better hearing ear, and cost-effectiveness. However, the disadvantages are that in young children it is difficult to determine hearing status of the unimplanted ear to see if they have enough residual hearing, that patients may refuse to use the hearing aid if it doesn't perform well for them, and that bimodal listening can in some cases reduce performance achieved with the CI alone.
2. In cases with good hearing aid performance, it may be necessary to have the patient stop using the hearing aid for a few weeks in order for good performance with the CI to be achieved.
3. Bimodal stimulation is recommended for all young children until the hearing status of the non-implanted ear is adequately determined, and for any patients who want to restore binaural hearing and who have enough residual hearing in the better ear for good hearing aid performance.

4. Loudness should be balanced between the devices.

For bilateral cochlear implants, Offeciers *et al.* (2005) concluded the following:

1. Bilateral cochlear implantation has the advantages of always implanting the better ear, allowing bilateral cortical stimulation and development, and the possibility of restoring binaural hearing. It has the disadvantages of procedure costs, and possibly making future techniques difficult or impossible.
2. Bilateral CIs should be recommended for candidates for whom benefits from a unilateral CI are poor, in patients who are developing cochlear ossification from meningitis so that full insertion can still be achieved in both ears, in those who want or need for their job to restore binaural hearing, and in children with bilateral profound hearing loss.
3. Simultaneous bilateral implantation (which they called "the one-stage technique") is recommended when possible and with experienced surgeons, due to cost-effectiveness. For sequential implantation (which they called "the two-stage technique), long duration of deafness in one ear is not a contraindication for bilateral CIs because monaural input may maintain some stimulation of the auditory pathways given that there are both homolateral and contralateral projections. Nevertheless, they recommended an inter-surgery interval in post-lingual adults of no more than 12 years[12], and noted that in children a longer interval may result in the need for additional rehabilitation to avoid refusal of the second CI.
4. Bilateral CIs should be balanced for loudness, and sometimes in sequential surgery the first CI implanted should be switched off for a time in order to obtain stable CI performance on the second side.

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[12] Note that this value may be arguable based on some research showing benefit even with long periods of auditory deprivation.

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