Spoken Word Recognition Development in Children with Residual Hearing Using Cochlear Implants and Hearing Aids in Opposite Ears

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Objective: **With broadening candidacy criteria for cochlear implantation, a greater number of pediatric candidates have usable residual hearing in their nonimplanted ears. This population potentially stands to benefit from continued use of conventional amplification in their nonimplanted ears. The purposes of this investigation were to evaluate whether children with residual hearing in their nonimplanted ears benefit from bilateral use of cochlear implants and hearing aids and to investigate the time course of adaptation to combined use of the devices together.**

Design: **Pediatric cochlear implant recipients with severe sensorineural hearing loss in their nonimplanted ears served as participants. Ten children continued to use hearing aids in their nonimplanted ears after cochlear implantation; 12 children used their cochlear implants exclusively. Participants were tested longitudinally on spoken word recognition measures at 6-month intervals. The children who continued wearing hearing aids were tested in three sensory aid conditions: cochlear implants alone, hearing aids alone, and cochlear implants in conjunction with hearing aids. The children who did not continue hearing aid use were tested after surgery in their only aided condition, cochlear implant alone.**

Results: **The results suggest that children with severe hearing loss who continued using hearing aids in their nonimplanted ears benefited from combining the acoustic input received from a hearing aid with the input received from a cochlear implant, particularly in background noise. However, this benefit emerged with experience.**

Conclusions: **Our findings suggest that it is appropriate to encourage pediatric cochlear implant recipients with severe hearing loss to continue wearing an appropriately fitted hearing aid in the nonimplanted ear to maximally benefit from bilateral stimulation.**

(Ear & Hearing 2005;26;82S–91S)

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Criteria for cochlear implantation in children have changed dramatically since the first individual under 18 years of age received a cochlear implant in 1980 (Eisenberg & House, 1982). When the US Food and Drug Administration first approved cochlear implantation in children in 1990, criteria for implantation included bilateral profound deafness, age 2 years or older, and demonstration of little or no benefit from amplification (Staller, Beiter, & Brimacombe, 1991). Since that time, candidacy criteria have broadened to include children as young as 1 year of age with profound hearing loss and children at least 2 years of age with severe-to-profound hearing loss. These changes in candidacy criteria are due to improvements in cochlear implant technology and increasingly positive speech and language outcomes after cochlear implantation in many users (e.g., Skinner, Fourakis, Holden, Holden, & Demorest, 1996). These changes also have resulted in an increased number of children with cochlear implants who have some degree of residual hearing in their nonimplanted ears. Some of these children have enough residual hearing that they might receive some benefit from using a hearing aid in their nonimplanted ears. This is a relatively new population at cochlear implant centers and a number of investigators have begun to examine whether continued use of a hearing aid in the nonimplanted ear is beneficial for pediatric cochlear implant recipients (Ching, Psarros, & Hill, 2000; Ching, Psarros, Hill, Dillon, & Incerti, 2001).

There are a number of reasons why individuals with cochlear implants might benefit from continued hearing aid use in their nonimplanted ears. First, providing auditory input to the nonimplanted ear might help prevent neural degeneration that is associated with auditory deprivation. Chronic stimulation is known to influence spiral ganglion cell survival in animals (e.g., Miller, 2001). The importance of continued auditory stimulation also has been demonstrated in individuals with cochlear implants and in hearing aid users. In cochlear implant recipients, longer periods of profound deafness routinely are associated with poorer speech and language outcomes (Blamey et al., 1992; Cohen, Waltz-

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man, & Fisher, 1993; Gantz et al., 1988). Similarly, word recognition skills in the nonstimulated ear of individuals with bilateral hearing loss fitted with monaural amplification have been shown to worsen over time (Gatehouse, 1992; Hattori, 1993). Thus, the stimulation provided by a hearing aid might help maintain spiral ganglion cell survival in the nonimplanted ear for future advances in hearing restoration or future cochlear implantation.

A second reason why continued hearing aid use might be beneficial to cochlear implant users is that monaural listeners (whether it be due to unilateral hearing loss or monaural cochlear implant or hearing aid use in listeners with bilateral hearing loss) are unable to benefit from the advantages of bilateral listening, such as binaural summation, localization, squelch effects, head shadow, and aspects of precedence effects. Unable to take advantage of binaural benefits, monaural listeners achieve lower levels of spoken word recognition than binaural listeners, especially in noise (e.g., Giolas & Wark, 1967; Konkle & Schwartz, 1981). Bilateral input might be particularly important for children because they tend to spend much of the day in school classrooms with high noise levels and long reverberation times (Knecht, Nelson, Whitelaw, & Feth, 2002).

A final reason for continued contralateral hearing aid use in cochlear implant users is that the acoustic stimulation provided by a hearing aid might provide the user access to finer spectral and temporal pitch cues in the speech signal that are not resolved well by cochlear implants. A similar argument has been made by Henry & Turner (2003) in discussing the potential benefits of using a hearing aid in an ear implanted with a short electrode array. They suggested that preserving low-frequency hearing in the implanted ear by using a short electrode array and stimulating the apical areas of that cochlea with acoustic amplification (from a hearing aid) together might allow listeners better spectral resolution of the speech signal relative to using a long electrode array alone. Although sensorineural hearing loss in and of itself significantly reduces spectral resolution, Henry & Turner (Reference Note 1) demonstrated that individuals with sensorineural hearing loss using acoustic stimulation had better spectral resolution than that provided by a typical cochlear implant. Therefore, it is possible that providing acoustic amplification to the nonimplanted ear with residual hearing might provide additional spectral resolution that could aid in spoken word recognition. On the other hand, due to the severity of the sensorineural hearing loss in the nonimplanted ear of typical cochlear implant recipients, the benefit provided by acoustic amplification might be negligible.

Despite all of the potential benefits of hearing aid use in the nonimplanted ear of cochlear implant recipients, there is a concern that balancing the two discrepant signals between ears poses some challenges to the listener (Ching, Psarros, et al., 2001). Further, while they learn to use these two discrepant modes of stimulation, listeners must adapt to the novel sensory input provided by a cochlear implant. There also is concern that the stimulation received from the nonimplanted ear via a hearing aid might not only result in no further benefit beyond that received from the cochlear implant alone but could in fact cause interference. This interference might result in poorer spoken word recognition when both devices are used simultaneously than when the cochlear implant is used alone. In response, many audiologists recommend that children remove the hearing aid from their nonimplanted ears for several months after the initial cochlear implant stimulation while they learn to use the new auditory input. However, this may not be in the best interest of all children. Evidence is accumulating to suggest that continued use of a hearing aid in the nonimplanted ear of children with cochlear implants does in fact aid in speech perception.

A number of investigators have reported higher auditory-only speech perception scores in adults when they used cochlear implants and hearing aids bilaterally, especially in the presence of competing noise, than when they used either device alone (Armstrong, Pegg, James, & Blamey, 1997; Blamey, Armstrong, & James, 1997; Ching, Incerti, & Hill, 2001; Dooley et al., 1993; Hamzavi, Pok, Gstoettner, & Baumgartner, 2004; Shallop, Arndt, & Turnacliff, 1992; Tyler et al., 2002). Further, Tyler et al. reported that two of their three participants had improved localization ability, and Ching, Incerti, et al. (2001) found overall improved localization with combined bilateral cochlear implant + hearing aid use relative to monaural cochlear implant–only listening.

Similar results have been found in children. Ching et al. (2000) examined speech perception performance in five children (ages 6 to 18 years) with cochlear implants who wore hearing aids in their nonimplanted ears. Participants had used their cochlear implants for at least 6 months (mean length of cochlear implant use was approximately 1 year) and continued to wear hearing aids in their nonimplanted ears immediately after cochlear implantation. All of the children had profound hearing loss in their nonimplanted ears. Open-set sentence and closed-set consonant recognition (12 alternatives) in 4-talker babble (+10 dB signal-to-noise ratio [SNR]) were significantly better with combined cochlear implant + hearing aid use than with cochlear implant alone. These differences were primarily due to significantly improved transmission of voicing and manner cues but not place of articulation cues in the cochlear implant + hearing aid condition relative to the cochlear implant–alone condition. Further, four of the five children had improved horizontal localization abilities in the cochlear implant + hearing aid condition relative to the cochlear implant–only condition. Similar findings were reported in a larger sample of 11 children in the same age range (Ching, Psarros, et al., 2001). These children also had used their cochlear implants for at least 6 months (mean and individual length of cochlear implant use were not provided), continued hearing aid use in their nonimplanted ears immediately after cochlear implantation, and all but one had profound hearing loss in their nonimplanted ears. Children were tested in quiet and in 4-talker babble (+10 dB SNR) on open-set sentence recognition and closed-set consonant recognition (12 alternatives). In the background noise condition, both speech and babble were presented from 0 degrees azimuth to minimize head shadow and bilateral squelch effects, thereby underestimating bilateral advantage. Despite this, sentence recognition was significantly better in both quiet and background noise when using a cochlear implant combined with a hearing aid in the nonimplanted ear than when using either device alone. However, consonant recognition was significantly better only in the combined cochlear implant + hearing aid condition when compared with hearing aid–only performance, not when compared with cochlear implant–only performance. The advantage of combining the acoustic and electric stimulation bilaterally was due to better transmission of manner but not voicing or place of articulation cues.

At least one investigation did not find an advantage for combining acoustic amplification in the nonimplanted ear with a cochlear implant over using a cochlear implant alone in children, although such an advantage was noted for a group of postlingually deafened adults. In this early study, Waltzman, Cohen, & Shapiro (1992) reported that children who were deaf before age 5 years did not show better spoken word recognition performance when using their cochlear implants with FM systems in the nonimplanted ear than with their cochlear implants alone. Conversely, they found that postlingually deafened adults did show improved spoken word recognition when using both a cochlear implant and a hearing aid in the nonimplanted ear than when using either the cochlear implant or the hearing aid alone. Despite being fitted with FM systems that can provide more gain, higher output, and an improved SNR relative to hearing aids, the children failed to improve in the bilateral condition over cochlear implant alone. This developmental difference might stem from language delays typically experienced by the children with severe to profound hearing loss, a concern that would not be expected in postlingually deaf adults. Another particularly important difference was that the children had much less residual hearing in their nonimplanted ears than the adults. This probably influenced the amount of benefit they received from using an FM system in that ear.

Indeed, in a study of adult combined bilateral cochlear implant + hearing aid users, Tyler et al. (2002) suggested that the amount of residual hearing in the nonimplanted ear probably influences the ability of listeners to integrate and capitalize on the input to both ears together. Conversely, Ching, Psarros, et al. (2001) did not find a relation between amount of residual hearing in the nonimplanted ear and amount of benefit received by children wearing their cochlear implants and hearing aids together. However, the children who participated in the Ching, Psarros, et al. investigation had at least borderline profound hearing losses in their nonimplanted ears (pure-tone averages ranged from 88.3 to 118.3 dB HL). Therefore, amount of residual hearing could be an important factor in determining the benefits of bilateral acoustic-electric hearing in children. Specifically, if children with even more residual hearing were included in such studies, they might demonstrate more benefit from acoustic stimulation of the nonimplanted ear than children with profound hearing loss. With changes in cochlear implant candidacy criteria, there are now more children than ever with "aidable" residual hearing in their nonimplanted ears who could benefit from investigating these issues.

Pediatric cochlear implant recipients with residual nonimplanted-ear hearing represent a different population than has been studied in the past. The children included in this investigation, a subset of whom continued wearing hearing aids in their nonimplanted ears, have more residual hearing in their nonimplanted ears than those children studied by either Ching and colleagues or Waltzman and colleagues; thus, they potentially stand to gain more from acoustic input to their nonimplanted ears. Moreover, these children have been tested longitudinally. Although Tyler, Ching, and their respective colleagues have suggested that children show benefit from combined cochlear implant + hearing aid use, the greatest benefits of combined cochlear implant + hearing aid use might emerge over time as children learn to integrate the two different signals from each ear. The work done on bilateral acoustic-electric hearing typically has assessed performance at a single point in time, and therefore the time course of this development is not known. The pur-

TABLE 1. Demographic information for participants

Participant group	N	PTA, implanted ear (dB HL)	PTA, nonimplanted ear (dB HL)	Age at onset of deafness (mo)	Age at initial cochlear implant stimulation (mo)	Proportion using oral communication (percent)	Proportion female (percent)
NiEHA	10	95.0 (13.6)	81.1 (6.6)	4.4 (9.3)	83.5 (37.0)	80%	40%
No-NiEHA	12	89.5 (12.8)	78.4 (9.0)	0.3 (1.2)	49.1 (25.6)	33%	42%

PTA, pure-tone average; NiEHA, nonimplanted-ear hearing aids.

poses of this investigation were to determine (1) whether pediatric cochlear implant recipients with residual hearing in their nonimplanted ears benefit from the bilateral input received by using a hearing aid on their nonimplanted ears and (2) the time course over which this benefit might emerge.

METHODS

Participants

Inclusion criteria included onset of severe-to-profound sensorineural hearing loss in the implanted ear and severe sensorineural hearing loss in the nonimplanted ear by age 3 years, no other identified disability (such as physical, visual, or cognitive impairment), cause of hearing loss other than auditory neuropathy/dyssynchrony, and implanted with a current device and fitted with a current speech processing strategy. On the basis of these criteria, 22 pediatric cochlear implant recipients were identified for inclusion in this investigation. Ten of the participants continued nonimplanted-ear hearing aid use after cochlear implantation, whereas the remaining 12 children used their cochlear implants exclusively. Demographic information for the participants is displayed in Table 1. Mean pure-tone averages in the implanted and nonimplanted ears, age at onset of deafness, age at initial cochlear implant stimulation, proportion using oral communication, and proportion of female subjects for both the children who continued hearing aid use in the nonimplanted ear after cochlear implantation (NiEHA) and for the children who did not continue hearing aid use (No-NiEHA). Standard deviations, where appropriate, are displayed in parentheses in Table 1.

The children who continued wearing hearing aids were almost 3 years older at implantation than those who did not continue hearing aid use. This means that they were chronologically older at each testing interval than the children who ceased wearing hearing aids once they were implanted. However, they were also without electrical stimulation for a longer period of time than the children who did not continue hearing aid use. Finally, a greater proportion of NiEhearing aid children were oral communicators compared with No-NiEhearing aid children. Total communication combines oral speech with signing in English word order (otherwise known as Signed Exact English), whereas oral communication does not use any signing.

Sensory Aids

Table 2 displays the number of children implanted with each type of cochlear implant system and the speech processing strategies used. The children who continued wearing hearing aids in their nonimplanted ears were fitted with a variety of current hearing aids by each child's clinical audiologist. All of the hearing aids were behind-the-ear styles. The majority of the hearing aids were digitally programmable, with only a few being fully digital. Both the cochlear implants and the hearing aids were set at their regular-use settings during testing.

Materials

Two standard tests of spoken word recognition were administered to the children: the Phonetically Balanced–Kindergarten Word Lists (PB-K) (Haskins, Reference Note 2) and the Hearing-In-Noise Test–Children's Version (HINT-C) (Nilsson, Soli, & Gelnett, 1996). The PB-K is an open-set word recognition test

TABLE 2. Cochlear implant devices and processing strategies used by participants

Participant group	N	Cochlear implant			Processing strategy		
		Nucleus 24	Clarion	Med-El Combi 40+	CIS	SAS	ACE
NiEHA	10	4	5	1	1	5	4
No-NiEHA	12	5	2	5	7	2	3

CIS, continuous interleaved sampling; SAS, simultaneous analog stimulation; ACE, advanced combination encoder; NiEHA, nonimplanted-ear hearing aids.

that consists of four lists of 50 phonetically balanced monosyllabic words. However, only three lists are used because the fourth was shown to not be equivalent to the others in the Haskins thesis. For this test, the child is asked to repeat each word after it is presented, and the percentage of words correctly repeated is calculated. The HINT-C was modified for use as a test of spoken word recognition in which the percentage of words in a sentence correctly repeated at a fixed SNR was used as the dependent measure. The test is composed of 13 lists of 10 sentences that are identifiable to normal-hearing children as young as 5 and 6 years old. One list was presented in each testing condition. Performance was scored by calculating the percentage of words correctly repeated.

Procedure • The tests were administered before cochlear implantation and at approximately regular 6-month intervals after the cochlear implant was first activated for 1 to 2 years. Not every child was assessed on every test in the battery at each 6-month interval because of missed appointments or inability to maintain attention for all tests in a session. Therefore, the reader should note that the number of participants tested in each group varied across tests and testing intervals. The number of participants tested at each interval is noted in the figures. The tests were administered after surgery in three conditions to the children who continued nonimplanted-ear hearing aid use: (1) hearing aid only, in which each listener's cochlear implant was turned off and the child wore his or her hearing aid at everyday-use settings; (2) cochlear implant only, in which each listener's hearing aid was removed and the child wore his or her cochlear implant at everyday-use settings; and (3) cochlear implant + hearing aid, in which both the cochlear implant and hearing aid were activated and worn at everyday-use settings. In contrast, children who did not continue hearing aid use completed postoperative testing in the cochlear implant condition only.

Licensed speech-language pathologists with training in working with children with cochlear implants administered and scored all of the test measures. Both the PB-K and the HINT-C were administered in an auditory-only format. In contrast to test administration, test instruction for all measures was carried out in the child's primary mode of communication. Both spoken and/or signed responses were acceptable responses for all test measures.

The PB-K was administered in quiet. Due to a slight protocol difference between testing sites, the PB-K was administered live-voice at approximately 70 dB SPL in a quiet room in one laboratory (Indiana University School of Medicine) and via recorded compact disc at 70 dB SPL in a double-walled sound booth in the other laboratory (House Ear Institute). Four children (all of whom were nonimplanted-ear hearing aid users) were tested in the laboratory that used recorded PB-K materials; the remaining children completed testing in the laboratory that used live-voice presentation. Using a one-way analysis of variance (ANOVA) with type of PB-K presentation format (recorded and live-voice) as the between-participant factor and cochlear implant–only score at each testing interval as the dependent measure, we found no significant differences in performance on the PB-K when scored by either phoneme or word correct between the four children tested using recorded materials and those who received the materials live-voice at any testing interval. Furthermore, using a separate one-way ANOVA, no significant performance differences at any testing interval using any sensory aid condition (cochlear implant only, hearing aid only, and cochlear implant + hearing aid) were found between the children tested using the recorded materials and the children who received the materials live-voice. Therefore, the data were collapsed across test administration format in analyzing and reporting the results.

The HINT-C was administered in a double-walled sound booth, using recorded stimuli at an average long-term rms of 70 dB SPL at both laboratories. The HINT-C sentences were presented in quiet and +5 dB SNR. For the latter condition, the noise was presented at an average level of 65 dB SPL. Both the speech and noise, where appropriate, were presented from a single speaker located at 0 degrees azimuth from the listener.

RESULTS

The data were collapsed from blocks of two consecutive 6-month intervals, and mean scores by year will be reported to increase statistical power in each interval. If a child were tested once during two consecutive 6-month intervals, that score was used in our calculation; if a child were tested twice, the score from the later test interval was used in our calculations.

Mean group data and ±1 SD on the PB-K are shown in Figure 1. Performance of the children who continued hearing aid use (NiEHA) is shown by unfilled bars (hearing aid-only condition), gray-filled bars (cochlear implant-only condition), and black-filled bars (cochlear implant + hearing aid condition). For comparison purposes, the striped bars indicate performance of the children who did not continue hearing aid use (No-NiEHA). Note that the data from the No-NiEHA group reflect performance with a hearing aid before cochlear implantation (0 years of cochlear implant use) and with their co-

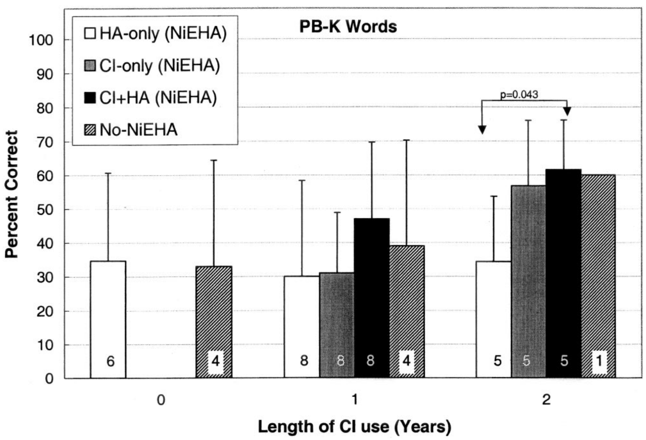

Fig. 1. Mean group data and ±1 SD on the Phonetically Balanced–Kindergarten Word Lists (PB-K) in quiet. Performance of the children who used nonimplanted-ear hearing aids (NiEHA) is indicated by unfilled bars (hearing aid–only condition), gray-filled bars (cochlear implant–only condition), and black-filled bars (cochlear implant + hearing aid condition). Group data for children who did not continue to wear hearing aids in their nonimplanted ears (No-NiEHA) are indicated by striped bars. Numbers on each bar indicate the number of participants tested in a particular group and time interval. No data for the cochlear implant or cochlear implant + hearing aid conditions are displayed at 0 years of cochlear implant use because, by definition, participants had not yet received their cochlear implants at this interval.

chlear implant-only at 1-year intervals after cochlear implantation. The numbers on each bar indicate the number of participants tested from that particular group for the given 1-year interval. No data for the cochlear implant–only or cochlear implant + hearing aid conditions are displayed at 0 years of cochlear implant use because, by definition, participants had not yet received their cochlear implants at this interval. The data from the NiEHA group were analyzed by use of the Wilcoxon signed ranks test to evaluate differences among device testing conditions. After 2 years of cochlear implant use, the children had significantly higher PB-K word identification scores using their cochlear implants and hearing aids simultaneously than using their hearing aids alone [$z = -2.023$, $p = 0.043$ (two-tailed)]. In fact, all five children tested after 2 years of cochlear implant use showed this effect. The difference between using cochlear implants and hearing aids together and using a hearing aid alone 1 year after cochlear implantation approached significance [$z = -1.897$, $p = 0.058$ (two-tailed)]. At this interval, 7 of the 8 children had higher word recognition scores using both devices simultaneously than using their hearing aids alone.

Before cochlear implantation, word recognition performance on the PB-K of the children who would later continue nonimplanted-ear hearing aid use and those children who would not continue hearing aid use was very similar (mean scores differed by 2%). Further, the variability across participants within each group was similar. This indicates that there were no gross preimplant differences in spoken word recognition in quiet between children who continued hearing aid use and children who stopped wearing hearing aids after cochlear implantation. Few children in the No-NiEHA group were tested on the PB-K after cochlear implantation, so we were unable to evaluate performance differences statistically.

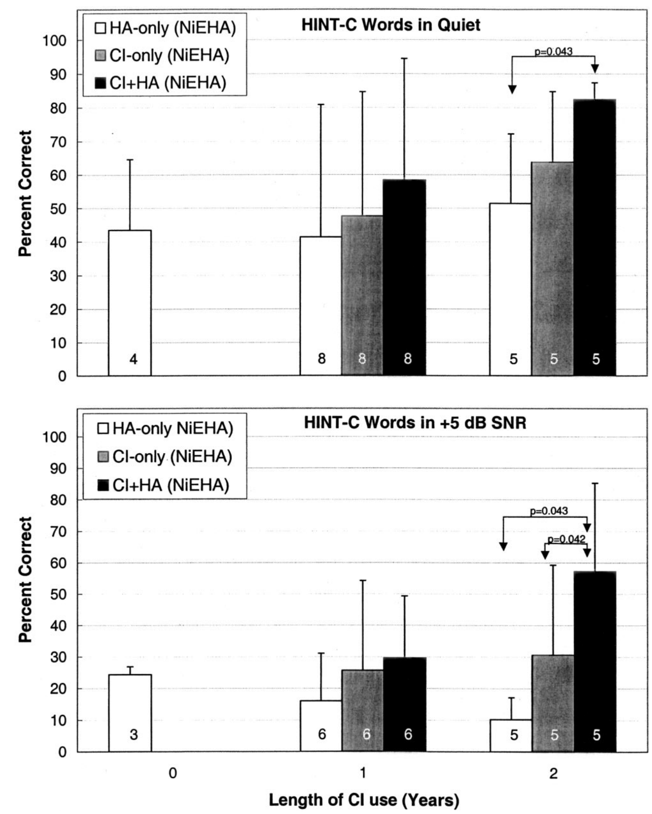

Fig. 2. Mean group data and ±1 SD on the Hearing-In-Noise Test–Children's Version (HINT-C) sentences scored by words correctly repeated in quiet (top panel) and in +5 dB signal-to-noise ratio (bottom panel) for the children who used nonimplanted-ear hearing aids (NiEHA). Unfilled bars indicate performance in the hearing aid–only condition; gray-filled bars indicate performance in the cochlear implant–only condition; and black-filled bars indicate the performance in the cochlear implant + hearing aid condition. Numbers on each bar indicate the number of participants tested in a particular group and time interval. No data for the cochlear implant or cochlear implant + hearing aid conditions are displayed at 0 years of cochlear implant use because, by definition, participants had not yet received their cochlear implants at this interval.

Figure 2 displays mean group data and ±1 SD on HINT-C for the children who continued wearing hearing aids after cochlear implantation. The top panel shows the results in quiet and the bottom panel shows the results in +5 dB SNR. Similar to the results for the PB-K, the only significant difference between sensory aid conditions in the quiet condition was at 2 years after cochlear implantation between hearing aid + cochlear implant and hearing aid only [$z = -2.023$, $p = 0.043$ (two-tailed)]. All five participants had higher HINT-C word recognition scores in quiet using both sensory aids together than using their hearing aids alone. In contrast to the results in quiet, word recognition in noise was significantly better after 2 years of cochlear implant use in the combined cochlear implant + hearing aid condition than in either cochlear implant-alone [$z = -2.023$, $p = 0.042$ (two-tailed)] or hearing aid alone [$z = -2.023$, $p = 0.043$ (two-tailed)]. In both cases, all five participants demonstrated this effect.

Using a repeated-measures ANOVA (within factor was years of cochlear implant use [1 and 2 years after surgery] and the between factors were noise condition [quiet and +5 dB SNR] and the sensory aid configuration [hearing aid, cochlear implant, and cochlear implant + hearing aid]), performance was significantly better in quiet than in noise [F (1, 19) = 9.908, $p = 0.005$]. There was no interaction between device and noise condition. However, there was a significant effect for length of device use [F (1, 19) = 5.857, $p = 0.026$] and an interaction between length of device use and sensory aid configuration [F (2, 19) = 5.578, $p = 0.012$]. In light of the results from the Wilcoxon signed rank test, performance increased more between 1 and 2 years of experience by using a cochlear implant and hearing aid simultaneously than using either a hearing aid or a cochlear implant-alone.

DISCUSSION

The results from this investigation suggest that after 2 years of cochlear implant use, cochlear implanted children with severe hearing loss in the nonimplanted ear demonstrate significantly better word recognition skills when combining a hearing aid on their nonimplanted ears with their cochlear implant than when using their hearing aids alone in quiet listening environments. However, this word recognition benefit does not extend to quiet listening conditions in which they use their cochlear implant alone. In contrast, spoken word recognition in background noise is significantly improved by combining a hearing aid with a cochlear implant than by using either device alone after 2 years of cochlear implant experience. These results were found despite the discrepant signals received by the two ears.

Keys (1947) and Pollack (1948) observed that binaural auditory thresholds are about 3 dB better than monaural thresholds. Based on a 3-dB shift on the performance-intensity functions for words, this improvement in auditory thresholds can result in an 18% improvement in word recognition (Konkle & Schwartz, 1981). Cochlear implant + hearing aid PB-K word recognition performance in quiet was between 5 and 16% higher than cochlear implant–only performance, somewhat less than the 18% bilateral improvement predicted by Konkle and Schwartz, based solely on binaural summation. There are at least three reasons why the actual increase in performance was less than predicted. First, the signals presented to each ear were quite different—one being acoustic and one being electric. Konkle and Schwartz' predictions were based on both ears receiving similar acoustic signals. Second, Konkle and Schwartz' predictions were based on typical normal-hearing data, whereas our data are from children with severe-to-profound hearing losses. Finally, the majority of children in this investigation displayed delays in their vocabulary development (based on their scores on the Peabody Picture Vocabulary Test [Dunn & Dunn, 1997]), which can negatively influence performance on word recognition measures (Boothroyd, 1993; Carney et al., 1993; Moeller, Osberger, & Escarius, 1986). Despite the differences in mode of auditory stimulation and participant characteristics, these pediatric cochlear implant recipients achieved some degree of the bilateral benefit in spoken word recognition; however, it was less than that predicted by Konkle and Schwartz, based solely on binaural summation, just one of the identified benefits of bilateral listening.

The individual data also support these group results. After 1 and 2 years of cochlear implant experience, four of the eight children and two of the five children tested on the PB-K, respectively, had significantly higher scores in the bilateral condition than in the cochlear implant–only condition [based on the 95% confidence intervals for a 50-item list by Thornton and Raffin (1978)]. No child had significantly lower scores on the PB-K in the bilateral condition than in either the cochlear implant–only or hearing aid–only conditions. The HINT-C scores cannot be directly analyzed by using the confidence limits determined by Thornton and Raffin because the words scored are presented in sentences and are not independent of one another. However, descriptively, scores were equivalent to or higher in the bilateral condition than in the cochlear implant-only condition for 6 of the 8 children tested in quiet on the HINT-C after 1 year of cochlear implant experience. The bilateral scores for the two children who failed to show improvement after 1 year of cochlear implant use were 6% and 13% lower than cochlear implant-only scores, respectively. After 2 years of cochlear implant use, 4 of the 5 children tested had higher scores in the bilateral condition than in the cochlear implant-only condition. The fifth child already was scoring at ceiling in the cochlear implant-only condition and her/his cochlear implant + hearing aid score was only 6% below his or her cochlear implant–only score after 2 years of cochlear implant use.

For the HINT-C in noise, performance was significantly better in the bilateral condition than in either the cochlear implant- or hearing aid-only conditions after 2 years of cochlear implant use. Two of the six children tested after 1 year of cochlear implant use had substantially higher word recognition scores in the bilateral condition than the cochlear implant-only condition and two others had nearly equivalent cochlear implant + hearing aid and cochlear implant-only scores. The bilateral scores for the two children who failed to show improvement after 1 year of cochlear implant use were 5% and 23% lower than cochlear implant-only scores, respectively. The child with the substantial drop in bilateral relative to cochlear implant-only performance had much better (42%) bilateral than hearing aid-only performance, however. All five children tested after 2 years of cochlear implant use had higher scores in the bilateral condition than in either the cochlear implant- or hearing aid-only conditions. Moreover, the increase in spoken word recognition received from bilateral listening was larger in noise than it was in quiet, particularly after 2 years of cochlear implant experience (27% in noise versus 19% in quiet). These results suggest that the benefit derived from bilateral auditory input is greatest in the presence of background noise.

Large spoken word recognition gains did not appear until at least 2 years of cochlear implant use in the cochlear implant-only and the combined cochlear implant + hearing aid condition. In other words, children with severe hearing loss in their nonimplanted ears require over 1 year of both cochlear implant experience and combined cochlear implant + hearing aid experience to begin demonstrating gains in cochlear implant-only and combined cochlear implant + hearing aid word recognition in both quiet and in the presence of background noise. This finding suggests that experience with both signals is needed before monaural cochlear implant-only and bilateral cochlear implant + hearing aid benefit is evident.

These results support previous work carried out by Ching et al. (2000) and Ching, Psarros, et al. (2001) in which children who had used their cochlear implants for at least 6 months demonstrated better spoken sentence and consonant recognition in quiet and noise when using their cochlear implants and hearing aids simultaneously than when using their cochlear implants alone. However, our results expand upon theirs by examining the performance of children with more residual hearing in their nonimplanted ears who stand to benefit more from acoustic amplification (e.g., Tyler et al., 2002). Specifically, children in our study had severe hearing loss, whereas those studied by Ching and colleagues had profound hearing loss. Additionally, the children who participated in the current study were followed longitudinally for up to 2 years of cochlear implant use, whereas those studied by Ching and colleagues were tested at a single time interval [approximately 1 year after cochlear implantation in Ching et al. (2000)]. The longitudinal nature of our study is important because our results suggest that children with severe nonimplanted-ear hearing loss who continue to use hearing aids in their nonimplanted ears might require up to 2 years of experience before they demonstrate sufficient integration of both signals effectively enough to show significant gains from bilateral input relative to using either device alone.

In conclusion, children with severe hearing loss in their nonimplanted ears benefit from combining the acoustic input received from a hearing aid in the nonimplanted ear with the electric input received from a cochlear implant, particularly in background noise, a very common listening environment. However, the benefit emerges after the children adapt to the novel input from the cochlear implant and gain experience combining the two signals from the cochlear implant and the hearing aid. Importantly, there was only one instance in which bilateral listening was related to a relatively large drop (23%) in word recognition performance relative to the cochlear implant-only condition. This occurred for one participant on the HINT-C sentences in noise after 1 year of cochlear implant experience. Because this participant was not tested again after 2 years of cochlear implant use, we are unable to determine whether the same pattern of performance was maintained with more experience combining the input from both devices.

Overall, our data do not support the concern that input from a hearing aid in the contralateral ear of a cochlear implanted child will cause interference that results in poorer word recognition than when a cochlear implant is used alone, even early on when the child is learning to use the novel input from the cochlear implant. Indeed, our findings suggest that it is appropriate to encourage children receiving cochlear implants with severe hearing loss in their nonimplanted ears to continue wearing an appropriately fitted hearing aid in their contralateral ears in order to maximally benefit from the input offered to both ears. If a child appears to be struggling to adapt to the novel input of the cochlear implant in combination with his or her hearing aid, it might be prudent to arrange training to the novel cochlear implant stimulation without the input from her/his hearing aid during specified listening times. However, our data suggest that these children will likely learn to adapt to both signals over time and will benefit in their spoken word recognition ability from doing so.

This area of research would benefit from investigating whether the advantages of combining a cochlear implant with conventional amplification on the contralateral ear seen in a controlled laboratory setting transfer to more real-world settings, such as school, home, and other child-centered activities where both noise and reverberation frequently exist. Further, the benefits of bilateral listening might extend beyond increased word and sentence recognition to improved localization skills, comprehension, attention, and academic achievement. Longitudinal follow-up in these additional areas of development might help determine if the benefits observed in the laboratory influence functional skills needed to participate in all daily living activities. Finally, research comparing children who use cochlear implants and hearing aids in contralateral ears to children with bilateral cochlear implants would be of great benefit. Quantifying any performance differences between these two groups of children would have important implications regarding cost-effectiveness and risk of additional surgery in bilateral cochlear implantation. If significant performance differences are not found, the combination of cochlear implants and nonimplanted-ear hearing aid use arguably allows for improved spoken word recognition skills over a cochlear implant alone, while simultaneously reducing auditory deprivation in the nonimplanted ear, thereby preserving that ear for future technological advances in cochlear implantation or hearing restoration.

ACKNOWLEDGMENTS

This research was supported by Training Grant T32 DC00012 and Research Grant R01 DC00064, both from the NIH/NIDCD, and Psi Iota Xi National Philanthropic Organization. Preliminary findings were presented at the 8th International Cochlear Implant Conference in 2004 (Indianapolis, IN), the 10th Symposium on Cochlear Implants in Children in 2005 (Dallas, TX), and the 2005 American Auditory Society meeting (Scottsdale, AZ). We thank the children and their families who participated in this research, as well as the audiologists and speech-language pathologists at Indiana University School of Medicine and House Ear Institute who collected the data.

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Received December 10, 2004; accepted March 29, 2005

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