Bilateral Cochlear Implants in Children

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Abstract

This paper provides a brief overview of the advantages of two ear hearing in children and discusses the limitations, from a psychophysical and a technical perspective, which may limit the ability of cochlear implant users to gain these benefits. The latest outcomes for children using bilateral cochlear implants are discussed which suggest that results are more favorable for children who receive both devices before the age of 3.5 to 4 years. The available studies that have investigated electrophysiological responses for children receiving bilateral implants are discussed. These also support the notion that optimum development of binaural auditory skills may be more difficult after the age of 3.5 to 4 years. Studies that investigate the alternative for some children of using a hearing aid on the opposite ear to the cochlear implant are briefly discussed. These indicate that advantages for speech perception in noise and localization can be obtained consistently for children with significant residual hearing in the non-implanted ear. The paper concludes with an attempt to bring the available scientific evidence into the practical clinical context with suggestions that may assist clinicians in making recommendations for families considering bilateral cochlear implantation. Although the evidence remains limited at this time, it is reasonable to suggest that bilateral cochlear implantation can provide improved auditory skills over a single implant for children with severe and profound bilateral hearing loss. The available data suggest that the benefit may be maximized by introducing both implants as early as possible, at least before 3.5 to 4 years of age.

Key words: bilateral cochlear implants, children, hearing loss, speech perception, localization

Learning objectives: After completing this paper the reader will be familiar with the main advantages of bilateral hearing and the possible limitations for children using bilateral cochlear implants. They will also be brought up to date with some of the recent outcomes for bilaterally implanted children and the implications of these for clinical practice.

Introduction

This paper will attempt to draw together the current scientific evidence related to bilateral cochlear implantation in children and discuss the implications for clinical practice. Data from recent studies will be presented that provide evidence that may be useful in assisting clinical decision making. Although it is an almost trivial exercise to demonstrate that two ears are better than one for normal listeners (try listening to your iPod with one ear), the introduction of hearing loss and the use of cochlear implants and/or hearing aids changes the scenario and introduces many additional questions. The use of these hearing devices will change the auditory information delivered to each ear, and in children with congenital hearing loss, the ability to use this information may be compromised due to limited development of central auditory processing. These complexities, coupled with the practicalities relating to the costs of implant systems, make decisions about bilateral implantation quite challenging.

This paper will examine the potential benefits that may be available to children using bilateral cochlear implants. We will then address the ability of cochlear implant systems to provide the auditory cues necessary for these benefits. Studies relating to the ability of children to learn to use these cues to improve their auditory skills will be presented, including a discussion of factors that may affect the development of binaural processing. We will briefly address the available evidence on the use of cochlear implants with hearing aids in children as an alternative to bilateral implantation, and the latest evidence on predicting the benefits of bilateral implants for individual cases will be discussed. The paper will conclude with some practical clinical guidelines for making recommendations to families regarding bilateral implantation.

1. What are the potential benefits of bilateral cochlear implantation in children?

With normal bilateral hearing, differences in the acoustic signals arriving at the two ears are processed within the central auditory system to provide additional information about the acoustic environment. The major acoustic cues are often defined as interaural timing differences (ITD) and interaural loudness differences (ILD). The sophisticated processing of ITDs and ILDs in the central auditory system allows accurate identification of sound sources in space and the perceptual separation of acoustic signals arising from different locations. This latter ability in normal listeners can generate benefits for speech perception in competing noise of up to 10-15dB[1]. In psychoacoustics, this is known as binaural unmasking[2,3], sometimes also called binaural squelch. In addition, some advantages arise simply from the two ears being in different positions in relation to multiple sound sources, and the ability of the listener to attend to the ear with the more advantageous signal to noise ratio (SNR).

The benefits of two ears to normal listeners can be summarized in terms of accurate localization of sound and significant advantages to hearing in competing noise environments. The limitations of current cochlear implant devices in providing the cues necessary for these advantages will be addressed, but firstly some additional practical benefits of having two cochlear implants are discussed.

The performance of cochlear implant users is not always symmetrical in each ear. Factors such as duration of hearing loss, pathology and anatomical differences can affect the speech perception outcomes differently and unpredictably for each ear. A cochlear implant in each ear ensures that the better-performing ear is captured with significant benefits in a proportion of cases. A major practical advantage for children that is provided by bilateral implants is that the child can remain "on the air" when minor equipment problems (batteries, cables, etc) affect the performance of the sound processor on one side. In the unfortunate case of a failure of the implant itself, the ability to use the opposite ear while the failed implant is replaced may reduce significantly the trauma for the child and family. Over a lifetime, the ability to have a backup hearing option may prove to be one of the most significant advantages of bilateral cochlear implantation.

2. Can current cochlear implant systems provide suitable auditory information for true binaural hearing?

<u>Advantages of two ears for normal listeners</u>

True binaural hearing requires the simultaneous use of signals at both ears. As an example, speech intelligibility in noise can be improved by the addition of the second ear even when the SNR is worse for that ear. In normal hearing, a large part of this benefit is due to binaural unmasking (as defined above), which results from sophisticated analysis of timing and loudness differences at the two ears. The intelligibility gain can be reasonably well predicted from pure-tone binaural masking level differences (BMLDs)[2,3] determined as the decreases in threshold for out-of-phase versus in-phase signal presentation in diotic narrow-band noise. The BMLD can be as large as 10-15 dB at 500Hz in listeners with normal hearing[1]. For frequencies above 1500 Hz, where ITD sensitivity diminishes rapidly, BMLDs are much smaller and largely derived from interaural envelope cues rather than fine-timing ITDs. Binaural low-frequency ITDs also play an important role in sound localization, whereas at higher frequencies, interaural level differences (ILDs) are more important.

An additional advantage for detecting or understanding speech in noise comes from the so-called “head shadow effect” that makes use of the fact that the signal to noise ratio is often more favorable at one ear than the other. When the noise source is from a specific direction, the ear on the side away from the noise is protected to some degree by the attenuation provided by the head, particularly for higher frequencies (up to 20dB).

The use of both ears also offers benefits even when signals at the two ears do not differ. A small but robust benefit of 1-2 dB is available in normal hearing when listening to speech in noise when the two are presented from the same source directly in front of a listener [4]. This effect is often referred to as binaural redundancy. Listening with both ears also results in summation of loudness, which makes quiet signals easier to detect.

Thus for normal two ear listeners, in addition to the localization provided by ITD and ILD cues, there are at least three mechanisms at work that can improve the effective signal to noise ratio in realistic acoustic environments: binaural unmasking, the head shadow effect and binaural redundancy.

Delivering binaural cues with cochlear implant systems

To obtain similar advantages with bilateral CI, an optimal sound-processing strategy should ensure stimulation is well matched across the two ears when the signal is the same at each ear's microphone, and faithfully preserve both ILDs and ITDs when signals at the two ears differ. With regards to ILD cues, this requires that well matched microphones are used and that non-linear compression schemes, such as automated gain control circuits, are either disabled or apply the same gain modifications to the signals for both ears simultaneously to avoid distorting ILD cues [5]. If both broadband and narrowband cues are to be coded correctly, loudness mapping procedures require loudness to be matched for matched frequency binaural electrode pairs. Even when several of these objectives are at least theoretically achievable with existing implant systems, they may often not be met due to clinical demands. ITD cues are not well coded in clinical sound processing strategies that have been largely designed from a monaural listening perspective. Typically, a bank of band-pass filters is used to separate the microphone-signal into different frequency bands. The output of each band is processed to extract the *envelope* of the signal in that band, and the rate at which the envelope information is sampled is referred to as the update rate. The sampled envelope information is used to set stimulation levels on an electrode associated with that frequency band. Stimulation is often at a fixed rate, or at least at rates unrelated to the signal content. Such strategies can therefore preserve level and timing differences only in the envelope, and not the fine-timing information in the signal. In fact, by using fixed stimulation rates that are not related to the signal characteristics, these strategies potentially introduce disruptive fine-timing cues even if they are perceptible [6].

Binaural advantages in adults

Despite the limitations outlined above, results to date with adult bilateral implant users show clear improvements over unilateral device use in both sound localization abilities and speech understanding in spatially distinct noise [7-11]. As we would expect, however, those benefits are largely attributable to level cues at the two ears, with little indication that interaural timing plays a role [7, 11, 12]. There are several reasons why that may be so. Perhaps foremost among them is the salience of timing information with electrical pulse-trains. Psychophysical data with adult bilateral implant users have shown that at electrical pulse rates of 100 Hz, listeners with good sensitivity can hear ITDs of around 100μs, as can normal-hearing listeners attending to 100-Hz pure tones [13], but as rate increases electrical ITD sensitivity becomes considerably worse [7, 12, 14-18]. In normal-hearing listeners, that is also the case for high-frequency envelope ITDs, but for low-frequency pure tones sensitivity instead improves up to 1 kHz [13]. Although ITD sensitivity at 1 kHz can be substantially improved for CI users by introducing amplitude or pulse-rate modulation, it remains much poorer than the pure tone result in normal hearing. Poor ITD performance at higher rates may largely account for why the benefits derived from fine-timing cues have been minimal for bilateral implant users to date, even when using sound-coding strategies that specifically preserve that cue. In everyday listening that issue is further compounded by multi-channel interactions and the presence of multiple sound sources, both leading to effective increases in rate, and hence decreases in ITD salience. Although ITD salience may also be affected by inexact place matching between electrodes in the two ears, the relatively broad spread of excitation with present stimulation methods may moderate the impact of imperfect place matching [19,12]. Should new stimulation methods become available with more focused excitation, the effect of place matching will likely become more important in binaural sound processing.

In summary, the psychophysical studies of bilaterally implanted adults and an analysis of the way most cochlear implant systems code the acoustic signal, show that it is not possible to convey the subtle timing differences between ears that contribute significantly to binaural unmasking and localization in normal hearing. It is, however, expected that interaural loudness differences and variations in the relative SNR at each ear (head shadow effect) could contribute significantly to enhanced localization and speech perception for bilateral implant users. Careful programming of the speech processors and the use of similar settings (sensitivity, compression knee-points, automatic gain control, noise reduction schemes, etc.) for bilateral devices may be important in the actual performance. Adults using bilateral implants consistently report other benefits including an improvement in the overall quality of sound, ease of listening and the practical advantages of having a backup when technical issues arise.

3. Can children learn to take advantage of information from bilateral implants?

<u>Practical advantages for children with bilateral cochlear implants</u>

Laboratory-based assessments have indicated that children of all ages can gain additional perceptual benefit from bilateral cochlear implants compared with one implant alone. Some of the potential advantages of bilateral implants are due simply to having two “ears”; these “two-ear advantages” include having a back-up device, the head-shadow effect and the flexibility of being able to attend to one device or the other. A back-up device is of significant value because it allows the child to continue to hear with a single implant in the short-term when batteries go flat or there are hardware problems, or in the longer-term if a re-implantation is required due to problems with the internal device.

Benefit from the head-shadow effect has been demonstrated in assessments of closed-set word perception in background noise for sequentially-implanted older children receiving a second implant after 3 years of age [20] or 4 years of age [21-23](refer to Figure 1) and speech detection in background noise for sequentially-implanted younger children [24] (refer to Figure 2). For both groups, performance has been significantly better in the bilateral condition for the majority of participants tested.

Other potential advantages of bilateral cochlear implants derive from binaural processing requiring the listener to be able to compare and combine the information arriving at each ear. Demonstrating the ability to localise sound or improved speech perception due to binaural unmasking in spatially-separated speech and noise conditions would suggest the presence of binaural processing. Assessments conducted so far with sequentially-implanted children receiving a second implant after the age of 4 years have failed to provide any evidence of this level of processing [21](refer to Figure 3). These older children have generally performed equally poorly in the unilateral and the bilateral conditions on assessments of localisation using a frontal, 180^0 array of loudspeakers. They have also failed to demonstrate improved speech perception in the bilateral over the unilateral condition when noise was presented contralateral to the first implant [21, 23] (refer to Figure 4). Superior performance in the bilateral condition would have suggested that binaural unmasking was occurring.

Limited testing has been conducted with younger children who were sequentially implanted before 4 years of age. Options for speech perception testing are particularly limited by the immaturity and variation in language ability across children. The use of a speech detection task in competing noise has allowed as many children as possible to be tested with the same protocol. Such testing has generally resulted in similar performance in the unilateral and bilateral implant conditions, thus providing no evidence that binaural unmasking is occurring for these young sequentially-implanted children [24] (refer to Figure 5). It is possible that an effect was present but was too small to detect with the test used and the sample size. Localisation testing with young children is limited to two-alternative forced-choice tasks, using fixed loudspeaker locations or changing locations (as in minimum-audible angle testing). The results of such testing suggested superior performance in the bilateral condition [20, 24, 25]. Galvin, et al., showed that the majority of sequentially-implanted children who received a second implant before four years of age were able to turn in the correct direction when a sound was presented from the left or right [24] (refer to Figure 6). Observation of the children during testing indicated clear differences in the nature of their responses in the two device conditions: those in the bilateral condition being made in a faster and more confident manner. With increased age these children will be capable of completing more complex and extensive testing which will enable a better understanding of their listening skills. It is also possible that their binaural listening skills will develop further with age, but at this stage there is only limited evidence of the development of true binaural processing.

<u>Timing of first and second implants for children</u>

Children receiving a second implant at a younger age can be assumed to have greater neural plasticity, a shorter period of auditory deprivation, and a shorter period in which there has been domination of the auditory pathways from the first-implanted side. All of these advantages would suggest that there is a greater likelihood of this group developing binaural processing through the use of bilateral implants. Electrophysiological measures for children using bilateral cochlear implants add weight to this view. Auditory brainstem responses recorded from children with early onset deafness have indicated that the central pathways stimulated by the "first" implant may dominate over the pathways stimulated later by the second implant [26, 27]. The work of Sharma and colleagues [28, 29] indicates that the latencies of auditory cortical evoked responses elicited in children with cochlear implants approach normal values over time when the implant occurs under the age of 3.5 years, but may not do so when the implant occurs after this age. These studies suggest that shorter delays between the first and second implants (ideally simultaneous bilateral implantation) would be more conducive to the development of central binaural processing in early deafened children. As noted above, evaluating the development of binaural processing in young children will only be possible once they become capable of completing more complex assessments.

4. Can CI systems provide practical advantages in everyday listening situations?

Objectively measuring performance with bilateral implants in the laboratory provides only a particular view of the outcomes of bilateral implants. From a clinical point of view, it is also important to answer questions such as:

Do children and young adults usually wear their second implant?

Do they like to use bilateral implants?

Can parents observe any benefit in real life when two implants are worn?

Can the second implant be usefully used alone in real life?

These questions are of interest to clinicians and researchers, and they are also the types of questions parents and children are asking when they are considering bilateral implants.

Investigation of these issues is therefore important in the improvement of pre-operative selection and counselling procedures, as well as post-operative management [30, 31].

Our group has addressed these issues through monthly interviews of parents and recipients following bilateral implantation [21, 23, 24]. Data collected from the parents of eleven sequentially-implanted children who received their second implant before the age of 4 years is shown in Figure 7. These young participants were using the two implants full time within two months. The majority were happy to wear the two devices without the need for particular encouragement or reward from their parents. Most were comfortable using the second implant alone within four months, with the majority achieving levels of daily communication similar to those achieved with the first implant. Most parents reported that their child demonstrated a preference for two implants over either one alone within five months, and that daily listening performance was superior with two implants.

Data for those who received their second implant as an adolescent or young adult (i.e. >10 years of age) was collected from parents or the young adult [23] (refer to Figure 8). The milestones data for this group has also been generally positive, though a longer period was usually taken to achieve each milestone. Another noteworthy difference is the fact that few in this older group achieved similar daily communication ability with either implant alone, that is, the first implant remained dominant, at least at the time of data collection.

Evidence that bilateral cochlear implants provide an advantage in everyday listening situations has also been collected using a questionnaire derived from “The Speech, Spatial and Qualities of

Hearing Scale (SSQ)”, a questionnaire for adults designed with some emphasis on binaural hearing functions. The adult SSQ was modified to produce a version for parents of children with impaired hearing and a version for older children. In each version there are three sections examining speech perception (in quiet, in groups and/or in noisy or reverberant environments), spatial hearing (the location, direction and distance of sounds), and other qualities of hearing (segregating and identifying sounds and listening effort). In each item a type of listening situation is described; for example, “You are talking to your child in a room in which there are many other people talking. Can your child follow what you say?” The parent or the participant is asked to rate their child’s or their own performance in that situation on a scale from 0 to 10. To maximize the accuracy of their ratings, parents were asked to complete a minimum of one week of observation of their child in the specified types of listening situations prior to the completion of each of the three sections. The data collected for adolescents and young adults who were sequentially-implanted after the age of four years showed that most were rated as demonstrating improved performance at the post-operative point (in the bilateral condition) relative to the pre-operative point (in the unilateral or implant + hearing aid condition) [23]. As indicated by the results for 12 of these participants presented in Figure 9, improvement occurred in all three areas of the questionnaire: speech perception, spatial hearing, and other qualities of hearing. Given that this group showed no evidence of improved localisation in the bilateral condition in laboratory assessments, it is interesting to note the improvement shown in the spatial hearing section. It is possible that the questionnaire is examining a different area of spatial hearing to the objective tests, or that the improved ratings on the spatial hearing section are actually due to the participants’ increased awareness of, and monitoring of, the auditory environment. Although this data does not tell us why, it does indicate that the participants' performance in everyday situations is perceived to be superior when using bilateral implants.

5. Factors important to successful use of bilateral implants

As with unilateral cochlear implants, outcomes with sequential bilateral cochlear implants are influenced by a complex interaction of factors. Given that predictions can only be based on clinical and research experience with unilateral implants, combined with the limited pediatric bilateral studies conducted so far, outcomes cannot be accurately predicted for individuals at this point. Age at implant and consistency of device use are two factors which do influence outcomes. In general, younger children adapted faster and more easily to the use of bilateral cochlear implants [24] (refer to Figure 7). They were also more likely to be comfortable using their second implant alone, and to achieve similar listening skills with either device. The additional benefit provided by a second implant appeared to be greater for younger children, particularly with regard to locating sound sources. Direct comparisons of benefit, however, cannot be made until the younger children become capable of completing more sophisticated assessments. It must also be emphasised that there was no clear evidence for a cut-off age after which benefits from a second implant were curtailed, or, indeed, before which adaptation will occur easily. Some older children with more than 10 years between the first and second implants have demonstrated significant benefit in the bilateral condition, and of 30 children sequentially implanted under 4 years at the Melbourne Cochlear Implant Clinic, 10 demonstrated some difficulty in adapting to the use of two implants [32].

Consistency of device use also appears to be important [32]. Clinical experience has shown that children may adapt quickly to an absence of stimulation from one or both implants. Listening skills can deteriorate, previously appropriate speech processor programs may no longer be tolerated, and resistance to re-introduction of the device may occur when a speech processor is not worn for a period of time. The length of non-device use may vary from hours to weeks depending on the cause: ear infection, loss of device, issues with spare parts. Nevertheless, any regular period of non-use introduces the child to the concept that it is '*optional'* to wear both implants. An obvious exception to full-time bilateral use is during habilitation or training sessions where second implant alone listening skills are specifically developed.

The role of parents in achieving consistent device use varies with the age of the child. For the youngest children, device use is the parents' responsibility. For older children and young adults consistent device use will be their own responsibility. This shift of responsibility raises the issue of motivation, because as the responsibility shifts from the parent to the user of the implants, the role of motivation in successful use of bilateral implants increases. Older children and young adults are unlikely to use the second implant consistently if they lack self-motivation to learn to listen with that device and to gain whatever benefit is possible from using bilateral implants. Developing and maintaining a high level of motivation appears to be particularly difficult for the group of children aged around 7 to 12 years, with children in this age group more likely to be delayed in reaching important post-operative device use milestones [33]. Experience with this group suggests this may be because these children are old enough to have their own opinion regarding device use. In addition, this group may have had less input into the decision-making regarding the second implant than older children, and may have limited confidence that the second device will provide benefit.

There are a number of other factors which have been suggested to negatively influence performance with bilateral cochlear implants, including:

Limited or no consistent use of a contralateral hearing aid with the first CI,

Poorer than expected outcomes with the first CI,

Relatively advanced age at the time the 2nd CI is received,

Long delay between implants

Limited experience using the second CI alone, and

Limited habilitation targeting use of the second CI alone.

These factors may indeed be influential; however outcomes for individuals indicate that none of these factors alone precludes successful use of bilateral implants [21].

6. Can children learn to use complementary information from acoustic amplification and cochlear implants?

Cochlear implants have been shown to provide comprehensive access to speech sounds and have lead to significant improvements in speech perception for children with severe [34-36] and profound hearing loss [37-41]. Recent studies have indicated average scores of 53% words and 79% phonemes correct for open-set monosyllabic words for 82 young Australian children [42] and 60% words and 83% phonemes correct for 33 children in Oral/Aural programs in the USA using similar tests [43]. This speech perception performance is comparable to that achieved by children with moderate hearing loss using conventional hearing aids [42]. Children with significant residual hearing have been shown to benefit more from unilateral cochlear implants than their existing hearing aids [34]. In this study 16 children with 3-Freq PTA from 73 to 122 dB HL and between 30% and 87% open-set sentence scores prior to implantation, demonstrated significantly better scores with their cochlear implant. They also demonstrated better speech perception for open-set words and sentences using both the cochlear implant and a hearing aid in the opposite ear compared with the cochlear implant alone, or hearing aid alone.

Hearing aid or second cochlear implant?

The successful application of unilateral cochlear implants to the wider population of young children with severe and profound hearing loss has created an intriguing clinical dilemma for clinicians and parents. Should my child persist with his/her hearing aid in the ear contralateral to the implant, defined for the purpose of this paper as a 'bimodal' device user, or would a second cochlear implant, that is, 'bilateral CI' use, provide more benefit than the 'bimodal' condition? As is typical in the research regarding intervention for children with hearing loss, few studies may be classified as providing the highest 'levels of evidence' (randomized controlled clinical trials (Level 1), or matched-pair designs (Level 2). Current studies attempting to address the 'bimodal' versus 'bilateral CI' debate typically provide Level 3 evidence and include results extrapolated from bilateral hearing aid users and reports containing small numbers of subjects. The field of cochlear implant research is further complicated by the interactions between variables such as 'age at access to hearing', 'duration of device use', 'matching/optimising the signals from each device' and notions such as 'acclimatization' and 'maturation' in the developing child.

Paediatric bilateral hearing aid fitting, bimodal and bilateral CI studies

Historically, bilateral hearing aid fitting was empirically unsupported. It seemed reasonable to assume that if one hearing aid improved access to speech, then two was better. In the l960s, and largely in reaction to the maternal Rubella epidemic, large numbers of children were diagnosed with congenital bilateral hearing loss. Many children were fitted with a single body worn device (carried in a harness or pocket) from which two leads emerged; one to each ear. The microphone was centrally located in the body worn device thus affording no potential for bilateral cues such as interaural time delays or interaural loudness cues. When behind-the-ear (BTE) hearing aids became available in the 1960's the bilateral fitting was consistently recommended. The subsequent evidence supporting binaural fitting of hearing aids indicated improvements in speech understanding in noisy listening conditions [44-48] and sound source localisation benefits [49-51].

The issue of bilateral cochlear implants cannot be treated with the same "two must be better than one" approach as the risks of surgery and costs of implant devices must be considered. Prior to considering bilateral CI fitting, whether simultaneous (occurring during the same general anaesthetic) or sequential (in successive anaesthetics with an interval of days or years), more conservative parents will tend to 'wait-and-see' and the bimodal option is potentially less invasive. Clinicians need to be able to advise parents regarding two significant parameters. What is the unaided audiometric configuration beyond which a cochlear implant is a better option than a hearing aid? Given the likely reduction in a child's ability to adjust to new devices over time, at what age should the decision be taken for bilateral implantation or continued bimodal device use?

How much hearing is too much hearing for a CI?

A few studies have reported bimodal advantages for speech perception [52-57]. Chmiel and colleagues (1995) described enhanced speech perception and speech imitation skills in the bimodal condition for six children aged between 4 and 13 years, who all used hearing aids in the post-implant period. The unaided and aided PTA for each child were not provided but can be derived from their figure to range from 100 to 112 dB between 500 and 2 kHz. Three subjects demonstrated a significant bimodal advantage over monaural performance in the speech perception tasks. Four subjects demonstrated higher bimodal speech imitation scores over the monaural implant alone condition, but two subjects performed worse, and differences were not statistically significant. The authors suggested that vocal quality was improved for the bilateral-bimodal condition compared to implant alone but the differences in speech intelligibility for bilateral-bimodal compared to implant alone did not reach significance.

Ching and colleagues [52] examined hearing aid adjustments for 16 bimodal subjects aged between 6 and 18 years (mean 11.4 years; SD 3.2 years). The average PTA ranged from 80.3 to 115.3 dB HL at 250 to 4 kHz. Bimodal sentence perception in quiet and in noise, and localisation ability was significantly better than monaural implant alone, or hearing aid alone for the 11 subjects who were tested. In particular, Ching et al., found no cases where the hearing aid caused interference in speech perception tasks [52].

Dettman, Wai, van Hoesel et al., [58] reported speech perception and localisation ability for 11 children using cochlear implants with a hearing aid on the opposite side. The group mean 3-

frequency PTA on the hearing aid side was 105.7 dB HL with a range from 88dB to 125 dB HL. Despite relatively poor performance for the hearing aid alone condition, results indicated that speech perception in noise was significantly improved by the addition of the hearing aid when noise was presented on the implant side (see Figure 10). Eight of the 11 subjects also participated in a sound source identification study which showed significantly better performance for the combined implant and hearing aid condition than with the implant alone. This study showed that even with limited hearing on the non-implanted side, children could make use of some binaural cues to improve speech perception and localisation performance. Mok, et al. [59] showed similar outcomes for a group of adults using hearing aids with cochlear implants, although there was some indication that high frequency information from the hearing aid side could interfere with speech perception.

More recently, studies have examined the importance of low-frequency cues provided by hearing aids for language acquisition [60,61]. Low frequency cues such as stress and pitch contours are important for the infant acquiring his/her native language as these prosodic cues may be used to identify word and phrase boundaries [62]. Dettman [60] determined that primary caregivers who used more pitch and stress in speech directed to their two year olds pre-implant and in the first year post-implant had children who demonstrated better speech perception and language outcomes at seven years of age. Nittrouer and Chapman[61] found improved mean length of utterance and use of pronouns (but not auditory comprehension and expressive one-word vocabulary measures) for their group of children with some bimodal experience, compared with the children using only one CI or bilateral CIs. Both studies suggested that, even in children with significant hearing loss, the early use of low frequency cues may assist language learning.

These studies and clinical experience suggest that most implanted subjects can learn to use limited cues from the non-implant side to improve auditory and linguistic skills using conventional hearing aids. The use of low frequency hearing in conjunction with a cochlear implant appears to provide complementary information and for this reason, bilateral implantation in children should be considered carefully when there is significant residual hearing in the non-implant ear.

7. What are the practical implications of research to this point?

As the benefits of bilateral implantation are becoming more widely reported, clinicians, cochlear implant recipients and parents of children using implants are more regularly asking if, and when, bilateral cochlear implantation is warranted. While the findings discussed above are promising, the benefits of binaural hearing are not always available to people who use hearing aids and/or cochlear implants. The decision to surgically implant both ears, therefore, requires some consideration, as does the process for assisting children to get maximum benefit from both implants. To establish if a child is likely to be better off using a cochlear implant in both ears, consideration needs to be given to a number of issues.

<u>The potential for improved hearing in the ear to be implanted</u>

Determining the potential for improved hearing in the ear to be implanted can be based on an estimation of potential performance for each individual ear. Standard guidelines for unilateral implantation can be applied to the individual ears to predict the likelihood of improvement in hearing with an implant compared to what can be obtained with a hearing aid.

It is widely accepted that children with bilateral profound hearing loss will perform better with a cochlear implant compared to a hearing aid [63, 64, 43]. In these cases, provided medical and otological issues have been considered, a recommendation for bilateral cochlear implants can be made without hesitation. For children with one or both ears in the severe or severe-to-profound hearing loss range, evaluation of the use of residual hearing is warranted prior to making a recommendation for bilateral implantation.

Evaluation of residual hearing and bimodal or binaural advantage

Many children considering bilateral cochlear implantation will be obtaining some useful hearing in both ears from a cochlear implant and/or hearing aids. In order to evaluate a child's use of residual hearing and/or potential loss of a bimodal or binaural benefit, a comparison of a child's speech perception abilities when listening with one ear versus two ears can be performed.

It is usually difficult to gauge a binaural/bimodal advantage in young children as they are typically just beginning to demonstrate responses to sound. Observation of their reaction to sound when listening with one versus two ears may, however, indicate if there is a bimodal/binaural advantage. Parents and clinicians working with the child can observe the child in the bimodal/bilateral condition and unilateral conditions and look for differences in the child's responsiveness.

The importance of acoustic information

Some people rely on acoustic information for their appreciation of music, voice pitch recognition and ‘pleasantness’. Electrical stimulation from bilateral cochlear implants is not likely to replicate these features at the current time. Questioning the child and parents about their listening goals can be helpful and can guide discussions about expectations.

“Saving an ear” for future technology

Central binaural processing development appears to have a “critical” period. Currently, therefore, unless a child has significant residual hearing and is well aided, bilateral cochlear implantation is the only option for supporting binaural development. If a unilaterally implanted child’s second ear does not receive auditory input during the critical period of cortical development, later technology, no matter how advanced, may end up providing input to an auditory system that has limited ability to process the information.

The timing of implantation of the second ear

The child’s age and duration of deafness are important factors to consider for both unilateral cochlear implantation and second side implantation, and may have a significant effect on the amount of benefit obtained and a the child’s willingness to use the second device. Evidence to date suggests that children who receive bilateral cochlear implants at a younger age have better outcomes than those who receive their second implant at a comparatively older age. On average, younger children, adapt more quickly to the second implant (when implanted sequentially) and develop better sound localization and speech recognition in noise than those who receive their second implant at an older age.

Simultaneous bilateral implantation may have advantages for easier adaptation to the sound and devices, especially for young children and is supported by the available electrophysiological evidence [26-29], but may pose greater medical complications and challenges in programming the devices. The latest analysis of surgical outcomes for young children undergoing simultaneous bilateral implantation, however, suggests that this procedure does not entail additional risk to unilateral implantation [65].

Developmental and cognitive delay

Developmental and cognitive delays can limit a child's ability to process auditory cues. When this is indicated, it may affect the decision to proceed with unilateral cochlear implantation. Currently there is no research specific to the benefits of bilateral implants for children with developmental and cognitive delay. If the child demonstrates speech perception benefits with the first implant, it is reasonable to assume that bilateral implantation could offer additional auditory information. Therefore, until experience or research suggests otherwise bilateral implantation should be considered in such cases.

Medical and otological contra-indications to surgery

The same otological, radiological and medical guidelines apply to bilateral cochlear implantation as for unilateral implantation. These include; evidence that the auditory nerve is present and accessible to a cochlear implant electrode array, absence of middle ear disease, and medical suitability to undergo a general anaesthetic.

Post operative considerations

Until experience suggests otherwise, the approach to programming bilateral cochlear implants varies little from programming one implant. Allowance does need to be made, however, for a potential increase in the number of programming sessions, especially in the period immediately post-implantation. Ideally, both ears would be programmed in each session, particularly in cases of simultaneous implantation, as judgements are likely to be more consistent within a session. This may, however, be time consuming and exhausting for children.

Clinical experience to date suggests that useful speech processor programs can be created for individual ears in separate sessions as long as some allowance is made to ensure comfort in the bilateral condition due to potential loudness summation. As the main advantages gained from bilateral cochlear implantation rely on timing and amplitude cues the aim should be for both implant systems to provide equal overall intensity and if possible, be pitch-matched. The overall intensity of each implant can be compared roughly within the session by asking the child to listen to a sentence or paragraph using one ear alone and remember how loud it is. Adjustments can be made to the individual ear speech processor programs until equal loudness is achieved.

Young children will not be capable of comparing the intensity of speech processor programs. To minimize the potential for a large discrepancy between ears, a consistent approach for setting maximum comfort levels (C-levels) should be used. For example, using the same percentage reduction for each ear when setting C-levels based on loudness discomfort levels. Consideration should also be given to the possibility of loudness summation in the binaural listening condition.

The perception of sounds with the second cochlear implant may be quite different to those heard with the first. This may affect a child's motivation to use the second implant. Children, who are implanted in their second ear some time after having received their first implant, may struggle to adjust to the 'new' sound. The adjustment process may be assisted by recommending the child spends short periods of time in the early stages listening with the second implant alone. This can be done in controlled and safe environments such as therapy or auditory familiarization sessions in the clinic, with a child's own speech pathologist or teacher of the deaf, or at home with familiar and predictable activities. Most of the child's normal daily listening experience should capitalise on hearing via their bilateral implants.

8. Conclusion

Having reviewed some of the recent findings for bilateral implantation, we are now in a position to give tentative answers to the questions posed at the beginning of this paper. We know that current cochlear implants cannot provide the sophisticated binaural processing that is available for normal listeners, however it has been demonstrated that bilateral implantation can improve speech perception in background noise and provide limited localisation of sound. In a practical sense, bilateral implants may provide the extra few decibels of advantage in noisy environments that leads to success in the classroom environment. Studies suggest that a child with profound hearing loss in both ears is very likely to benefit from bilateral implantation. The evidence also suggests that earlier is better both for the first implant, and for the second. That is, simultaneous or sequential bilateral implantation with minimum delay is indicated for children with bilateral profound deafness as early as possible.

When residual hearing is in the range between 70dB and 90dB HL in one or both ears, there is a need to consider bilateral implantation more cautiously. The configuration of the hearing loss is relevant as the ability for cochlear implants to provide good access to speech sounds in the higher frequencies is well-documented. A sloping bilateral hearing loss with high frequency thresholds in the profound range (PTA=80dB HL) may warrant a recommendation for bilateral implantation, whereas a hearing loss with the same PTA, but with a flat or rising configuration should be considered differently due to the improved potential to provide high frequency access with conventional amplification. Auditory information from the use of low frequency "natural" hearing may be complementary to that provided by cochlear implants and may provide better appreciation of non-speech sounds such as music. Some studies have suggested that children can learn to use such information effectively when combined with electrical hearing on the opposite side. As with unilateral implantation, the individual child's characteristics need to be considered carefully along with any medical, otological and developmental issues. Ultimately, the choice to proceed with bilateral implantation will lie with the child's family and should be based on objective evidence and clinical experience provided by their cochlear implant clinical team.

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Figure Legends

Figure 1: Mean SNR at which each of 10 participants achieved the criterion level of performance on the AdSpon (4-AFC spondee recognition) test in the first implant (CI-1) alone and bilateral implant (BiCI) conditions when speech was presented from 0^0 and noise was ipsilateral to CI-1. Error bars represent +/- 1SD. Participants received a second implant at 5 to 14 years of age (mean: 9.0y; SD: 3.0y) and were assessed 6 months later; the mean time between implants was 6.2y (SD: 2.5y).

Figure 2: Detection signal-to-noise ratios for each of nine participants in the first implant (CI-1) alone and bilateral implant (BiCI) conditions when speech was presented from 0^0 and noise was ipsilateral to CI-1. Error bars represent +/- 1SD. Participants received a second implant before 4 years of age (mean: 2.8y; SD: 0.7y) and were assessed at 6 months later (24 months for P3); the mean time between implants was 1.6y (SD: 0.9y).

Figure 3: Mean RMS error in degrees in identifying the correct loudspeaker in the first implant (CI-1) alone and bilateral implant (BiCI) conditions for each of nine participants. Results are collapsed across eight loudspeakers from a frontal arc spanning 180^0 (16 presentations per loudspeaker). Error bars represent +/- 1SD. Participants received a second implant at 5 to 14 years of age (mean: 9.4y; SD: 3.0y) and were assessed 6 months later; the mean time between implants was 6.6y (SD: 2.3y).

Figure 4: Mean SNR at which each of 10 participants achieved the criterion level of performance on the AdSpon (4-AFC spondee recognition) test in the first implant (CI-1) alone and bilateral implant (BiCI) conditions when speech was presented from 0^0 and noise was contralateral to CI-1. Error bars represent +/- 1SD. Participants received a second implant at 5 to 14 years of age (mean: 9.0y; SD: 3.0y) and were assessed 6 months later; the mean time between implants was 6.2y (SD: 2.5y).

Figure 5: Detection signal-to-noise ratios for each of nine participants in the first implant (CI-1) alone and bilateral implant (BiCI) conditions when speech was presented from 0^0 and noise was contralateral to CI-1. Error bars represent +/- 1SD. Participants received a second implant before 4 years of age (mean: 2.8y; SD: 0.7y) and were assessed at 6 months later (24 months for P3); the mean time between implants was 1.6y (SD: 0.9y).

Figure 6: Percentage of correct turns made by 15 participants in the first implant (CI-1) alone and bilateral implant (BiCI) conditions in response to stimuli presented from 90^0 to the left or right. Visual-reinforcement-audiometry was used and the presentation level varied by +/-4dB. Participants received a second implant before 4 years of age (mean: 2.5y; SD: 0.8y) and were assessed 6, 12 months or 24 months later; the mean time between implants was 1.2y (SD: 0.9y).

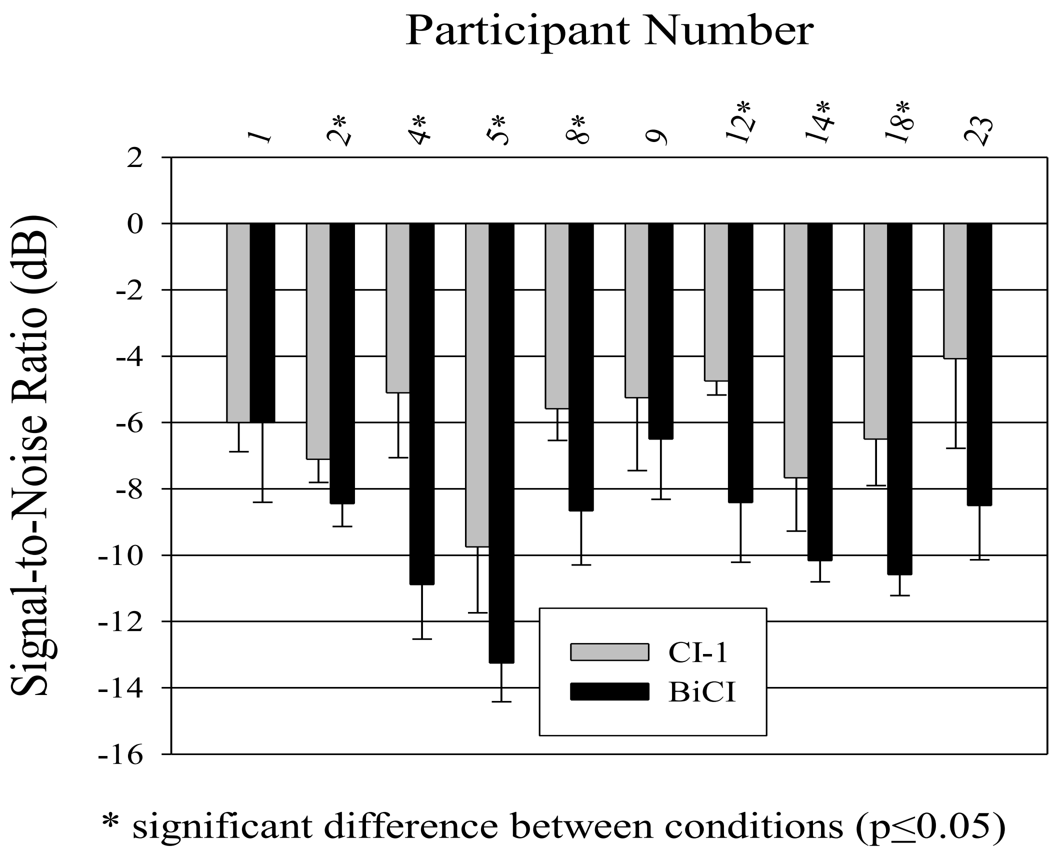
Figure 7: Post switch-on point (in months) at which parents reported specified milestones were achieved using the second implant (CI-2) alone and bilateral implants (BiCIs) for eleven participants (S20 has no CI-2 alone milestones as only BiCIs were tolerated, and a tenth subject chose not to wear CI-2 in the assessment period and has no milestones). Arrows indicate that the

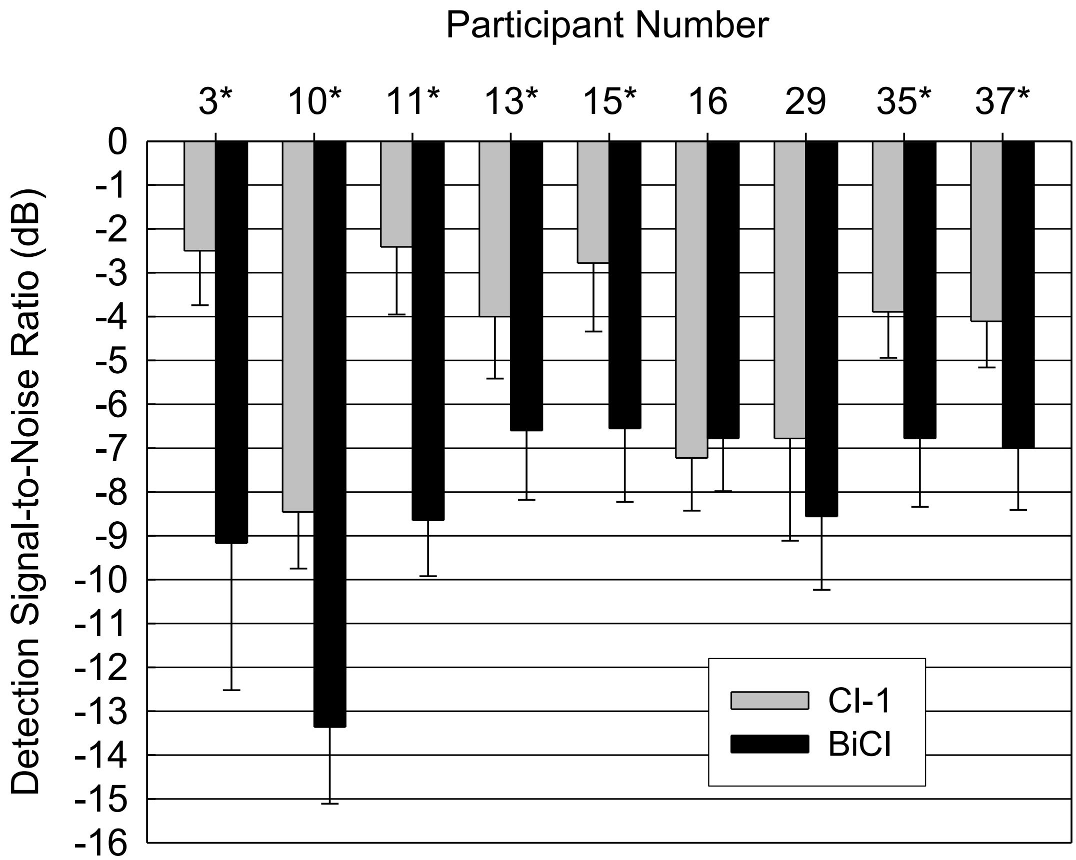
milestone was not achieved within the 6 months. Participants received a second implant before 4 years of age (mean: 2.6y; SD: 0.4y); the mean time between implants was 1.5y (SD: 0.8y).

Figure 8: Post switch-on point (in months) at which specified milestones were reported as achieved using the second implant (CI-2) alone and bilateral implants (BiCIs) by ten participants. Arrows indicate that the milestone was not achieved within the 12 months. Participants received a second implant between the ages of 10 and 19 years (mean: 14.4y; SD: 3.3y); the mean time between implants was 10.2y (SD: 3.1y).

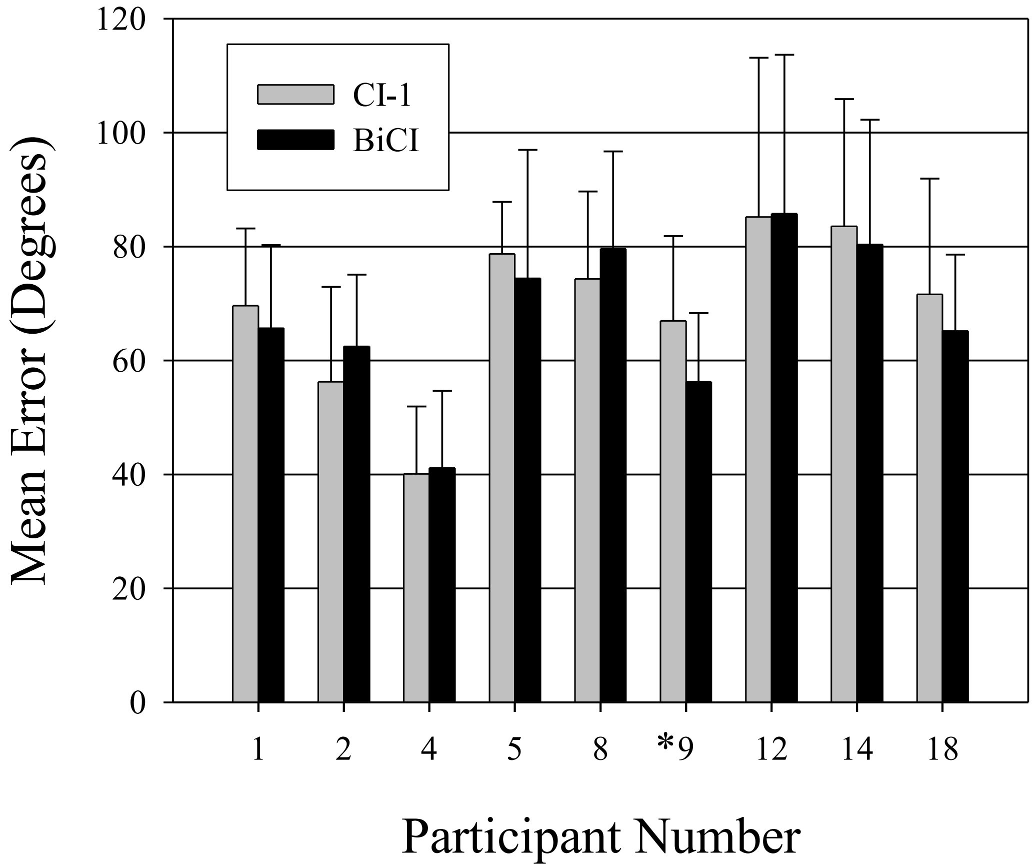
Figure 9: Median pre-operative and 12-months post-operative performance ratings out of 10 for twelve participants for the three section of the SSQ Scale: Speech Perception, Spatial Hearing, and Other Qualities of Hearing. Post-operative ratings were provided without reference to pre-operative ratings. Ratings were self-ratings for P25 and P26; all other ratings were provided by a parent. Participants received a second implant between the ages of 5 and 19 years (mean: 12.1y; SD: 4.5y); the mean time between implants was 8.3y (SD: 3.3y).

Figure 10: Speech Perception Results. Average percentage of key words correctly identified (open set BKB/A sentence lists) for 11 subjects: three device conditions *(bimodal-bilateral, implant alone* and *hearing aid alone*) and four stimulus conditions (in *quiet*, *noise-front*, *noise-hearing aid*, and *noise-implant*).

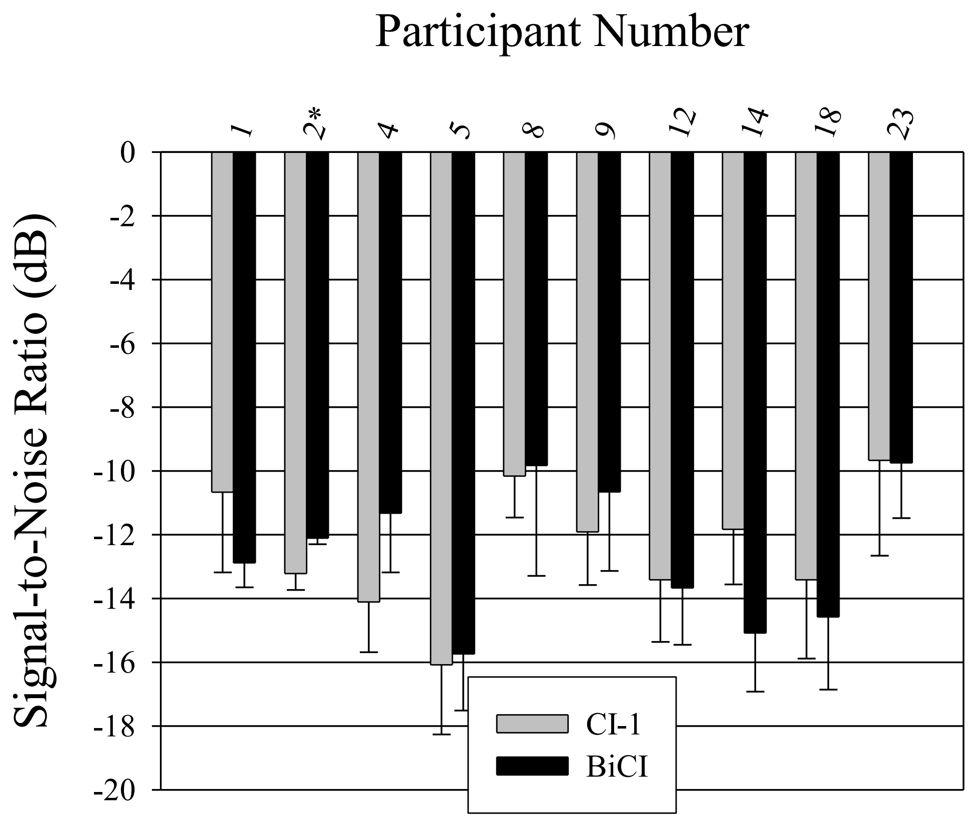

Participant Number
1
2*
4*
5*
8*
9
12*
14*
18*
23
Signal-to-Noise Ratio (dB)
2
0
-2
-4
-6
-8
-10
-12
-14
-16
CI-1
BiCI
* significant difference between conditions (p≤0.05)



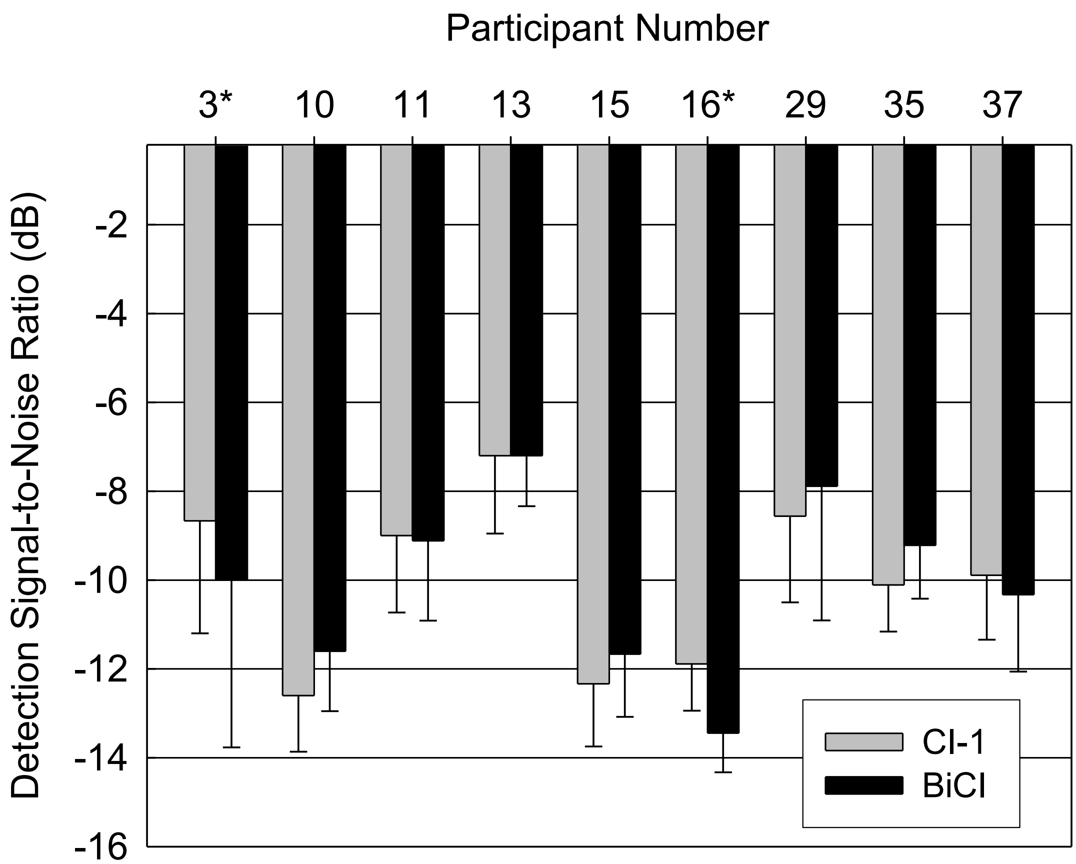
* significant difference between conditions ($p<0.05$)



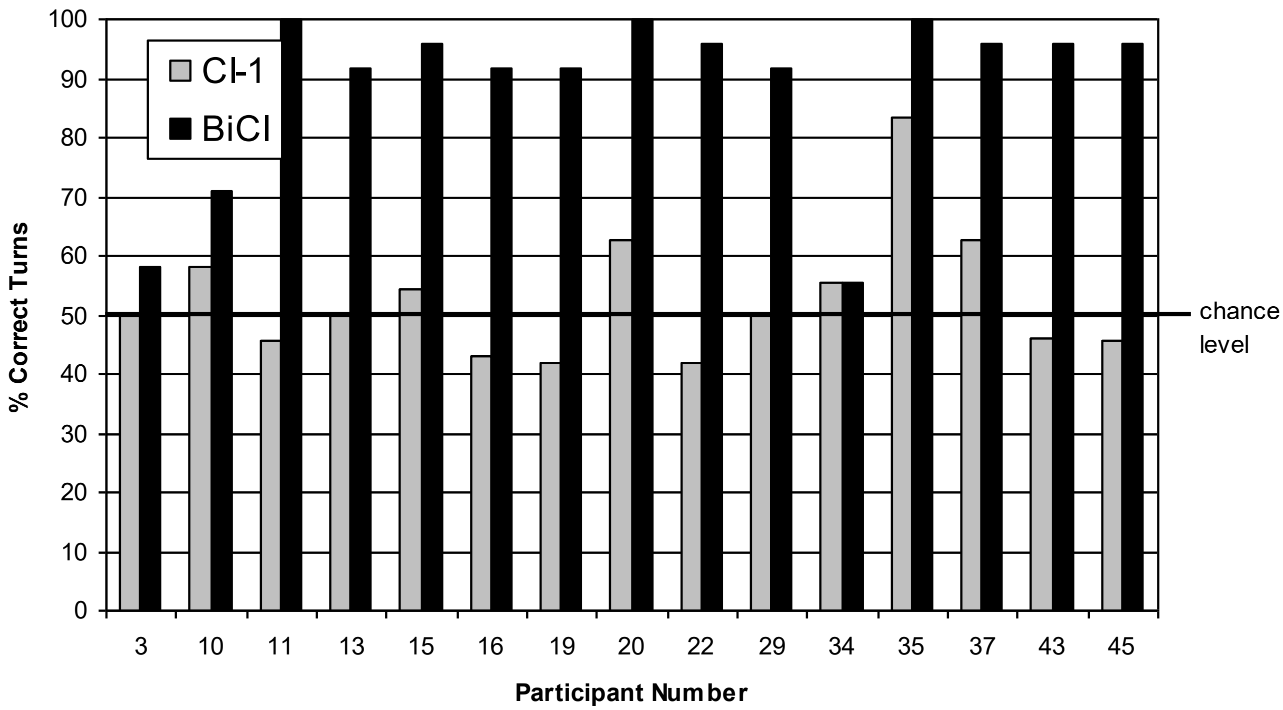
* significant difference between conditions (p≤0.05)

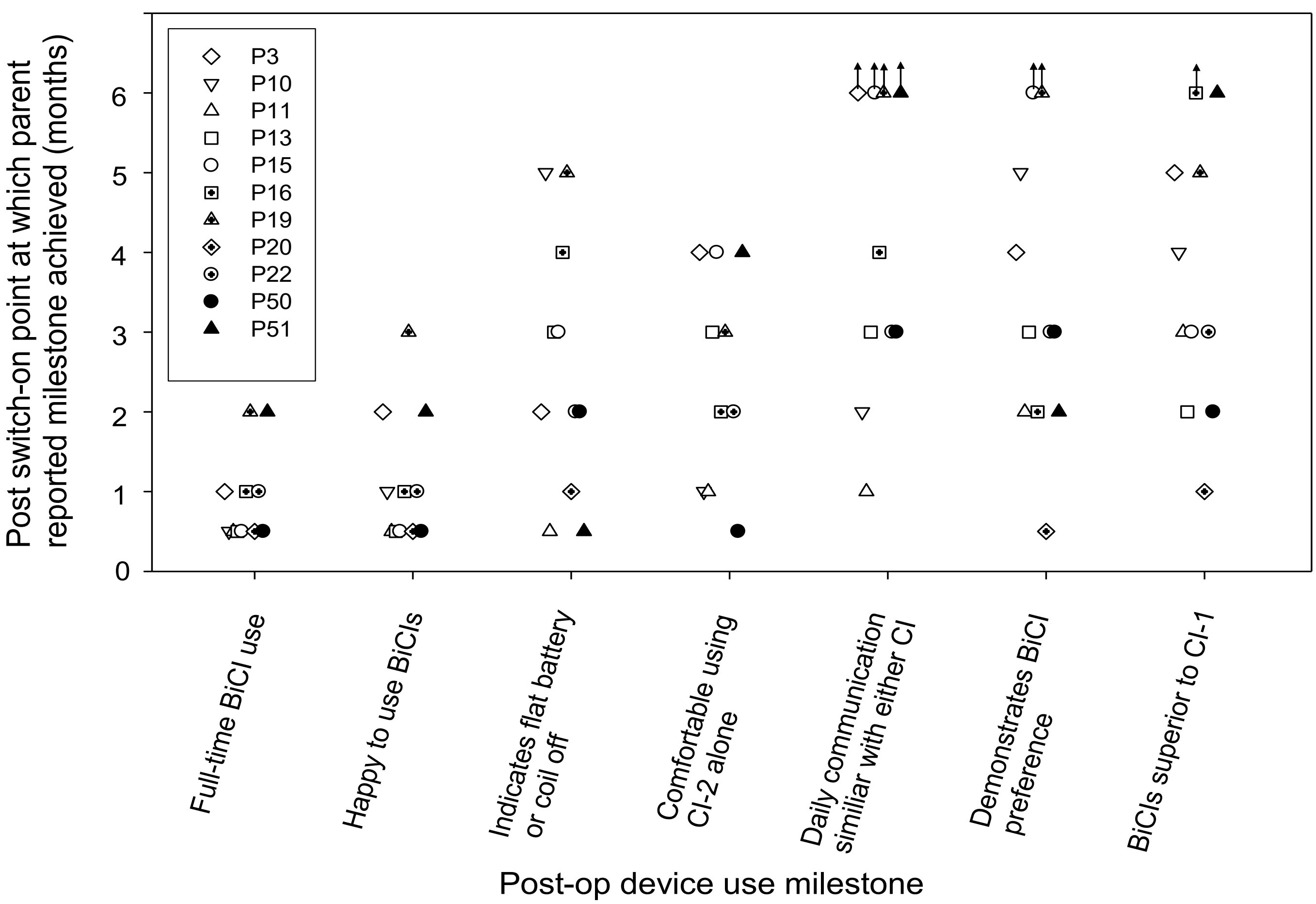


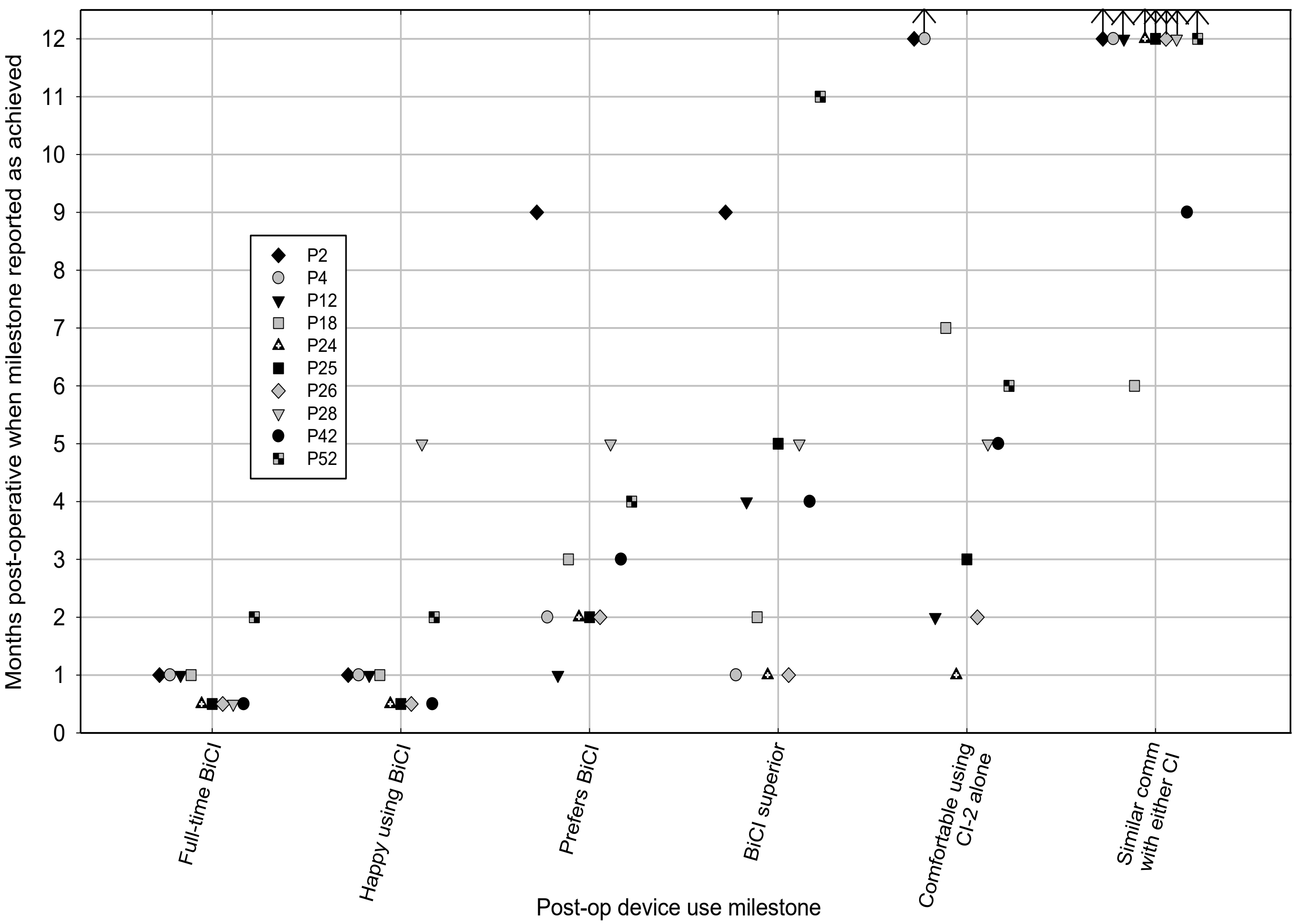
* significant difference between conditions ($p \leq 0.05$)

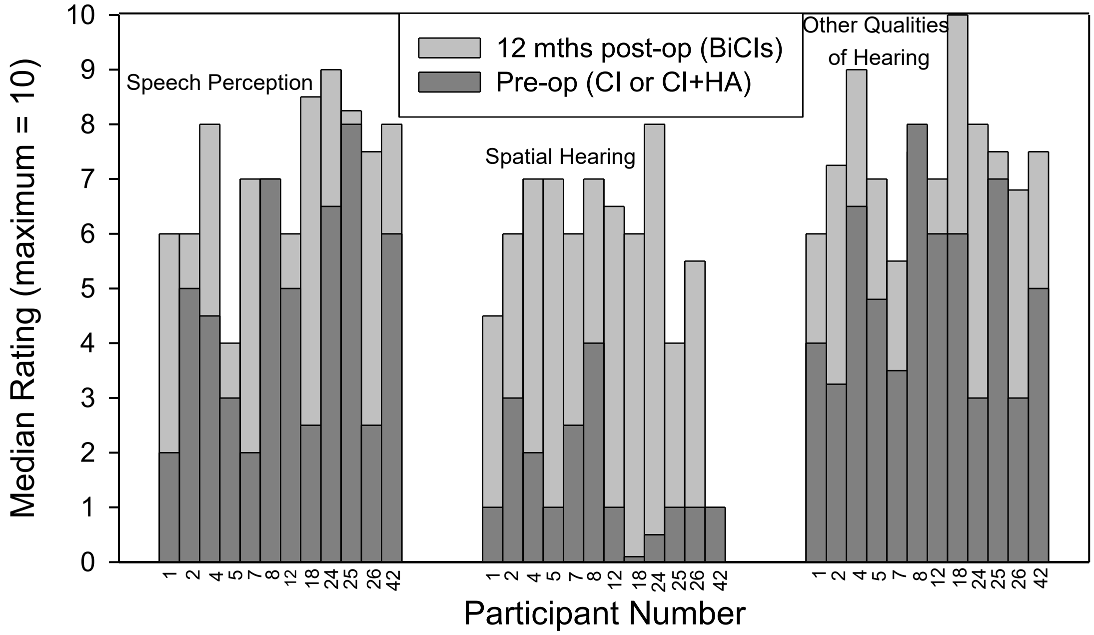


* significant difference between conditions (p<0.05)

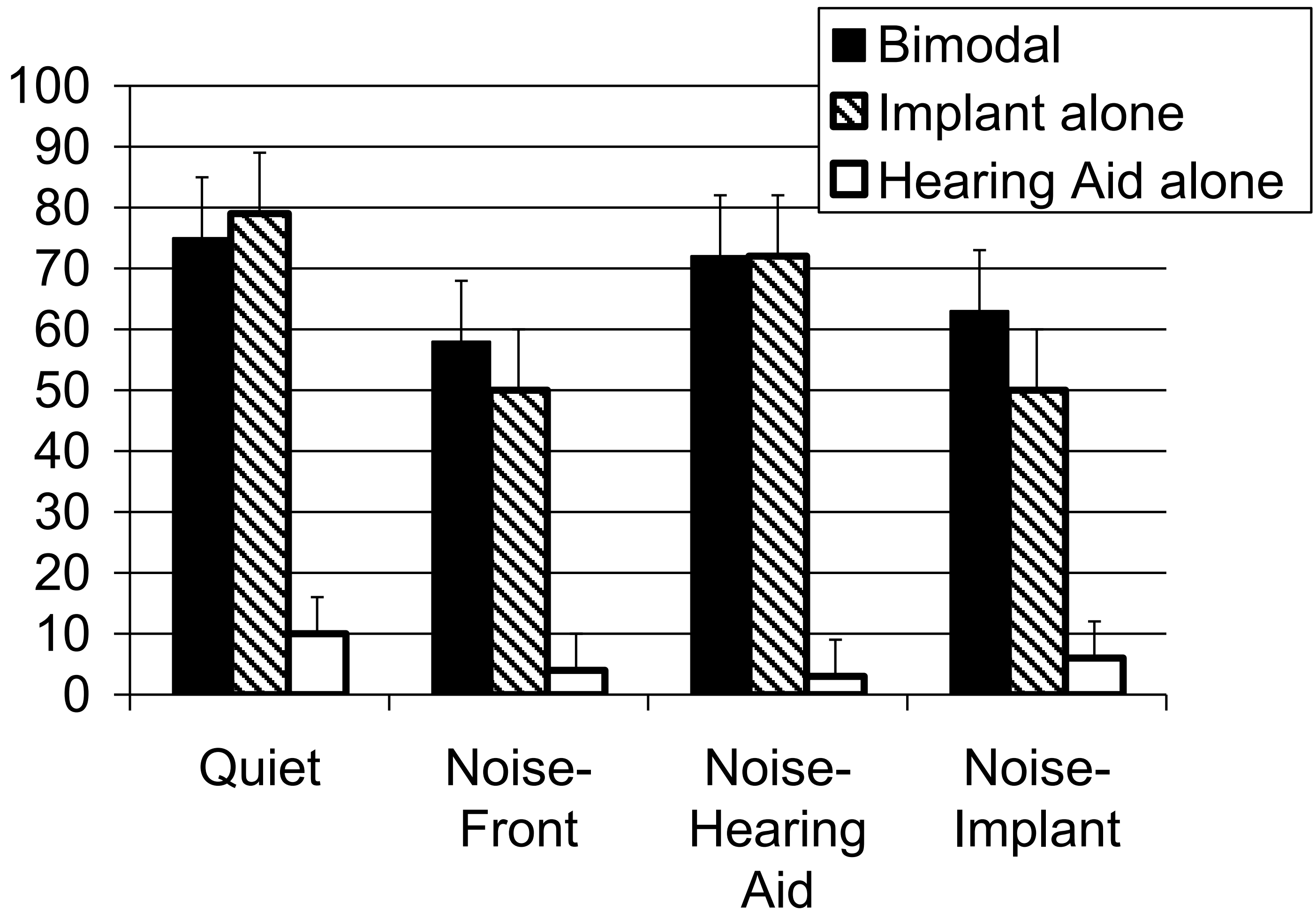

100
90
80
70
60
50
40
30
20
10
0
CI-1
BiCI
% Correct Turns
chance
level
3
10
11
13
15
16
19
20
22
29
34
35
37
43
45
Participant Number


P3
P10
P11
P13
P15
P16
P19
P20
P22
P50
P51
Post switch-on point at which parent reported milestone achieved (months)
0
1
2
3
4
5
6
Full-time BiCI use
Happy to use BiCIs
Indicates flat battery or coil off
Comfortable using CI-2 alone
Daily communication similar with either CI
Demonstrates BiCI preference
BiCIs superior to CI-1
Post-op device use milestone


Months post-operative when milestone reported as achieved
0
1
2
3
4
5
6
7
8
9
10
11
12
P2
P4
P12
P18
P24
P25
P26
P28
P42
P52
Full-time BiCI
Happy using BiCI
Prefers BiCI
BiCI superior
Comfortable using CI-2 alone
Similar comm with either CI
Post-op device use milestone



Median Rating (maximum = 10)
Participant Number
12 mths post-op (BiCIs)
Pre-op (CI or CI+HA)
Speech Perception
Spatial Hearing
Other Qualities of Hearing
0
1
2
3
4
5
6
7
8
9
10
1 2 4 5 7 8 12 18 24 25 26 42
1 2 4 5 7 8 12 18 24 25 26 42
1 2 4 5 7 8 12 18 24 25 26 42


Bimodal
Implant alone
Hearing Aid alone
100
90
80
70
60
50
40
30
20
10
0
Quiet
Noise-Front
Noise-Hearing Aid
Noise-Implant