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The Effectiveness of Bilateral Cochlear Implants in Adults and Children: a Critical Review

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The Effectiveness of Bilateral Cochlear Implants in Adults and Children: a Critical Review

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Abstract

Unilateral cochlear implants are routinely provided to individuals who present with bilateral severe to profound sensorineural hearing loss. Unilateral implantation is widely accepted as the standard of care by most insurance companies, though bilateral implantation has the potential to restore some of the advantages of binaural listening in these patients. The aim of this literature review is to discuss recent research concerning benefits of bilateral cochlear implantation relative to performance with a single implant in both the pediatric and adult populations. Electronic databases and reference lists were searched using a pre-determined search strategy and were reviewed for relevant information. This critical review focused on the following questions: 1) What are the benefits of bilateral cochlear implantation compared to unilateral CI or bimodal arrangements in the areas of speech perception in quiet and noise, sound localization, and expressive and receptive speech and language acquisition?; 2) What benefits, if any, are provided when simultaneous implantation is performed versus sequential implantation?; and 3) What impact does age at implantation have on the benefits seen with bilateral cochlear implantation in children? Throughout this review, mixed evidence of bilateral benefit was reported for various outcomes including speech perception in quiet and noise, sound localization, and speech and language acquisition. Both sequential and simultaneous implant subjects received bilateral benefit. Continued research regarding benefits observed with earlier age at implantation, the impact of hearing aid use in the non-implanted ear between sequential surgeries, and speech and language outcomes in bilaterally implanted children is necessary.

Introduction

Cochlear implants (CIs) have been a successful technology for restoring audibility to individuals with bilateral severe to profound sensorineural hearing loss since the 1980s (Sarant, Harris, & Bennet, 2015). When hearing aid (HA) amplification is not effective due to the severity and configuration of an individual's hearing loss, a unilateral CI has historically been used to improve speech perception abilities (Schafer, Amlani, Paiva, Nozari, & Verret, 2011). The unilateral CI paradigm has demonstrated potential for improved communication abilities in children and adults.

The current candidacy criteria for cochlear implantation in young children is the documentation of a severe to profound hearing loss as shown through audiometric and electrophysiologic testing (Schwartz et al., 2012). Implantation typically follows a trial with appropriately fit hearing aids and the documentation of lack of benefit or progress in language development as judged by the family and healthcare team. For adults, candidacy for implants was initially only for individuals who presented with bilateral profound deafness, measured by thresholds of greater than 100 dB and 0% sentence understanding, and who derived no benefit from maximally powered hearing aids. However, those criteria have been expanded to include adults with some preserved hearing, defined by thresholds greater than 70 dB and ≤ 50% sentence understanding. These criteria for cochlear implantation are set by the United States Food and Drug Administration (FDA), and that set of criteria is what the private insurance companies most often use for the purposes of determining reimbursement. Due to the high cost of the implantation surgery, CIs are typically only offered to those who qualify based on their insurance coverage. Qualification for bilateral implantation could be assumed if the criteria for a unilateral implant have been met; however, insurers in the United States do not universally cover a second implant. Because of this, there has been a need for further research demonstrating the benefit from a second implant as a prerequisite for insurance coverage.

A large body of research over several decades has established significant benefits of unilateral cochlear implantation in adults and children and the unilateral CI paradigm as the treatment norm for individuals with bilateral severe to profound hearing loss by restoring auditory function to these patients (Schwartz et al., 2012). Bimodal arrangements, or the use of a CI on the worse ear and a hearing aid on the better ear or the non-implanted ear, are also a consideration for individuals who have preserved hearing in their non-implant ear. Through the additional acoustic stimulation provided from the hearing aid, speech perception has been shown to improve (Dorman and Gifford, 2010). This method is also an option because of the reluctance to damage both ears, as the surgical placement of an electrode array into the cochlea may result in the loss of residual hearing. In this review, research regarding whether bimodal listening arrangements are enough to overcome the debilitating effects of noisy conditions, or whether a bilateral CI listening arrangement is better will be discussed.

Areas of potential bilateral benefit from current research examined in this review include speech perception, sound localization, sequential versus simultaneous implantation, and expressive and receptive speech and language acquisition for bilateral CI users compared with unilateral CI and bimodal (HA+CI) performance. Speech perception can be measured in both quiet and in noise (Johnston, Durieux-Smith, Angus, Connor, & Fitzpatrick, 2009). Sound localization is the ability of an individual to identify and locate the source of a sound in space and is typically measured on a horizontal plane. Speech perception in noise is enhanced through three binaural phenomena: binaural squelch, binaural summation, and the head-shadow effect (Schafer et al., 2011). Binaural squelch is the ability of the brain to suppress the effect of competing noise when it is spatially separated from the speech signal, and this ability has been shown to improve speech perception performance in noise. Binaural summation, which is an increased sensation of loudness of the incoming signal relative to listening with a single ear, has also shown to improve listening performance. Finally, speech perception in noise is enhanced by either reducing or taking advantage of the head shadow effect. Depending on the location of the speech and noise sources relative to the listener, head shadow may improve the signal-to-noise ratio at one of the listener's ears, which in turn may contribute to improved speech perception. Because accurate perception of binaural cues is critical for sound localization in the horizontal field and perception of speech in noisy environments, new research methods are being developed to measure a subject's ability to benefit from these cues such as the anticipatory eye movement paradigm described in Winn, Kan, & Litovsky (2019).

Bilateral implantation is performed either sequentially or simultaneously. Sequential implantation is performed at different times, whereas simultaneous implantation occurs when both implant devices are provided at the same time (Sharma et al., 2007). Because development of the auditory pathways has been shown to have a sensitive period, with better outcomes seen in children implanted before 3.5 years of age, some have expressed concerns that a sequential implantation plan may not allow optimal binaural processing to develop in deaf children (Sharma et al., 2007). Nonetheless, candidacy for simultaneous bilateral implants is likely dependent on a variety of factors, including the preference of the patient or the patient's family, the preference of the surgeon, and the likelihood of payment by an insurer for the second implant (Schwartz et al., 2012). It may also be challenging to obtain insurance approval for a second implant for those individuals who have already been implanted unilaterally because of the requirement for documentation of medical necessity. With one implant functioning, these individuals may no longer satisfy the criteria for insurance coverage based on audiometric configuration. This literature review will summarize recent findings describing potential benefit from bilateral implantation in child and adult cochlear implant candidates.

Methods

SELECTION CRITERIA FOR STUDIES

All research articles investigating both pediatric and adult bilateral cochlear implantation were included. Longitudinal studies, retrospective studies, reviews, qualitative studies, cross-sectional, cohort studies, meta-analyses, and repeated measures were eligible for inclusion. No exclusion criteria were set based on the number or age of participants. Publication in a peer-reviewed journal was required.

TIME FRAME

The review included studies published between 2002 and February 2019. Because of the amount of current research available and lack of articles predating 2002, it was reasonable to commence the search from this time forward to provide the most recent information.

OUTCOME MEASURES

Outcomes measures of interest included speech perception in quiet and noise, sound localization, and expressive and receptive speech and language acquisition. Studies comparing benefit of those listeners with sequential and simultaneous bilateral implantation were of particular interest.

SEARCH STRATEGY

Electronic databases, EBSCOhost and PubMed, were used to search articles related to both pediatric and adult bilateral cochlear implants. As seen in Table 1, the primary search terms were “bilateral,” “cochlear implant,” “pediatric,” and “speech perception.”

INCLUSION/EXLUSION CRITERIA

Inclusion criteria for this critical review were pediatric and adult subjects, bilateral cochlear implant surgery, and publication in a peer-reviewed journal. Areas excluded from this review include complications from surgery, hybrid CIs, differences in performance between manufacturers, and information from non-peer reviewed sources.

RESEARCH QUESTIONS:

1. What are the benefits of bilateral cochlear implantation compared to unilateral CI or bimodal arrangements in the following areas: speech perception in quiet and noise, sound localization, and expressive and receptive speech and language acquisition?
2. What benefits, if any, are provided when simultaneous implantation is performed versus sequential implantation?
3. What impact does age at implantation have on the benefits seen with bilateral cochlear implantation in children?

Table 1
Databases Searched and Search Terms Used

Database	Search Terms
PubMed	Bilateral; cochlear implants; speech perception; pediatric; candidacy; language outcomes; localization; sequential; simultaneous
Milner Library Database	Bilateral; cochlear implants; speech perception; quiet; noise; pediatric; candidacy; language outcomes; localization; sequential; simultaneous

Search terms were utilized in conjunction with each other (i.e. "cochlear implants AND speech perception").

Results

SPEECH PERCEPTION

Speech perception in quiet

Multiple studies in adults have examined potential benefits of binaural listening in speech perception in quiet tasks for bilateral implant users (Muller, Schon, & Helms, 2002; Tyler et al., 2002; Litovsky, Parkinson, Arcaroli, & Sammeth, 2006a; Yoon, Li, Kang, & Fu, 2011; Dunn, Tyler, Witt, Ji, & Gantz, 2012; Gifford & Dorman, 2018). Various listening conditions were compared, including bimodal versus bilateral CI and unilateral CI versus bilateral CI. Stimuli used included Consonant-Nucleus-Consonant (CNC) monosyllabic words (Tyler et al., 2002; Litovsky et al., 2006a; Dunn et al., 2012; Gifford & Dorman, 2018), Freiburg monosyllabic words (Muller et al., 2002), and consonant and vowel discrimination (Yoon et al., 2011). Speech stimuli were presented in each of these studies at 0 degrees azimuth at a distance of 1 meter. Presentation levels ranged from 60 dB SPL to 70 dB SPL, with Dunn et al. (2012) utilizing a level of 70 dBC.

Results from the monosyllabic word testing revealed statistically significant improvement in scores in the bilateral CI condition across two studies (Litovsky et al., 2006a; Muller et al., 2002). Litovsky et al. (2006a) found that 32 of 33 (97%) subjects scored higher in the bilateral CI condition than at least one unilateral CI condition, and 21 subjects (67%) scored better in the bilateral CI condition than both of the unilateral CI conditions. Similarly, Muller et al. (2002) found subjects in the bilateral CI condition scored 18.7 percentage points higher than the unilateral CI condition, which was statistically significant.

Despite the statistical significance observed in the studies above, other reports did not find significant differences in performance between listening conditions (Tyler et al., 2002; Yoon et al., 2011; Dunn et al., 2012; Gifford & Dorman, 2018). Gifford & Dorman (2018) reported a mean score of 81% correct in the bimodal condition, a mean of 76% in the best unilateral CI condition, and a mean of 82% in the bilateral CI condition. These results were comparable to Dunn et al. (2012) where subjects in the unilateral CI condition scored 67% correct for monosyllabic words, and the bilateral CI subjects scored 70% correct. Neither of these studies resulted in statistically significant differences between the various conditions tested, except for two subjects in Dunn et al. (2012) who performed significantly better in the bilateral CI condition than the unilateral CI condition. However, one subject performed significantly worse in the bilateral CI condition when compared to the unilateral CI condition (Dunn et al., 2012). Both Tyler et al. (2002) and Yoon et al. (2011) reported substantial bilateral benefit in a minority of bilateral implants users (2 out of 9 participants in each study). Besides the one subject who performed significantly worse in the bilateral CI condition when compared to the unilateral CI condition in Dunn et al. (2012), none of the three other studies reported any subjects who showed a significant decrease in performance in the bilateral CI condition (Tyler et al., 2002; Dunn et al., 2012; Gifford & Dorman, 2018).

Multiple studies have also found pediatric bilateral cochlear implant recipients show benefit from binaural listening in speech perception in quiet tasks under some test conditions (Asp et al., 2012; Asp et al., 2015; Reeder, Firszt, Cadieux, & Strube, 2017). The studies had similar testing environments, with the administration of monosyllabic words presented at 0 degrees azimuth. The presentation level for the studies ranged from 60 dB SPL to 65 dB SPL. The subjects presented in these studies served as their own controls, with the unilateral CI and bilateral CI conditions undergoing intrasubject comparisons only. Further, Reeder et al. (2017) examined a single list of 20 sentences from a standardized set in quiet. These sentences were presented at a softer level of 50 dB SPL to avoid ceiling effects and to determine understanding abilities for soft conversational speech (Reeder et al., 2017).

Two of the three studies reported a ceiling effect for both the bilateral CI and unilateral CI conditions, with multiple subjects scoring over 80% to 90% (Asp et al., 2012; Asp et al., 2015). When ceiling effects are evident in both conditions, it is less likely that bilateral benefit can be observed. In one study, 51% of subjects (29 of 57) demonstrated higher speech perception in the bilateral CI condition when compared to the unilateral CI condition (Asp et al., 2012). However, only 11% of subjects (6 of 57) had statistically significant higher speech perception in the bilateral CI condition (Asp et al., 2012). This is in line with the findings of Reeder et al. (2017), who reported no statistically significant differences between the bilateral CI and unilateral CI conditions after 24 months of bilateral experience. Although the bilateral CI condition yielded results that were equal to or better than the unilateral CI condition, the differences only ranged from 2.5 to 8.6 percentage points between the two conditions (Reeder et al., 2017).

A statistically significant mean difference was found between bilateral and unilateral speech perception scores in children in two of the studies (Asp et al., 2012; Asp et al., 2015). However, this finding was only observed at the first of three visits occurring at one-year inter-test intervals as described in Asp et al. (2015), with no significant differences noted at visits two and three. Further, Asp et al. (2012) reported the 5% difference noted between the bilateral CI condition (87% correct) and the unilateral condition (82% correct) equated only to approximately one additional word correctly identified during the bilateral CI condition.

Speech perception in noise

Studies investigating the bilateral benefit for adults for speech perception in noise, with the presentation of speech and noise co-located at 0 degrees, have found some bilateral cochlear implant recipients show benefit from binaural listening compared to listening in a unilateral condition (Tyler et al., 2002; Litovsky et al., 2006a; Yoon et al., 2011). All three studies presented a combination of the signal and noise at 0 degrees azimuth from a distance of 1 meter. The presentation level used was 65 dB SPL (Litovsky et al., 2006a) or 70 dB SPL (Tyler et al., 2002), with Yoon et al. (2011) using a varied output level, ranging from 65 dB SPL to 70 dB SPL, which corresponded to a most comfortable loudness level based on the Cox Loudness Scale rating. Stimuli used included sentences from the BKB speech-in-noise test (Litovsky et al., 2006a) and the Hearing in Noise Test (HINT) (Tyler et al., 2002; Yoon et al., 2011). Noise types included 4-talker babble and speech-shaped steady state noise at a signal-to-noise ratio (SNR) ranging from 0 dB to +10 dB.

Overall, these three studies showed minimal but significant bilateral benefit in a subset of listeners. A small bilateral benefit was shown in 4 of 9 subjects and 5 of 9 subjects in Tyler et al.

(2002) and Yoon et al. (2011), respectively. Both studies reached statistical significance for those subjects showing benefit in the bilateral CI condition. Litovsky et al. (2006a) found 15 of 34 subjects (44%) demonstrated significant bilateral benefit over one of two unilateral conditions, 2 of 34 subjects (6%) showed a significant decrement in the bilateral condition relative to the unilateral score, and 17 of 34 subjects (50%) showed no effect.

Studies in pediatric populations have also investigated the bilateral benefit for speech perception in noise and have demonstrated benefit from binaural listening in speech perception in noise tasks while listening with bilateral cochlear implants (Kim et al., 2009; Reeder et al., 2017). Both studies presented words and noise in front of the subject at a fixed signal-to-noise ratio (SNR) ranging from +8 dB to +10 dB SNR. Kim et al. (2009) utilized an open-set word-list, whereas Reeder et al. (2017) used standardized consonant-nucleus-consonant (CNC) words because of the large availability of lists. Additionally, Reeder et al. (2017) administered two sentences in noise tests: BKB sentence-in-noise (BKB SIN) and the Hearing in Noise Test (HINT). The BKB SIN was presented at 65 dB SPL with four talker babble at SNRs that progressed from +21 dB to 0 dB in 3 steps. The HINT was performed at 60 dB SPL using restaurant noise with the first sentence having a +12 dB SNR, with a step size of +/- 4 during the first four sentences, and +/- 2 for the remaining sixteen sentences. Results from Kim et al. (2009) demonstrated significantly better performance during the bilateral CI condition when compared to the unilateral CI condition. However, Reeder et al. (2017) reported bilateral CI performance to be comparable to that of the unilateral CI for all measures studied. Although both studies tested subjects who had congenital deafness and waited several years between their first and second CI implants, the discrepancies in results may be attributed to differences in statistical power arising from the larger sample size of twenty-four subjects in Reeder et al. (2017) compared to the eleven subjects in Kim et al. (2009).

Studies in adults investigating potential head shadow benefit for speech perception in noise when speech and noise are not co-located at 0 degrees have found benefit from binaural listening for some bilateral cochlear implant recipients compared to unilateral and bimodal conditions (Muller et al., 2002; Tyler et al., 2002; Litovsky et al., 2004; Litovsky et al., 2006a; Dunn et al., 2012; Gifford & Dorman, 2018). Speech was presented at levels of 65 dB SPL to 70 dB SPL at 0 degrees azimuth (Muller et al., 2002; Tyler et al., 2002; Litovsky et al., 2004; Litovsky et al., 2006a; Gifford & Dorman, 2018). Dunn et al. (2012) used a varied presentation level dependent on the subject, with a minimum level for speech presentation of 60 dBA to prevent floor and ceiling effects. Speech materials consisted of Bamford-Kowal-Bench sentences (Litovsky et al., 2004; Litovsky et al., 2006a), the Hochmair-Schulz-Moser (HSM) prerecorded sentence test (Muller et al., 2002), CNC monosyllabic words, CUNY sentences, and HINT sentences (Tyler et al., 2002). A carrier phrase was used to capture the attention of the subject in one study (Dunn et al., 2012). Background noise was presented at a signal-to-noise ratio (SNR) where 50% of key words were correctly identified (Litovsky et al., 2004; Litovsky et al., 2006a; Dunn et al., 2012; Gifford & Dorman, 2018). Both Muller et al. (2002) and Tyler et al. (2002) used a varying noise level per each individual subject to prevent floor and ceiling effects. For the presentation of background noise, Dunn et al. (2012) utilized an eight-speaker array on a 108-degree arc, while the remaining studies presented the competing background noise from 0 degrees, 90 degrees, and 270 degrees azimuth.

Litovsky et al. (2004) reported no improvement in binaural listening when speech and noise were co-located at 0 degrees azimuth. All five studies reported a bilateral benefit when compared to the unilateral condition when speech and noise were spatially separated. A large bilateral effect was demonstrated in Litovsky et al. (2004) when the background noise was presented from the side of the poor ear, defined by the ear with the poorer speech reception threshold, and speech was presented from the side of the better ear. Additionally, when comparing the bilateral CI condition to the unilateral CI condition, 7/7 subjects showed improvement in the bilateral condition in Tyler et al. (2002) when the second implant was on the side opposite of the noise source. All subjects except three obtained equal or higher scores in the bilateral condition in Muller et al. (2002), 32/34 (94%) subjects had a significant advantage for the bilateral condition in Litovsky et al. (2006a), and 8/13 subjects demonstrated significant bilateral benefit in Dunn et al. (2012). Results from Muller et al. (2002) further showed the average scores for sentence understanding was 31.1 percentage points higher with both cochlear implants compared with the cochlear implant on the same side of the noise alone, and 10.7 percentage points higher with both cochlear implants compared with the cochlear implant on the opposite side of the noise alone, with these findings being statistically significant. Further results from Dunn et al. (2012) had the remaining 5/13 subjects show no difference between the bilateral CI and unilateral CI conditions. Also, Litovsky et al. (2006a) reported no subjects had a decrement in performance for the bilateral CI condition compared to the unilateral CI condition.

In addition to the bilateral CI benefit found in comparison to the unilateral CI condition, Gifford & Dorman (2018) reported a bilateral CI advantage when being compared to a bimodal listening arrangement. This study had an eight-speaker array which surrounded the subject in a

360-degree arc. The speech test used was the recorded Hearing in Noise Test (HINT), which was presented from a loudspeaker at 0 degrees azimuth at an adaptive level where 50% of key words were accurately identified during a speech perception task. The background noise was proprietary restaurant noise, presented from all 8 speakers, at a fixed level of 72 dB SPL. Because the task was adaptive, standard benefit represented in dB was used to demonstrate the bilateral benefit observed. Bilateral benefit for bimodal subjects regarding the adaptive HINT ranged from -5 dB to 8 dB, with a mean of 1.0 dB, whereas the bilateral benefit for bilateral CI subjects ranged from 1 dB to 8 dB, with a mean of 4.9 dB. Overall, a significant difference was noted between the bimodal and bilateral CI users for the adaptive HINT testing, with better performance observed for bilateral CI subjects.

Multiple studies investigating the pediatric population have shown head-shadow benefit for bilateral cochlear implant users during speech in noise tasks (Steffens et al., 2008; Galvin, Hughes, & Mok, 2010; Asp et al., 2012; Asp et al., 2015). For each of the four studies, subjects served as their own control, with an intrasubject comparison of the bilateral CI condition versus the unilateral CI condition. The speech signal for all four studies was presented at 0 degrees azimuth at approximately 1 to 1.5 meters in front of the subjects (Steffens et al., 2008; Galvin et al., 2010; Asp et al., 2012; Asp et al., 2015)., with fixed speech presentation levels ranging between 65-70 dB SPL for three of the studies. Galvin et al. (2010) used a presentation level of 62 dBA. Speech materials consisted of spondee words for both Steffens et al. (2008) and Galvin et al. (2010), whereas Asp et al. (2012) and Asp et al. (2015) used phonemically balanced monosyllabic standardized word lists. The noise in Steffens et al. (2008) was presented at an azimuth of +/- 45 degrees, which was like Asp et al. (2012) and Asp et al. (2015) where additional speakers were also added at +/- 135 degrees. Galvin et al. (2010) had speakers for noise set up at +/- 90 degrees. The noise levels were presented at a signal-to-noise ratio (SNR) determined by a range of 70% to 79.4% correct obtained in the bilateral CI aided condition for Steffens et al. (2008) and Galvin et al. (2010), respectively. Asp et al. (2012) and Asp et al. (2015) used a fixed SNR of 0 dB. Additionally, two of the four studies used a four-alternative-forced-choice paradigm for word recognition (Steffens et al., 2008; Galvin et al., 2010).

When speech was spatially separated from noise, as described in the four studies above, bilateral benefit was evident across each of these studies in at least one test condition. In Steffens et al. (2008), where three different speakers were used, significantly above chance was calculated to be greater than 40% correct. In this study, 19 of 19 subjects scored significantly above chance in the bilateral CI condition. Although all subjects scored better in the bilateral CI condition than the unilateral CI condition, 8 of 19 subjects in the unilateral CI condition also scored significantly above chance. This is in line with Asp et al. (2012) and Asp et al. (2015) where results revealed 78% (35 of 45 subjects) and 72-83% (dependent on which of the three annual visits was reviewed) of subjects demonstrated higher speech perception scores in the bilateral CI condition, respectively. However, Asp et al. (2012) reported only 13% (6 of 45 subjects) showed statistically significant improvement in the bilateral CI condition, whereas the results from Asp et al. (2015) demonstrated significantly higher mean speech perception scores in the bilateral CI condition than the unilateral CI condition. The mean bilateral CI speech perception in noise score (61%) was significantly higher than the mean unilateral CI score (48%); however, the 13% difference equated only to approximately 3 more correct words in the bilateral CI condition (Asp et al., 2012). Galvin et al. (2010) further investigated the effects of ipsilateral and contralateral noise in the bilateral CI and unilateral CI conditions. When noise was presented on the side of the first implanted CI in the bilateral CI condition, 5 of 9 subjects demonstrated superior performance compared to the unilateral CI condition. With noise presented on the side of the second implanted CI, no subjects showed superior performance in bilateral CI compared to unilateral CI. With performance shown to be superior in the bilateral CI condition with noise presented on the side of the first implanted CI, and no benefit observed with noise presented on the side of the second implanted CI, demonstration of a possible advantage of listening with the first-implanted ear is evident. These results are similar to those observed in adult subjects in Tyler et al. (2002) and Muller et al. (2002) where performance was significantly better with noise on the same side of the first implanted CI; however, Muller et al. (2002) also found significant bilateral benefit for subjects listening with noise presented on the side of the second implanted CI.

Head shadow benefit in children when comparing bilateral CI and bimodal listening arrangements was also reported in three studies (Litovsky, Johnstone, & Godar, 2006c; Schafer & Thibodeau, 2006; Mok, Galvin, Dowell, & McKay, 2009). Schafer and Thibodeau (2006) placed speakers at 135 degrees and 225 degrees azimuth to simulate a classroom listening environment for a child with preferential seating at the front of classroom, while Litovsky et al. (2006c) and Mok et al. (2009) used speakers at -90 degrees and 90 degrees. The target speech was located at 0 degrees azimuth and was presented at a varied level for both Litovsky et al. (2006c) and Schafer and Thibodeau (2006), and Mok et al. (2009) used a presentation level of 65 dB SPL. Continuous noise was presented at levels ranging between 55 dB SPL to 60 dB SPL (Litovsky et al. 2006c; Mok et al., 2009), and Schafer and Thibodeau (2006) used a 60 dBA noise level. The stimuli used were 10 simple phrases about body parts (Schafer & Thibodeau, 2006), a closed set of 25 children's spondees (Litovsky et al., 2006c), and consonant-nucleus-consonant words (Mok et al., 2009). No statistically significant differences for speech in noise thresholds were noted between the two binaural conditions in two of the three studies (Litovsky et al., 2006c; Schafer & Thibodeau, 2006). These results show both binaural listening arrangements provided listeners with similar head-shadow effects for speech perception tasks. However, Mok et al. (2009) reported that bilateral CI subjects demonstrated significantly greater advantage when noise was presented from the side, with the bimodal subjects not having any significant advantage. This report demonstrates a greater head shadow advantage for bilateral CI subjects when compared to bimodal subjects. The advantage for bilateral CI subjects regarding this measure may be explained by head shadow being a high frequency phenomenon, and the hearing aid for bimodal subjects providing little to no access to high frequency sounds.

LOCALIZATION

Studies in adults investigating the impact of bilateral CIs in comparison to a unilateral CI condition regarding the localization of a sound source were reviewed (Tyler et al., 2002; Litovsky et al., 2004; Dunn et al., 2012). Within these three studies, bursts of noise were presented at a level of 65 dB to 70 dB (Tyler et al., 2002; Litovsky et al., 2004), or everyday sounds were presented at 60 dBC (Dunn et al., 2012). Litovsky et al. (2004) and Dunn et al. (2012) both utilized an eight-speaker array, whereas Tyler et al. (2002) had two speakers positioned at 45 degrees azimuth to the right and left of the subjects. An example of a speaker array used in localization tasks is shown in Figure 1. Responses were obtained in various ways including reporting a speaker number corresponding to the perceived sound location (Litovsky et al., 2004), by the subject pressing a number button corresponding to the perceived location of the target sound using a touch screen (Dunn et al., 2012), and indicating whether the sound was perceived to the right or left of the subject (Tyler et al., 2002). All three studies employed a unilateral CI condition and a bilateral CI condition; however, Dunn et al. (2012) added 50 dBC of background noise to the localization task. The noise used in Dunn et al. (2012) consisted of male and female voices repeating sentences, and the noise was presented from a different speaker than the everyday sounds utilized in the study. The background noise would begin playing from a random speaker, and the subject was informed to press play on the touch screen when they were ready for the target sound to play.

In Tyler et al. (2002), all seven subjects scored significantly above chance in identifying the target speaker in the bilateral CI condition, with only 3/7 subjects scoring above chance in the unilateral CI condition. The scores for the bilateral CI condition were higher than the unilateral CI condition for all subjects; however, for one subject this difference failed to reach statistical significance. These results align with Litovsky et al. (2004) where the unilateral CI condition resulted in significantly higher error than the bilateral CI condition, with mean unilateral localization performance being approximately 58 degrees off target, while bilateral listening resulted in a mean average of approximately 26 degrees off target. Dunn et al. (2012) also reported similar findings, with 9/13 subjects demonstrating significant improvement in the bilateral CI condition when compared to the unilateral CI condition. Of the 13 subjects, only 4 had no significant difference in localization ability between the unilateral and bilateral CI conditions. Bilateral benefit was also shown in Dunn et al. (2012), with 13/13 subjects in the bilateral CI condition scoring better than chance, and only 3/13 subjects in the unilateral CI condition scoring better than chance on localization tasks. Overall, results from these three studies demonstrated significant localization benefit for the adult bilateral CI users.

Four studies investigated the impact of bilateral CIs on the ability of children to localize the source of a sound when compared to the unilateral CI paradigm (Steffens et al., 2008; Asp et al., 2012; Asp et al., 2015; Reeder et al., 2017). A variety of speaker arrays were utilized, ranging from -140 degrees to 140 degrees with 3 to 15 total speakers. Stimulus presentation levels were 60 to 65 dB SPL across the four studies, using a range of stimuli including pulsating white noise, two recorded animal sounds (e.g. dog barks for low frequency stimulus and cricket chirps for high frequency stimulus), and monosyllabic words. Stimuli were presented from one of the speakers in the array at a time, and the source speaker was selected in a randomized sequence across trials. Subjects were instructed to either choose a number on the labeled speaker or point to the speaker to identify the perceived source of the presented stimulus, and accuracy in localization was calculated as percent correct. In Steffens et al. (2008), a bilateral benefit for the bilateral CI condition was found to be 18% greater for localization accuracy in comparison to the unilateral CI condition. Overall, the mean correct scores were 75% for bilateral CIs and 58% with a unilateral CI. This finding agrees with Asp et al. (2012) and Asp et al. (2015) where the mean sound localization accuracy in the bilateral CI condition for both high and low frequency stimuli showed statistically significantly higher performance than the mean unilateral CI condition. Specifically, the low frequency dog bark stimulus resulted in 57% to 76% correct performance in the bilateral CI condition, and the high frequency cricket chirp stimulus had a correct response rate of 74% to 83%. The unilateral condition for both high and low frequency stimuli resulted in near chance performance (Asp et al., 2012; Asp et al., 2015). However, Reeder et al. (2017) failed to demonstrate a statistically significant difference between the bilateral CI and unilateral CI performance of the child's first implanted ear, though localization was significantly poorer than both the first implanted ear and bilateral condition when listening with the second implanted ear alone. This lack of significance may be in part to subjects in Reeder et al. (2017) having a mean inter-implant interval of 9.14 years, compared to mean inter-implant intervals of 2.6 years, 2.5 years, and 4 years observed in Asp et al. (2012), Asp et al. (2015), and Steffens et al. (2008), respectively.

The impact of bimodal listening arrangements on sound localization ability was compared to bilateral CI conditions in two studies in children (Litovsky et al., 2006b; Reeder et al., 2017). Both studies utilized a 15-speaker array with a stimulus presentation level of 60 dB SPL and had speakers at +/- 70 degrees around the horizontal plane arc. Spondaic and monosyllabic words were used as the stimulus in Litovsky et al. (2006b) and Reeder et al. (2017), respectively. Further, Litovsky et al. (2006b) reported the minimum audible angle (MAA), or the smallest change in the position of a sound source that can be reliably discriminated. The thresholds for this measurement were defined as the smallest angle at which performance reached 70.9% correct. Overall, 9 of 13 bilateral CI subjects were able to achieve MAA thresholds of less than or equal to 40 degrees, with 8 of 9 of those subjects reaching thresholds of less than or equal to 20 degrees (Litovsky et al., 2006b). The MAA thresholds for the bimodal listening subjects were significantly higher compared to the bilateral CI listeners, with an overall group mean of approximately 45 degrees. However, Reeder et al. (2017) reported individuals with sequential CI surgeries who utilized a bimodal listening arrangement between surgeries performed 10 to 30 degrees better in the bilateral CI condition compared to the unilateral CI condition. Sound localization performance appears to be poorer in a bimodal condition in comparison to a bilateral CI condition; however, utilizing the bimodal arrangement between surgeries in a sequential implantation has potential to promote the development of sound localization ability once that ear is implanted relative to unilateral CI listening alone prior to receiving a second implant.

SIMULTANEOUS VS. SEQUENTIAL

One study examining the benefits and shortcomings of the sequential CI implantation paradigm in the adult population failed to find an impact on the length of time between CI surgeries regarding bilateral benefit (Dunn et al., 2012). Dunn et al. (2012) investigated sequential CI subjects with an average duration of deafness of 11 years prior to their first CI implantation, with an average delay of 74 months between surgeries. Statistically significant bilateral CI benefits for sequentially implanted listeners were demonstrated under various conditions including speech and noise co-located at 0 degrees azimuth, speech and noise not co-located at 0 degrees azimuth, and localization tasks. There were no correlations in the data suggesting a longer delay between implants is harmful to potential bilateral benefit.

In children who receive sequential implants, unilateral performance tends to be poorer in the second implanted ear. The disadvantage of the second implanted ear for unilateral listening appears to be related to age at second implant and/or time between surgeries. Two additional studies examining children who received sequential implants specifically focus on the potential impacts of age at implantation of the second CI on bilateral benefit (Galvin, Mok, & Dowell, 2007; Graham et al., 2009). Galvin et al. (2007) examined subjects who received a second sequential CI between the ages of 3 and 14. A speech in noise task was used where the speech and noise were not co-located at 0 degrees azimuth. Speakers were set up at 0 degrees azimuth, along with 90 degrees to the right and left, with speech always being presented from the speaker at 0 degrees. An adaptive spondee discrimination test (AdSpon) was utilized with a four-alternative-forced-choice paradigm. Continuous speech-shaped broadband noise was enabled at a signal-to-noise ratio (SNR) that resulted in 79.4% correct. Results from this study indicated that none of the 9 subjects tested gained additional benefit in the bilateral CI condition when the noise was presented on the opposite side of the first implanted CI. However, when the noise was presented on the same side as the first implanted CI, 8 of 10 subjects had superior performance, or a lower SNR, in the bilateral CI condition than the unilateral CI condition. Graham et al. (2009) compared subjects who received a second sequential implant between ages 3 and 13, and those subjects who received a second CI over the age of 13 years. All subjects received benefit from the first CI and were in turn implanted with a second sequential CI. The Bamford Kowal Bench (BKB) sentence test in quiet was used. Performance when listening with the second implanted ear alone indicated that 18 of 25 subjects who received the second CI between ages 3 and 13 years scored 60% or more in quiet. On the other hand, 0 of 9 subjects aged 15 or older at the time of the second CI scored more than 30% in quiet when listening using the second implanted ear alone, with 7 of 9 subjects scoring 7% or less. These results are noteworthy because the subjects who received their second implant at age 15 or later scored between 84 to 100% when using their first implant alone.

One study investigating the pediatric population also looked at a comparison of localization ability in subjects with either simultaneous or sequential cochlear implantation (Killan, Scally, Killan, Totten, & Raine, 2018). This study utilized a prerecorded stimulus saying, “Hello, what’s this?” The speakers were set up at -60 degrees to 60 degrees azimuth, with 5 speakers total. The presentation level was set to 70 dBA, and the subjects were instructed to face directly ahead for the presentation of the target stimulus and to say or point to the number located at the correct speaker. Results for subjects with simultaneous implants revealed a mean RMS error of 21.6 degrees (SD 11.07 degrees), and the sequentially implanted subjects had a mean RMS error of 29.5 degrees (SD 12.7 degrees). Those with sequential implants were also shown to have an increased RMS error with longer inter-implant intervals, with each month’s wait being associated with a decrease in localization accuracy of 0.14 degrees RMS error. Overall, it would appear that potential for bilateral localization benefit in children decreases with longer intervals between surgeries.

SPEECH AND LANGUAGE ACQUISITION

A few recent studies have evaluated the development of speech and language in pediatric subjects who have received either bilateral CIs, a unilateral CI, or who utilize a bimodal amplification paradigm (Boons et al., 2012; Ching et al., 2014; Valimaa et al., 2017). Two of the studies also assessed the impact of simultaneous CI implantation versus sequential CI implantation on speech and language acquisition and whether there is an observed benefit with a shorter interval between sequential implant surgeries (Boons et al., 2012; Ching et al., 2014). Expressive and receptive language outcomes were assessed throughout all three studies. Various assessment materials were utilized including the Standardized Finnish version of the CDI Infant Form: Words and Gestures (Valimaa et al., 2017), the Dutch version of the Reynell Development Language Scales (RDLS) and the Schlichting Expressive Language Test (SELT) (Boons et al., 2012), and the Preschool Language Scale 4th Edition (Ching et al., 2014).

Boons et al. (2012) and Ching et al. (2014) examined comparisons of speech and language acquisition for bilateral CI subjects and unilateral subjects, with Ching et al. (2014) additionally looking at bimodal subjects. Both the RDLS and SELT are norm-referenced measures with average standard scores of 100 and standard deviations of 15. Language delay is indicated in subjects with scores more than two standard deviations below the mean, though mild delays may be identified using a criterion of more than one standard deviation below the mean. Boons et al. (2012) reported both expressive and receptive language ability was significantly better in the bilateral CI group when compared to the unilateral CI group. On the receptive RDLS test, the bilateral CI group had a mean score of 85.6, while the unilateral CI group scored a mean of 76.2. These results revealed the unilateral CI group had 12 subjects (48%) with a language delay more than two standard deviations below the mean, and the bilateral CI group only had two subjects (8%) more than two standard deviations below the mean. For the expressive Word Development Subscale of the SELT test, the bilateral CI group had a mean score of 86.1, with the unilateral CI group having a mean score of 70.4. This test revealed the unilateral CI group had 14 subjects (56%) more than two standard deviations below the mean, while the bilateral CI group only had 3 subjects (12%) more than two standard deviations below the mean. Finally, the Sentence Development Subscale of the SELT expressive test revealed a mean score of 86.8 for the bilateral CI group, and a mean score of 77.0 for the unilateral CI group. There were 7 subjects (28%) in the unilateral CI group who scored more than two standard deviations below the norm, and the bilateral CI group had 2 subjects (8%). Overall, the bilateral CI subjects scored significantly better than the unilateral CI subjects. However, the significantly greater expressive and receptive language abilities in bilateral CI subjects compared to unilateral CI subjects in Boon et al. (2012) was not replicated in Ching et al. (2014). The overall effect of device configuration was not determined to be significant, whether the configuration was bimodal, unilateral CI, or bilateral CIs (Ching et al., 2014). Bimodal subjects had scores 6.6 points lower than the bilateral CI subjects for outcomes of expressive and receptive language development, and unilateral subjects had scores 8.9 points lower than the bilateral CI subjects. Neither of these results successfully reached statistical significance, although scores were lower for the bimodal and unilateral CI subjects. A consistent finding was that bilateral implant users tended to have language delays relative to peers with normal hearing. Results from Valimaa et al. (2017) found language delays in bilateral CI subjects when compared to normal hearing subjects. Valimaa et al. (2017) reported subjects at 9 months post bilateral CI activation reached the mean receptive vocabulary growth of 14-month-old infants with normal hearing. At that time, the subjects' mean chronological age was 21.9 months, resulting in a delay of 7 months in acquisition of receptive vocabulary. Additionally, with a mean chronological age of 24.9 months at 12 months post bilateral CI activation, expressive vocabulary for the bilateral CI subjects was 148.6 words, whereas 24-month old children with normal hearing have approximately 300 words (Valimaa et al., 2017).

Further, Boons et al. (2012) and Ching et al. (2014) reported on the potential benefits for speech and language acquisition from simultaneous implantation versus sequential implantation. Ching et al. (2014) noted that earlier age at first cochlear implantation activation was significantly associated with better outcomes, with a delay from 10 to 24 months in cochlear implant activation being associated with a decrease of 8.1 points in outcomes scores. This decrease is equivalent to a decrement of more than one-half of a standard deviation. Boons et al.

(2012) also reported that better results were observed across all three tests utilized in the study for sequential implantation subjects who had a shorter interval between the two CI activations. However, the simultaneous group did not perform better than the sequential group on the RLDS receptive test or the SELT expressive Sentence Development Subtest (Boons et al., 2012). Of those subjects in the sequential implantation group, the second implant was received between the ages of 1.08 and 5.01 years; one subject received the second implant within one year of the first implant, nine subjects within the second year, and seven subjects within the third year. The simultaneous group did however perform significantly better on the Word Development Subtest of the SELT than the sequential group. Additionally, one subject scored one standard deviation above the norm on the RLDS receptive test, and that subject was simultaneously implanted at 1.02 years.

Discussion

SPEECH PERCEPTION IN QUIET

There was mixed evidence for bilateral CI benefit when compared to the unilateral CI paradigm in quiet listening conditions. Statistically significant findings were established for bilateral benefit in two of the six studies in adults (Muller et al., 2002 & Litovsky et al., 2006a). However, three additional studies found essentially no bilateral benefit for most subjects (Tyler et al. 2002; Yoon et al., 2011; Dunn et al., 2012). Surprisingly, Dunn et al. (2012) had one subject who performed significantly worse in the bilateral CI condition when compared to the unilateral CI condition. The findings from the studies in adults align with the studies in children, with no consistent, statistically significant differences noted between the bilateral CI and the unilateral CI paradigms, though performance was never shown to be worse in the bilateral CI condition for the studies in children. These findings suggest the bilateral CI paradigm tends to be associated with limited or no benefit compared to the unilateral paradigm while listening under quiet conditions for most listeners.

SPEECH PERCEPTION IN NOISE

Small but significant bilateral benefits were reported for speech perception in noise, in adults when the speech and noise were co-located at 0 degrees azimuth. Again, though not all bilateral CI subjects performed significantly better than in the unilateral CI condition, performance with bilateral CIs was almost always equal to or better than performance with a unilateral CI. However, Litovsky et al. (2006a) did have two subjects who had a significant decrement in performance during the bilateral CI condition relative to the unilateral CI score. Only two studies investigating the pediatric population were found for this review and they presented with conflicting results. Reeder et al. (2017) reported comparable performance for both the bilateral CI and unilateral CI conditions, whereas Kim et al. (2009) reported significantly better performance during the bilateral CI condition. This discrepancy was thought to be because of the smaller sample size observed in Kim et al. (2009), resulting in lower statistical power.

When reviewing the head shadow benefit for speech perception in noise, using experimental paradigms where speech and noise were presented from different azimuths, all five of the studies in adults reviewed demonstrated bilateral benefit when compared to the unilateral condition. There were also no subjects who showed a decrease in performance while under the bilateral CI condition compared to the unilateral CI condition. Gifford and Dorman (2018) further demonstrated significant bilateral CI benefit when compared to the bimodal paradigm during speech in noise testing. Studies in children did not demonstrate as much benefit from head shadow when speech and noise came from different azimuths as in the studies with adults; however, bilateral CI performance was always equal to or better than unilateral CI performance. Galvin et al. (2010) also demonstrated a possible advantage of listening with the first-implanted ear by showing superior speech perception performance when noise was presented on the side of first implanted CI, and no difference in performance when noise was presented on the side of the second implanted CI.

LOCALIZATION

A consistent benefit of bilateral CIs when compared to other paradigms was found during localization tasks in both studies with adults and children. Overall, significantly higher error was reported during unilateral CI conditions, and most listeners had statistically better performance in the bilateral CI condition. Bimodal listening, while still poorer than bilateral CI performance, was demonstrated to improve localization performance for subjects who utilized that arrangement between surgeries in the sequential CI paradigm. These findings suggest the use of two ears is most beneficial in locating the source of a sound in space, and that it is important for unilateral CI subjects to continue to use a hearing aid in the opposite ear during this period of auditory development in childhood, if possible. Though bilateral benefit was consistently demonstrated for bilateral CIs in comparison to unilateral CI and bimodal paradigms, bilateral CI performance and access to binaural cues is still relatively poor compared to normal hearing listeners. In time, new technologies and fitting methods may lead to improved performance for bilateral CI listeners in comparison to normal hearing listeners.

SIMULTANEOUS VS. SEQUENTIAL

Studies in adults demonstrated significant bilateral benefit with both simultaneous and sequential CI paradigms. Bilateral benefit was observed during speech in noise tasks, localization tasks, and expressive and receptive language measures for both simultaneous and sequential users. Even when conditions were varied, bilateral CI subjects continued to perform significantly better than the unilateral CI and bimodal subjects. There was no evidence suggesting a longer delay between implants is harmful to potential bilateral benefit for the adult post-lingually deafened population.

Though pediatric recipients of sequential implants demonstrated bilateral benefit, earlier age at implantation and a shorter inter-implant interval were associated with better outcomes in multiple studies investigated. Children with both simultaneous and sequential bilateral CIs demonstrated significant benefit, though there is need for further studies investigating the impact of inter-implant interval between CIs on performance. Because current research trends suggest that early simultaneous implantation is beneficial for most individuals, this method may in turn emerge as the standard of care.

SPEECH AND LANGUAGE ACQUISITION

Overall, studies in children investigating the effects of listening arrangement on speech and language outcomes found a significant bilateral benefit. Both expressive and receptive language skills were typically better in the bilateral CI users when compared to either the unilateral CI or the bimodal users, though the results of Ching et al. (2014) failed to reach statistical significance related to the overall effect of device configuration as was observed in Boons et al. (2012). Authors of Ching et al. (2014) believed a larger cohort of participants may potentially yield a significant negative effect of device configuration, with unilateral CI performance being worse. Though bilateral CIs contributed to better language outcomes than unilateral or bimodal paradigms, the language skills for bilateral CI subjects often showed significant delays. This trend in the recent literature demonstrates the benefit that can be demonstrated when subjects are implanted with bilateral CIs. Though these subjects did fail to meet the language levels of normal hearing listeners, no subjects demonstrated a lack of benefit from the bilateral CI paradigm relative to the unilateral CI and bimodal paradigms.

Conclusion

The evidence presented in this literature review demonstrates the effectiveness of bilateral CIs when compared to a unilateral CI or a bimodal listening paradigm. Significant bilateral benefit was reported for most measures examined including speech perception in quiet and noise, sound localization, and speech and language acquisition, though some individual subjects performed significantly worse in the bilateral CI condition for measures of speech perception in quiet and noise. Language outcomes in the pediatric population revealed improved performance in the bilateral CI condition compared to the unilateral CI and bimodal listening conditions; however, language abilities of children with bilateral CIs consistently fell below their normal hearing peers. The head shadow effect and localization tasks consistently revealed binaural listening benefit, demonstrating the critical importance of listening with two ears for these types of tasks. Both sequential and simultaneous implant subjects were observed to receive significant bilateral benefit across multiple areas measured, though the length of time between implants may impact bilateral benefit and listening performance in the second-implanted ear in children.

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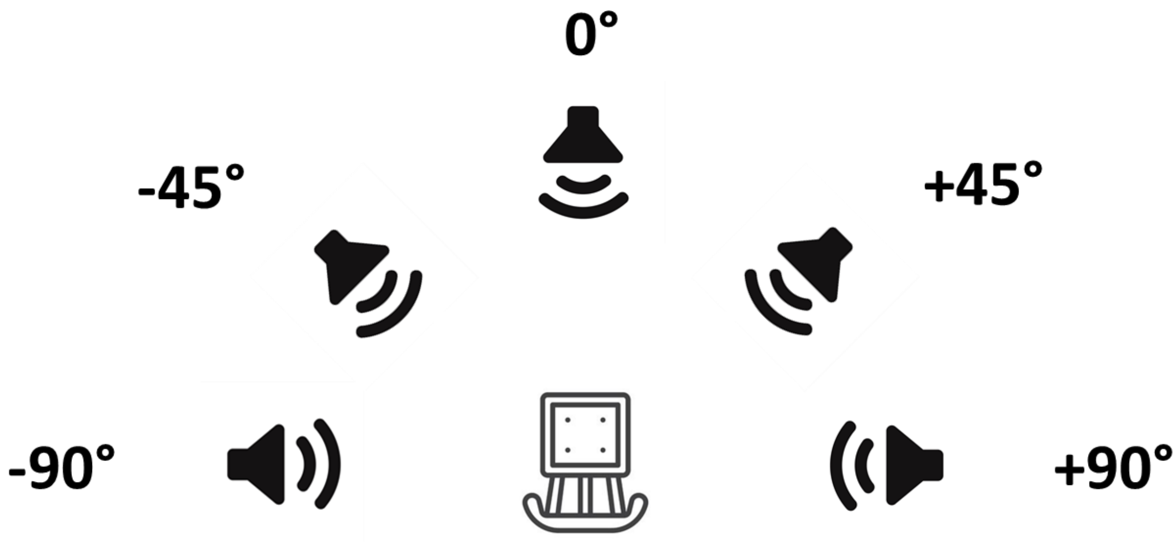

Figure 1. Schematic of a hypothetical five-speaker sound field array similar to those used in localization tasks.