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Spoken Word Recognition Development in Children with Cochlear Implants: Effects of Residual Hearing and Hearing Aid use in the Opposite Ear [1]

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Spoken Word Recognition Development in Children with Cochlear Implants: Effects of Residual Hearing and Hearing Aid use in the Opposite Ear

Abstract. 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 examine the speech and language development of pediatric cochlear implant recipients with either profound or severe hearing loss in their nonimplanted ears, including a subset with severe hearing loss who continued wearing hearing aids in their nonimplanted ears; to evaluate whether children benefit from binaural use of cochlear implants and hearing aids; and to investigate the time course of adaptation to combined use of the devices together. Children were tested on a battery of speech recognition measures in quiet and background noise and language measures in quiet. The results suggest that, although children with different degrees of residual hearing have improved speech recognition and language skills after cochlear implantation, the developmental time course differs for the two groups. Children with severe hearing loss required more than 1 year of cochlear implant experience to demonstrate spoken word recognition gains, whereas children with profound hearing loss showed more benefit during the first year after cochlear implantation. For measures in which group performance differed, children with severe hearing loss had better speech recognition and language skills than the children with profound hearing loss. Furthermore, 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. 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. They also suggest that speech and language gains for children with nonimplanted-ear residual hearing occur after children have at least one year of cochlear implant listening experience.

Introduction

Criteria for cochlear implantation in children have changed dramatically since the first individual under 18 years of age received a cochlear implant (CI) in 1980 (Eisenberg & House, 1982). When the U.S. 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 CI 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 CIs 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 (HA) in their nonimplanted ears. This is a relatively new population at CI centers and a number of investigators have begun to examine whether continued use of a

HA in the nonimplanted ear is beneficial for pediatric CI recipients (Ching, Psarros, & Hill, 2000; Ching, Psarros, Hill, Dillon, & Incerti, 2001).

There are a number of reasons why individuals with CIs might benefit from continued HA 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 CIs and in HA users. In CI recipients, longer periods of profound deafness routinely are associated with poorer speech and language outcomes (Blamey et al., 1992; Cohen, Waltzman, & 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 HA 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 HA use might be beneficial to CI users is that monaural listeners (whether it be due to unilateral hearing loss or monaural CI or HA 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 HA use in CI users is that the acoustic stimulation provided by a HA might provide the user access to finer spectral and temporal pitch cues in the speech signal that are not resolved well by CIs. A similar argument has been made by Henry and Turner (2003) in discussing the potential benefits of using a HA 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 HA) 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 and Turner (2003) demonstrated that individuals with sensorineural hearing loss using acoustic stimulation had better spectral resolution than that which is provided by a typical CI. 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 CI recipients, the benefit provided by acoustic amplification might be negligible.

Despite all of the potential benefits of HA use in the nonimplanted ear of CI 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 CI. There also is concern that the stimulation received from the nonimplanted ear via a HA might not only result in no further benefit beyond that received from the CI 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 CI is used alone. In response, many audiologists recommend that children remove the HA from their nonimplanted ears for several months following the initial CI 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 HA in the nonimplanted ears of children with CIs does in fact aid in speech perception.

A number of investigators have reported higher auditory-only speech perception scores in adults when they used CIs and HAs 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 CI+HA use relative to monaural CI-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 CIs who wore HAs in their nonimplanted ears. Participants had used their CIs for at least 6 months (mean length of CI use was approximately 1 year) and continued to wear HAs in their nonimplanted ears immediately after cochlear implantation. All of the children had profound hearing losses 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 CI+HA use than with CI alone. These differences were primarily due to significantly improved transmission of voicing and manner cues, but not place of articulation cues, in the CI+HA condition relative to the CI-alone condition. Further, 4 of the 5 children had improved horizontal localization abilities in the CI+HA condition relative to the CI-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 CIs for at least 6 months (mean and individual length of CI use were not provided), continued HA use in their nonimplanted ears immediately following 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 in order 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 CI combined with a HA in the nonimplanted ear than when using either device alone. However, consonant recognition was significantly better only in the combined CI+HA condition when compared to HA-only performance, not when compared to CI-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 CI over using a CI alone in children, although such an advantage was noted for a group of postlingually deafened adults. In this early study, Waltzman, Cohen and Shapiro (1992) reported that children who were deaf before age 5 years did not show better spoken word recognition performance when using their CIs with FM systems in the nonimplanted ear than with their CIs alone. Conversely, they found that postlingually deafened adults did show improved spoken word recognition when using both a CI and a HA in the nonimplanted ear than when using either the CI or the HA alone. Despite being fitted with FM systems that can provide more gain, higher output, and an improved SNR relative to HAs, the children failed to improve in the bilateral condition over CI-alone. This developmental difference might stem from language delays typically experienced by the children with severe to profound hearing loss, a concern which would not be expected in postlingually deafened adults. Another particularly important difference was that the children had much less residual hearing in their nonimplanted ears than the adults. This likely influenced the amount of benefit they received from using an FM system in that ear.

Indeed, in a study of adult combined bilateral CI+HA users, Tyler et al. (2002) suggested that the amount of residual hearing in the nonimplanted ear likely 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 relationship between amount of residual hearing in the nonimplanted ear and amount of benefit received by children wearing their CIs and HAs together. However, the children who participated in Ching, Psarros et al.'s investigation had at least borderline profound hearing losses in their nonimplanted ears (pure tone averages [PTAs] 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 CI candidacy criteria, there are now more children than ever with "aidable" residual hearing in their nonimplanted ears who could benefit from investigating these issues.

One reason why CI candidacy criteria have broadened is that children with some degree of open-set word recognition prior to cochlear implantation demonstrate better spoken word recognition after implantation than do children with very little or no pre-implantation open-set word recognition (Osberger & Fisher, 2000; Staller, Arcaroli, Parkinson, & Arndt, 2002; Zwolan et al., 1997). Furthermore, children with profound hearing loss who use CIs now have word recognition skills that are similar to children with severe hearing loss who use HAs (Boothroyd & Boothroyd-Turner, 2002; Eisenberg, Kirk, Martinez, Ying, & Miyamoto, 2004). Pediatric CI recipients with residual nonimplanted-ear hearing represent a different population than has been studied in the past. The children we studied, including a subset who 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, and thus potentially stand to gain more from acoustic input to their nonimplanted ears. Moreover, these children have been tested longitudinally. Although Tyler and Ching and their respective colleagues have suggested that children show benefit from combined CI+HA use, the greatest benefits of combined CI+HA use may emerge over time as the child learns to integrate the two different signals from each ear. The work done on binaural acoustic-electric hearing typically has assessed performance at a single point in time, and therefore the time course of this development is not known. In the current investigation, we followed children longitudinally over the course of 1 to 3 years post-CI activation to examine: 1) the effects of residual hearing on spoken language development in cochlear implanted children; 2) whether pediatric CI recipients with residual hearing in their nonimplanted ears benefit from the bilateral input received by using a HA on their nonimplanted ears; and 3) the time course over which this benefit might emerge.

Methods

Participants

Inclusion criteria included onset of severe-to-profound bilateral sensorineural hearing loss by age 3 years, no other identified disability (such as, physical, visual, or cognitive impairment), etiology of hearing loss other than auditory neuropathy/dysynchrony, and implanted with a current device and fitted with a current speech processing strategy. Based on these criteria, two groups of CI recipients were identified for inclusion in the portion of the investigation designed to examine the influence of amount of residual hearing (in the nonimplanted ear) on spoken language outcomes following cochlear implantation. The first group (Profound) consisted of 124 children with profound sensorineural hearing loss in their nonimplanted ears. The second group (Severe) consisted of 22 children with severe sensorineural hearing loss in their nonimplanted ears. Ten children in the Severe group continued wearing HAs in their nonimplanted ears following cochlear implantation (NiEHA), whereas the remaining 12 children used their CIs exclusively (No-NiEHA). These two Severe subgroups were included in the portion of the investigation examining the influence of nonimplanted-ear hearing use. Demographic information for the participants is displayed in Table 1. Mean PTAs in the implanted and nonimplanted ears, age at onset of deafness, age at initial CI stimulation, proportion using oral communication, and proportion of females are shown. Standard deviations are displayed in parentheses where indicated.

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)
Profound	124	114.5 (6.5)	113.4 (7.9)	1.6 (4.9)	36.9 (20.1)	61%	51%
Severe	22	92.1 (13.2)	80.0 (8.0)	2.2 (6.5)	64.7 (35.2)	55%	41%
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.

Table 1. Demographic information for participants.

The primary differences among these groups, other than degree of residual hearing, were amount of hearing loss in the implanted ear prior to cochlear implantation, age at implantation, and the relative proportion of children using oral communication and those using total communication. Although all of the groups on average had profound hearing losses in their implanted ears, hearing losses were approximately 20 dB worse in the Profound group than the other groups of participants. On average, the Severe children were implanted about 2.5 years later than the Profound children and the Severe NiEHA children were implanted approximately 4 years later than the Profound children. This likely reflects recent changes in candidacy criteria to include children with severe hearing loss over the age of 2 years and children with profound hearing loss age 1 year or older. Therefore, under FDA guidelines, a greater number of younger children are eligible for implantation with profound hearing loss than with severe hearing loss. Furthermore, until recently, most cochlear implant teams have been reluctant to implant children who demonstrated some speech understanding with a HA.

There was a slightly larger proportion of children in the Profound group using oral communication (61%) than in the Severe group (55%), although this trend did not extend to the subset of children in the Severe group who used HAs on their non-implanted ears, who were mainly oral communicators (80%). Total communication (TC) combines oral speech with signing in English word order (also known as Signed Exact English). Oral communication (OC) does not use any signing. One potential explanation for a greater proportion of children in the Profound group using OC than in the Severe group is that the children in the Severe group received their CIs much later in life than the children in the Profound group. Therefore, it is possible that children in the Severe group were encouraged to enroll in TC programs early on before they were considered CI candidates, as opposed to the children in the Profound group who received their devices much earlier and may have been encouraged to enroll in OC programs that promote the use of the auditory signal received from their CIs. We are unable to test this conjecture with this sample, but it is one explanation for the difference in proportion of OC users between the groups.

Sensory Aids

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

		Cochlear implant				Processing strategy					
Participant group	N	Nucleus 24	Nucleus 22	Clarion	Med-El Combi 40+	MPS*	SPEAK	CIS*	SAS*	ACE*	HiRes
Profound	124	58	40	23	3	4	51	18	5	45	1
Severe											
NiEHA	10	4	0	5	1	0	0	1	5	4	0
No-NiEHA	12	5	0	2	5	0	0	7	2	3	0

**MPS = Multiple Pulsatile Sample, CIS = Continuous Interleaved Sampling, SAS = Simultaneous Analog Stimulation, ACE = Advanced Combination Encoder*

Table 2. Cochlear implant devices and processing strategies used by the participants.

Test Battery

We used a battery of speech recognition and receptive and expressive language tests to evaluate the children's speech and language processing skills. A test battery approach was used for two primary reasons. First, some traditional clinical measures of speech and language processing skills may be insensitive to differences in speech and language abilities among pediatric CI users and within a single child over time (Kirk, Diefendorf, Pisoni, & Robbins, 1997). It is likely that these measures employ vocabulary too advanced for children with severe to profound hearing loss (Boothroyd, 1993; Carney et al., 1993; Moeller, Osberger, & Eccarius, 1986). Second, speech and language processing is hierarchical in nature and therefore, is best examined by combining results from different speech and language measures (Mendel & Danhauer, 1997).

The test battery that was used to examine the influence of amount of residual hearing on CI users' speech and language performance included open- and closed-set word and sentence recognition tests presented with auditory cues only (e.g., no visual cues via speechreading were provided), one test of receptive and expressive language, and one test of receptive vocabulary. A smaller set of spoken word recognition measures was selected for examining the influence of combining acoustic and electric stimulation across ears, because we primarily were interested in examining whether longitudinal changes were evident in listeners' spoken word recognition.

Tests of Spoken Word Recognition. The Grammatical Analysis of Elicited Language – Pre-Sentence Level Test (GAEL-P; Moog, Kozak, & Geers, 1983) was adapted for use as a closed-set word recognition measure. Before testing, the examiner familiarized each child with the test objects using auditory and visual cues. However, testing was conducted in the auditory-only modality via live-voice. During each trial, the child was presented with four objects: the target and three foils. After the examiner presented the word corresponding to the target item, the child was to respond by pointing to the target object. Performance was scored by percent correct, with chance equaling 25% correct.

The Mr. Potato Head Task (Robbins, 1994) employs a relatively familiar children's toy that consists of a "potato" body along with approximately 20 body parts and accessories that can be attached to the potato body. For some body parts and accessories, there is more than a single exemplar (e.g., several colors and styles of shoes). Children were given a list of 20 auditory-only sentence-length instructions on how to assemble the toy. Their responses were scored for sentence and word correct in percent. An example of one test item is, "He wants *green* *shoes*," in which "green" and "shoes" are the key words in the sentence. If the child picked up or pointed to any pair of shoes belonging to Mr. Potato Head or if the child picked up a green object, she/he would get 1 out of 2 possible key words correct, but not the sentence correct. If the child picked up or pointed to Mr. Potato Head's green shoes, she/he would get 2 out of 2 key words correct, but not the sentence correct. Finally, if the child put the green shoes on Mr. Potato Head, she/he would get both key words correct and the sentence correct. The word recognition task is considered closed-set because, by chance, the child could select 1 of the 20 body parts or accessories (chance performance = 5%). However, the sentence recognition task is open-set because the child could not carry out the instructions simply by chance.

The Phonetically Balanced–Kindergarten Word Lists (PB-K; Haskins, 1949) is an open-set word recognition test that consists of four lists of 50 phonetically balanced monosyllabic words. However, only three lists are used because the fourth was shown not to be equivalent to the others in Haskins' thesis. For this test, the child is asked to repeat each word after it is presented. Both word correct and phoneme correct scores were calculated in percent correct. Due to a slight protocol difference between testing sites, the PB-K was administered live-voice without lipreading cues in one laboratory (Indiana University School of Medicine) and via recorded compact disc in the other laboratory (House Ear Institute). Just four children in the Severe group (all of whom were also in the subgroup NiEHA) were tested in the laboratory that used recorded PB-K materials; the remaining children in the Severe group and all of the children in the Profound group tested on the PB-K were administered the materials in the laboratory that used live-voice presentation. Using a One-way ANOVA with type of PB-K presentation format (recorded and live-voice) as the between-participant factor and CI-only score at each testing interval as the dependent measure, we found no significant differences in performance on either phoneme or word correct between the four children tested using recorded materials and the other children in the Severe group 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 (CI-only, HA-only and HA combined with CI) were found between the children tested using the recorded materials and the other children in the NiEHA group who received the materials live-voice. Therefore, the data were collapsed across test administration format in analyzing and reporting the results.

The Lexical Neighborhood Test (LNT; Kirk, Pisoni, & Osberger, 1995) is a recorded open-set word recognition test. The LNT consists of two lists of 50 monosyllabic words. Within each list, half of the test items are lexically "easy" (e.g., they occur often in English and have few phonemically similar words, or lexical neighbors, with which they can be confused); the remaining items are "lexically hard" (e.g., they occur rarely in English and have many phonemically similar words with which they can be confused). The recorded version used in our laboratory has five different talkers (two male and three female) within each list (Kirk, Eisenberg, Martinez, & Hay-McCutcheon, 1999). The use of multiple talkers allows us to assess the child's ability to process speech in the presence of one source of variability encountered in real-world listening situations. Children respond by repeating each word they heard. Their responses were scored as the percent of lexically easy and lexically hard words correctly identified.

The Hearing-In-Noise Test–Children's Version (HINT-C; Nilsson, Soli, & Gelnett, 1996) was modified for use as a test of spoken word recognition in which the percent of words in a sentence correctly repeated at a fixed signal-to-noise ratio (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 the percent of words correctly repeated in each sentence.

Tests of Receptive and Expressive Language. The Peabody Picture Vocabulary Test, Third Edition (PPVT-III; Dunn & Dunn, 1997) measures receptive vocabulary development. During testing, the child is presented with a word and is asked to identify it from four line drawings. The presentation format of each word differs depending on the child's primary mode of communication (OC or TC): for children who use OC, the stimuli are presented with auditory and visual cues; for children who use TC, the stimuli are presented with auditory, visual, and sign cues. A receptive vocabulary age is derived and then is converted into a receptive language quotient (receptive vocabulary age divided by chronological age). Language quotients of 1.0 indicate that language and chronological age are equal. In other words, children with language quotients of 1.0 have age-appropriate receptive vocabulary skills. Children with better receptive vocabulary skills than children their age have language quotients above 1.0; children whose receptive vocabulary lags behind their chronologically age-matched peers have language quotients below 1.0.

The Reynell Developmental Language Scales (RDLS; Reynell & Huntley, 1985) assess both receptive and expressive language abilities. Both the receptive and expressive portions of the RDLS use 62 items arranged into 10 sections to assess language development. The receptive portion assesses children's comprehension of a hierarchy of language structures ranging from identifying named objects to inferencing and vocabulary/grammar; the expressive portion assesses children's ability to express a hierarchy of language structures ranging from object labeling to complex instructions. As with the PPVT-III, the RDLS is administered in each child's primary mode of communication and receptive and expressive language quotients were derived from each child's receptive and expressive vocabulary ages.

Procedure

Children were administered the test battery prior to cochlear implantation and at approximately regular 6-month intervals after the CI was first activated. Due to the longitudinal nature of this investigation, not all children were tested on every test administered at each interval due to time constraints, lack of attention for the full test battery, age of the child, or missed appointments. However, all of the participants were administered at least one of the measures in the test battery. 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.

Licensed speech-language pathologists with training in working with children with CIs administered and scored all of the test measures. The spoken word recognition measures were administered in an auditory-only format, whereas the language measures were presented in the child's primary mode of communication. 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. Testing was conducted in a quiet room using live-voice presented at approximately 70 dB SPL, with three exceptions: the PB-K at House Ear Institute, HINT-C sentences and the LNT at both laboratories were presented in a double-walled sound booth using recorded stimuli played through a clinical audiometer. The speech was presented at an average long-term rms of 70 dB SPL. The PB-K and LNT were always administered in quiet, whereas 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 placed at 0 degrees azimuth from the listener.

The subgroup of children who continued to wear HAs on their nonimplanted ears were tested in three additional conditions on the PB-K and the HINT-C sentences: 1) HA-only, in which each listener's CI was turned off and the child wore her/his HA at her/his everyday setting; 2) CI-only, in which each listener's HA was removed and the child wore her/his CI at her/his everyday setting; and 3) CI+HA, in which both the CI and HA were activated and worn at everyday settings.

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. 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. This allowed us to include more data points per 1-year testing interval.

Effects of Residual Hearing

Figures 1 through 6 display results from the speech and language measures for the children in the Profound and Severe groups in order to examine performance differences between children with differing amounts of residual hearing. The top panels show mean group data and +1 standard deviation for the Profound (unfilled bars) and the Severe (black-filled bars) groups. The numbers on the bars in the top panels represent the number of children tested in that specific group for that particular interval. The lower panels display either individual data for the Severe group and average group data for the Profound/TC and Profound/OC groups or average group data for Profound/TC, Profound/OC, Severe/TC, and Severe/OC groups. For test measures that were given to only a few children in the Severe group, individual data are shown; otherwise group data are displayed. Individual data from children in the Severe group who used TC (Severe/TC, light gray-filled bars) and Severe children who used OC (Severe/OC, dark-gray striped bars) appear in the lower panels of Figures 1, 2, and 5, along with mean group data and +1 standard deviation for the children in the Profound group who used TC (Profound/TC, unfilled bars) and who used OC (Profound/OC, black-filled bars). The numbers on each bar in the lower panels of Figures 1, 2, and 5 represent the participant identification (ID) number. Participant ID numbers are consistent, such that participant ID 3 represents the same participant across figures. The lower panels in Figures 3, 4, and 6 display mean group data for the Profound/TC, Profound/OC, Severe/TC, and Severe/OC groups rather than individual data. The numbers on the bars in the lower panels of Figures 3, 4, and 6 represent the number of children tested in that group for that particular interval.

Data from each test measure were entered into a two-way Analysis of Variance (ANOVA) with one repeated measure to determine whether performance changed over time. The between-participant factor was participant group and the within-participant factor was years of CI use. Because participants with missing data cannot be included in the ANOVA, there are instances in which the number of children included in the statistical analysis is smaller than the number of children administered in a given test measure. In some cases the number of children tested in multiple intervals in the Severe group was so small (e.g., one or two participants) that we selected to also analyze the data using multiple one-way ANOVAs to compare performance differences between the groups.

Figure 1 displays results from the GAEL-P across time. Recall that the GAEL-P is a closed-set measure of spoken word recognition in which chance performance is 25% (indicated by the dashed line in both panels of Figure 1). After 1 year of CI use, both groups demonstrated significant improvements in their spoken word recognition on the GAEL-P, $F(1, 79) = 7.724$, $p = .007$. Overall, the Severe group scores declined during the first year of CI use. However, the Severe children tested at both intervals (IDs 2, 3, and 8) demonstrated gains over time. Prior to cochlear implantation, the Severe group had significantly higher scores than the Profound group, $F(1, 88) = 28.015$, $p < .001$. After one year of device use, the significant difference between the groups disappeared. The bottom panel of Figure 1 shows that, prior to cochlear implantation, the Severe/OC children were performing at ceiling on the GAEL-P, whereas only one Severe/TC child performed above chance. The two children in the Severe/TC group who were tested both before implantation and 1 year post-operatively (IDs 2 and 3) showed improved closed-set word recognition after 1 year of device use, particularly participant ID 3.

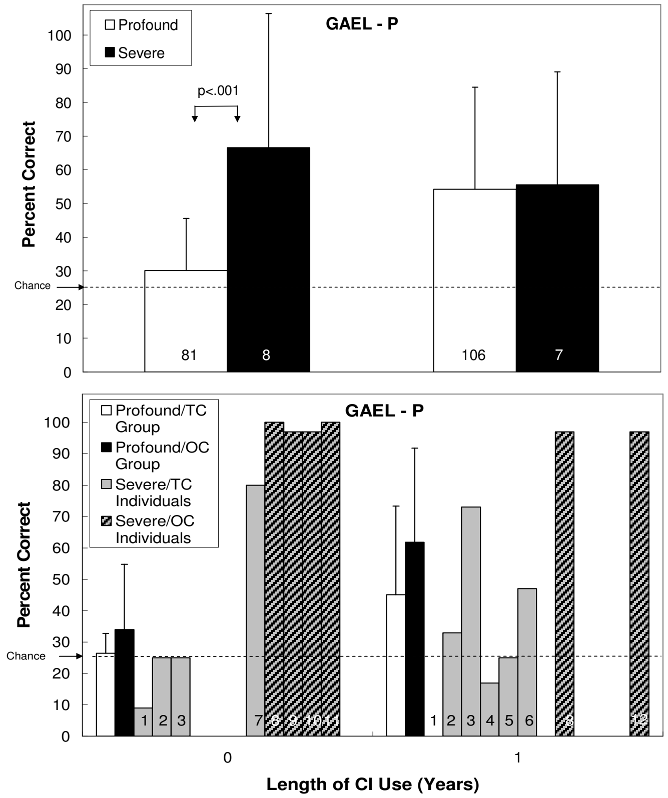

Figure 1. Test results from the GAEL-P. Note that participant 1 had a score of 0 after 1 year of CI use.

The results from the word and sentence recognition portions of the Mr. Potato Head Task are displayed in the first and second columns of Figure 2, respectively. Similar to the GAEL-P results, word recognition performance improved significantly after 1 year of device use for both groups, $F(1, 70) = 6.031$, $p = .017$, as did sentence recognition, $F(1, 68) = 4.957$, $p = .029$. Overall, the Severe group scores declined during the first year of CI use. However, the Severe children tested at both intervals (IDs 3 and 10) demonstrated gains in word and sentence recognition performance over time. Prior to cochlear implantation, the Severe group had significantly higher word and sentence recognition scores than the Profound group, *F*(1, 80) = 66.270, *p* < .001 and *F*(1, 78) = 32.913, *p* < .001, respectively. After one year of device use, the difference between the groups disappeared. With one exception (ID 7), individual Severe/OC children had higher word and sentence recognition scores than Severe/TC children at both testing intervals.

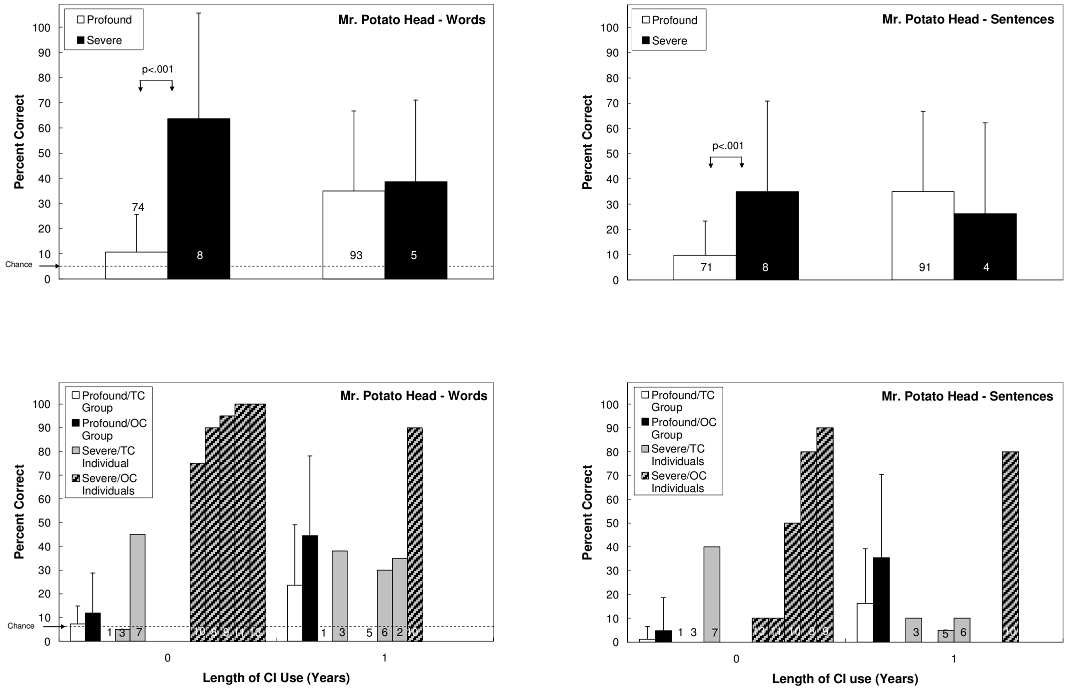

Figure 2. Test results from the Mr. Potato Head Task. Note that participants 1 and 5 had scores of 0 on the word recognition portion and participants 1 and 3 had scores of 0 prior to cochlear implantation on the sentence recognition portion.

Figure 3 displays the results from the phoneme recognition (first column) and word recognition (second column) portions of the PB-K. Unlike the previous word recognition measures, enough data were collected through 2 years of CI use to include this later interval. Including more longitudinal data revealed some interesting effects. Both groups had significant improvements in both phoneme and word recognition over time, *F*(2, 16) = 10.488, *p* = .001 and *F*(2, 18) = 6.813, *p* = .006, respectively. As with the previous word recognition measures, the Severe group performed significantly better than the Profound group prior to cochlear implantation for both phoneme and word recognition on the PB-K, *F*(1, 14) = 17.850, *p* = .001 and *F*(1, 14) = 10.368, *p* = .006, respectively, and the two groups performed similarly after 1 year of CI experience. However, after 2 years of CI use, the Severe group had significantly higher scores than the Profound group on both phoneme and word recognition, *F*(1, 27) = 5.943, *p* = .022 and *F*(1, 29) = 12.490, *p* = .001, respectively. For phoneme recognition, but not for word recognition, there was an interaction between length of device use and degree of residual hearing, *F*(2, 16) = 4.978, *p* = .021. That is, the Profound group made great gains during their first year of CI use, particularly in their phoneme recognition skills, and then plateaued between post-implantation years 1 and 2; whereas the Severe group's gains, although more moderate than those seen in the Profound group, were made between post-implantation years 1 and 2. Finally, there was a trend for OC users to have higher scores than TC users, regardless of degree of residual hearing.

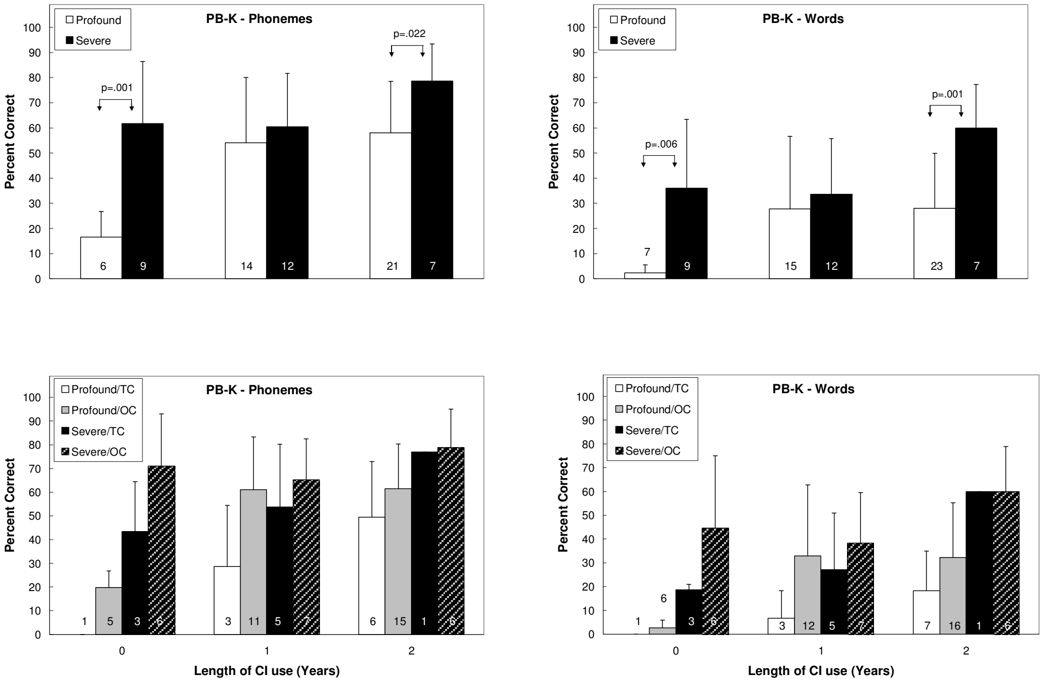

Figure 3. Test results from the PB-K. The phoneme recognition results are shown in the first column and the word recognition results are shown in the second column.

Figure 4 displays the results from the LNT. Too few children were tested on the LNT before cochlear implantation, particularly in the Profound group, to complete a repeated measures ANOVA. There are two reasons that few Profound children were tested near the time of their implantation: the recorded version of the LNT was not yet developed when some of these children received their CIs and many children in the Profound group were too young to be administered the LNT at early testing intervals. Therefore, we will concentrate most of the discussion on the results from the later testing intervals. After 3 years of CI experience, the average Profound participant correctly identified about 50% of the easy and nearly 40% of the hard words, whereas the average Severe participant correctly identified nearly 80% of the easy and greater than 60% of the hard words. Multiple one-way ANOVAs were carried out to examine differences between groups. The Severe group had higher word recognition scores for both lexically easy and hard words than the Profound group at every test interval except on hard words at 2 years post-operative interval (see Figure 4 for *p*-values). Although there were few Severe/TC children tested at any given interval, most of the difference between the Severe and Profound groups primarily was due to the higher average word recognition scores of the Severe/OC children. As shown in the bottom panels of Figure 4, the Severe/OC group had average scores that were at least 20% better after cochlear implantation than those for children in the Severe/TC, Profound/TC and Profound/OC groups.

The Wilcoxon Signed Rank Test was used to examine the effects of lexical difficulty for the Severe and Profound groups separately. The Severe group had significantly higher word recognition scores for easy words than hard words at 1 and 2 years after cochlear implantation, $z = -2.673$, $p = 0.008$ (2-tailed) and $z = -2.375$, $p = 0.018$ (2-tailed), respectively. Only after 3 years of CI experience were the

Profound group's word recognition scores significantly different for easy versus hard words, $z = -5.351$, $p < 0.001$ (2-tailed), with easy words identified with greater accuracy than hard words.

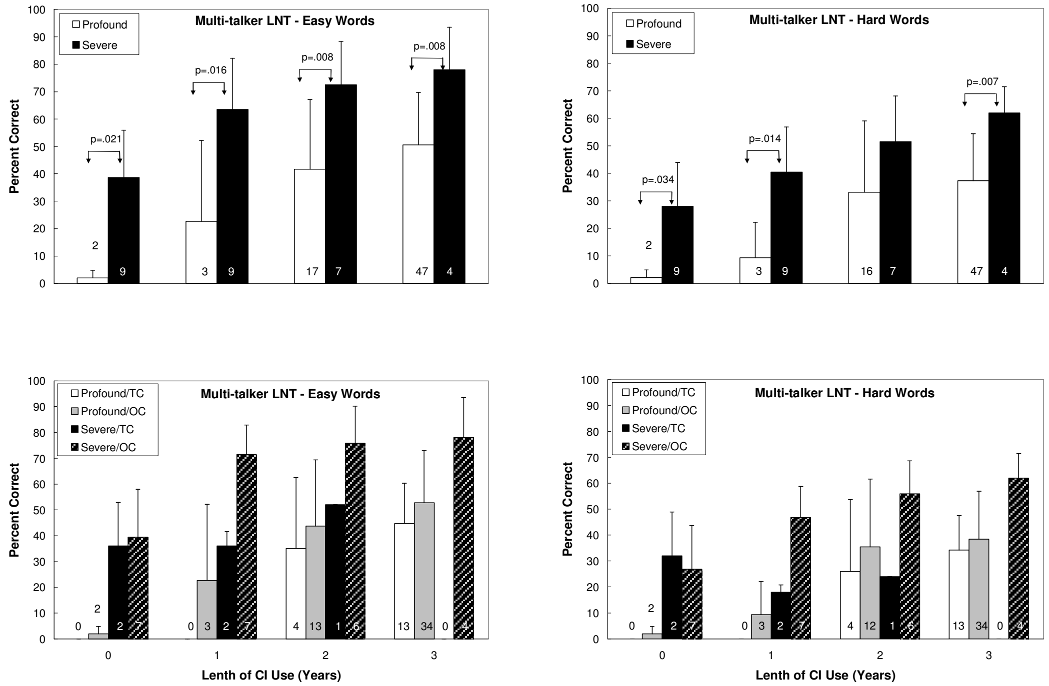

Figure 4. Test results from the LNT. The lexically easy and hard word recognition results are shown in the first and second columns, respectively. Note that no children from the Profound/TC group were tested before cochlear implantation and after 1 year of CI use.

Figure 5 displays the results from the receptive (left panels) and expressive (right panels) portions of the RDLS. Significant improvements in receptive, but not expressive, language beyond those expected by typical development were made by both groups over time, $F(1, 54) = 11.909$, $p = .001$. No significant differences were found between the Severe and Profound groups for both receptive and expressive language at the two intervals tested. Further, no child in the Severe/TC group scored higher at any interval than any Severe/OC child on either the receptive or expressive portion of the RDLS. All but two Severe children (IDs 5 and 8) tested at both intervals made receptive language gains beyond those expected by typical development. Similarly, all but two Severe children (IDs 5 and 10) made expressive language gains beyond those expected by typical development.

Finally, the results from the PPVT are shown in Figure 6. Both groups made significant gains in their receptive vocabulary beyond that expected by typical development through 2 years of CI experience, $F(2, 64) = 7.305$, $p = .001$. The Severe group had higher language quotients than the Profound group prior to cochlear implantation, $F(1, 75) = 15.178$, $p < .001$, at 1 year post-operatively, $F(1, 73) = 6.641$, $p = .012$, and at 2 years post-operatively, $F(1, 74) = 11.450$, $p = .001$. Further, the children in the Severe/OC group appear to be primarily responsible for the Severe group's high performance as a whole, because the Severe/TC group performed similarly to the Profound group (as is evident in the lower panel of Figure 6). Of note is that the Severe/OC group had average language quotients commensurate with their chronological ages after 2 years of CI experience. However, the language quotients at this interval for the Severe/OC group varied greatly from 0.57 to 1.65.

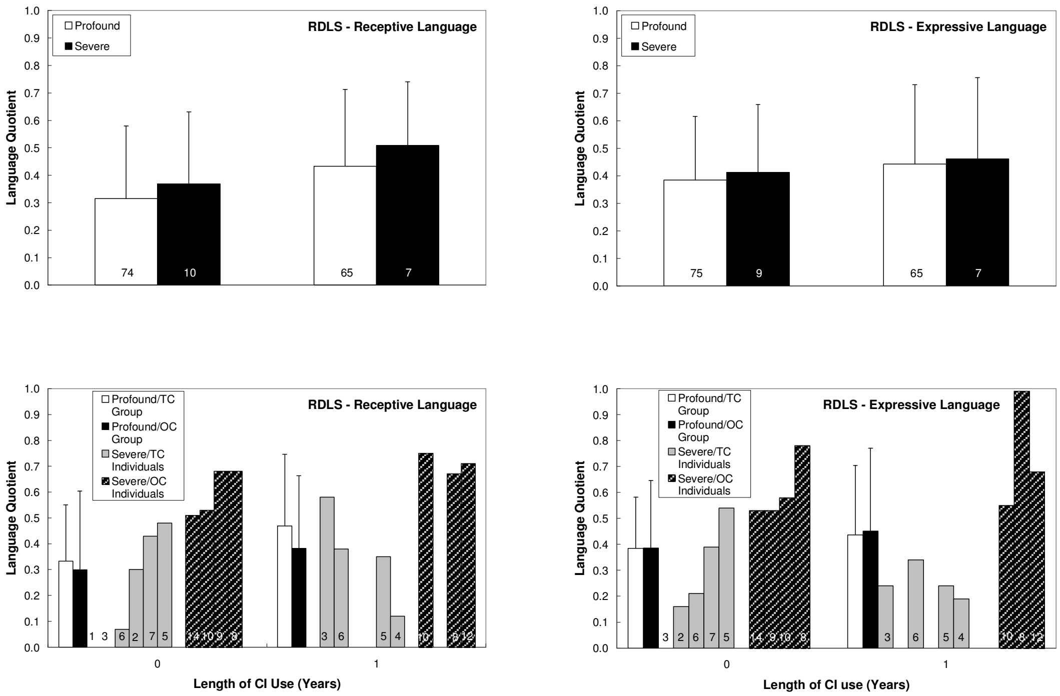

Figure 5. Test results from the RDLS. The receptive and expressive language results are shown in the first and second columns, respectively. Note that participants 1 and 3 had receptive language quotients of 0 and participant 3 had an expressive language quotient of 0 prior to cochlear implantation.

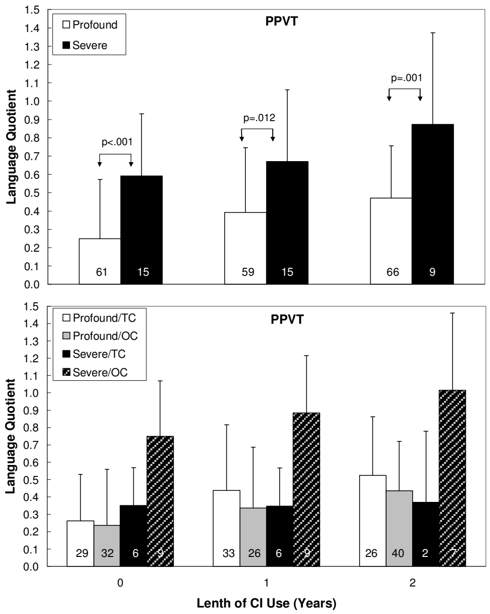

Figure 6. Test results from the PPVT.

Effects of Combined Cochlear Implant and Hearing Aid Use

The subset of participants with severe hearing loss who wore HAs on their nonimplanted ears (NiEHA group) underwent further evaluation of their individual-ear and binaural word recognition skills in both quiet and noise. The PB-K (scored by word correct) was administered in quiet, whereas the sentences from the HINT-C were given in both quiet and at +5 dB SNR. Mean group data and +1 standard deviation on the PB-K are shown in Figure 7. Performance of the children who continued HA use (NiEHA) is shown by unfilled bars (HA-only condition), gray-filled bars (CI-only condition), and black-filled bars (CI+HA condition). For comparison purposes, the striped bars indicate performance of the children who did not continue HA use (No-NiEHA). Note that the data from the No-NiEHA group reflect performance with a HA prior to cochlear implantation (0 years of CI use) and with their CI-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 CI-only or CI+HA conditions are displayed at 0 years of CI use because, by definition, participants had not yet received their CIs at this interval. The data from the NiEHA group were analyzed using the Wilcoxon Signed Ranks Test to evaluate differences among device testing conditions. After 2 years of CI use, the children had significantly higher PB-K word identification scores using their CIs and HAs simultaneously than using their HAs alone, $z = -2.023$, $p = 0.043$ (2-tailed). In fact, all five children tested after 2 years of CI use showed this effect. The difference between using CIs and HAs together and using a HA alone 1 year after cochlear implantation approached significance, $z = -1.897$, $p = 0.058$ (2-tailed). At this interval, 7 of the 8 children had higher word recognition scores using both devices simultaneously than using their HAs alone.

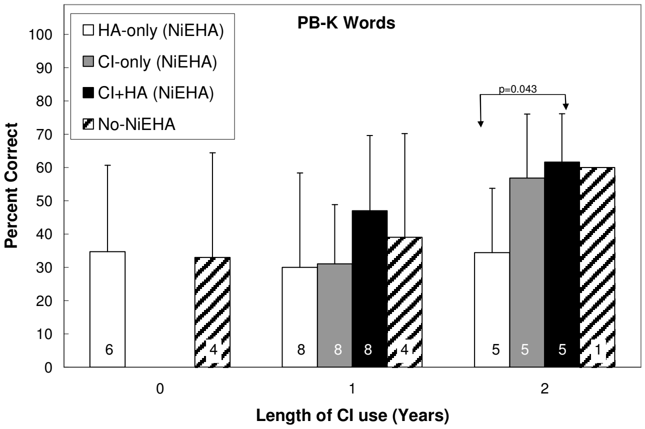

Figure 7. Mean group data and +1 standard deviation on the PB-K in quiet. Performance of the children who used nonimplanted-ear HAs (NiEHA) is indicated by the unfilled bars (HA-only condition), gray-filled bars (CI-only condition), and the black-filled bars (CI+HA condition). Group data for the children who did not continue to wear HAs in their nonimplanted ears (No-NiEHA) are indicated by the striped bars. The numbers on each bar indicate the number of participants tested in a particular group and time interval. No data for the CI or CI+HA conditions are displayed at 0 years of CI use because, by definition, participants had not yet received their CIs at this interval.

Before cochlear implantation, word recognition performance on the PB-K of the children who would later continue nonimplanted-ear HA use and those children who would not continue HA 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 pre-implant differences in spoken word recognition in quiet between children who continued HA use and children who stopped wearing HAs 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.

Figure 8 displays mean group data and +1 standard deviation on HINT-C for the children who continued wearing HAs 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 HA+CI and HA-only, $z = -2.023$, $p = 0.043$ (2-tailed). All 5 participants had higher HINT-C word recognition scores in quiet using both sensory aids together than using their HAs alone. In contrast to the results in quiet, word recognition in noise was significantly better after 2 years of CI use in the combined CI+HA condition than in either CI-alone, $z = -2.023$, $p = 0.042$ (2-tailed), or HA-alone, $z = -2.023$, $p = 0.043$ (2-tailed). In both cases, all 5 participants demonstrated this effect.

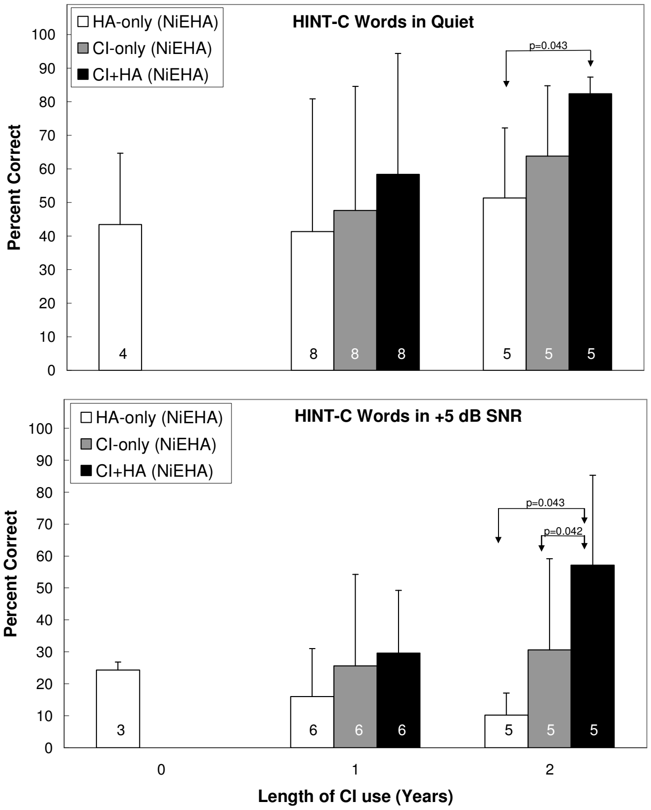

Figure 8. Mean group data and +1 standard deviation on the HINT-C sentences scored by words correctly repeated in quiet (top panel) and in +5 dB SNR (bottom panel) for the children who used nonimplanted-ear HAs (NiEHA). The unfilled bars indicate performance in the HA-only condition; the gray-filled bars indicate performance in the CI-only condition; and the black-filled bars indicate the performance in the CI+HA condition. The numbers on each bar indicate the number of participants tested in a particular group and time interval. No data for the CI or CI+HA conditions are displayed at 0 years of CI use because, by definition, participants had not yet received their CIs at this interval.

Using a repeated measures ANOVA (within factor was years of CI use [1 and 2 years post-operatively] and the between factors were noise condition [quiet and +5 dB SNR] and the sensory aid configuration [HA, CI, and CI+HA]), 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 using a CI and HA simultaneously than using either a HA or a CI alone.

Discussion

Effects of Amount of Residual Hearing

We hypothesized that children with more residual hearing (those in the Severe group) would demonstrate better spoken word recognition and language skills than children with less residual hearing (those in the Profound group) due to their greater number of residual functioning auditory neurons and presumably shorter periods of auditory deprivation. The results from the GAEL-P, Mr. Potato Head Task, and PB-K through 1 year of CI experience suggest that, although children with severe hearing loss in the nonimplanted ear start out with better spoken word and sentence recognition skills prior to cochlear implantation than children with profound hearing loss in the nonimplanted ear, both groups have similar skills after 1 year of CI use. An explanation for this finding is that often individuals in the Severe group who score near ceiling performance before cochlear implantation were not tested again on the same measure, leaving primarily lower performers being tested at the 1-year interval. For example, three of the high Severe/OC performers who were tested on the GAEL-P pre-operatively were not re-tested post-operatively because they had already reached ceiling performance. None of the children in the Severe group who scored above 75% prior to cochlear implantation on the Mr. Potato Head Task were tested 1 year after device use because they were already at ceiling performance. Another reason for the similar group performance after 1 year of CI experience is that the Profound group made gains during the first year of CI use that were significant from both statistical and practical points of view. As a group, the Profound children’s word and sentence recognition scores increased by over 20% after 1 year of CI experience, thereby closing the performance gap considerably between the two groups.

More data were collected at later intervals on the PB-K and LNT than the other spoken word recognition measures, allowing for a longitudinal examination of performance changes over a greater period of time. This analysis revealed some important findings. First, similar to the GAEL-P and Mr. Potato Head Task, the Severe group had better spoken word and phoneme recognition skills on the PB-K than the Profound group before cochlear implantation, but these differences disappeared after using a CI for 1 year. However, between post-implantation years 1 and 2, the Severe group showed significant improvements in word and phoneme recognition, whereas the Profound group’s performance plateaued between these two intervals. In other words, the children with profound hearing loss primarily made their open-set word recognition gains in the first year of device use, whereas the children with severe hearing loss started out with better spoken word recognition skills before cochlear implantation and, as a group, required over 1 year of device use before they began to demonstrate improvements in these skills. On the LNT, the Severe group’s recognition of lexically easy words was superior to that of the Profound group at all test intervals. Their recognition of lexically hard words was better than that of the Profound group after 1 and 3 years, but did not significantly differ after 2 years of CI use. Lexical difficulty effects were found for the Severe group at 1 and 2 years after cochlear implantation; that is, easier words were identified with greater accuracy than hard words. In contrast, the Profound group only showed this effect after 3 years of CI experience. Recall that lexically easy words have few phonemically similar words (e.g., reside in a sparse lexical neighborhood) with which to compete for recognition. Words in sparse lexical neighborhoods often can be accurately retrieved from memory even if the listener can encode only gross spectral differences. In contrast, lexically hard words have many phonemically similar words competing for attention in a dense lexical neighborhood. Accurate retrieval of lexically hard words from memory requires that the listener encode greater spectral information. Children in the Severe group obtained greater benefit from a HA prior to cochlear implantation than children in the Profound group; thus, they could use gross spectral cues to identify lexically easy words better than hard words even after cochlear implantation. Because a CI is not particularly good at conveying fine spectral detail in the speech signal (such as place of articulation cues), both groups were less proficient at identifying lexically hard words. It should be noted also that the children in the Severe group were implanted at later ages and thus were older at each testing interval than the children in the Profound group. Therefore, the Severe group's word recognition results also may reflect the influence of a better-developed oral vocabulary.

Both groups demonstrated significant improvements in receptive, but not expressive, language and receptive vocabulary beyond those expected by typical development after 1 to 2 years of CI experience, based on their RDLS and PPVT scores. Further, there were no differences on the RDLS in either receptive or expressive language quotients between the Severe and Profound groups. In contrast, group differences were found for receptive vocabulary on the PPVT. The children with severe hearing loss had significantly higher language quotients than the children with profound hearing loss. However, this difference held only for the children with severe hearing loss who use OC, but not for those who use TC. In other words, the children in the Severe group who use OC tended to have higher language quotients than those who use TC. This is in contrast to the Profound group in which children who use TC tended to have higher average receptive language quotients, but not expressive language quotients, than children who use OC. The results from the Profound group are consistent with previous findings from this population (Holt & Kirk, 2005; Kirk, Miyamoto, Ying, Perdew, & Zuganelis, 2002). One commonly cited explanation for TC users scoring higher on language measures than OC users is that the measures are administered in the child's primary mode of communication. Because some of the vocabulary used, especially on the PPVT, has accompanying signs that "look" like the test words, TC users may have an advantage over OC users on these measures. Although we do not know why the Severe group failed to show this typical pattern, we speculate that it might be due to their more intact auditory systems. Specifically, the children in the Severe group using OC might have been able to capitalize on their usable hearing to acquire a larger oral vocabulary in a way that children with Profound hearing loss and children using TC might not have been able to do, perhaps due to limited auditory abilities in the case of the former or more reliance on supplemental signing as opposed to oral skills in the latter.

Despite the fact that we are limited in our interpretation of the results for children using different communication modes, because we cannot randomly assign children to OC or TC environments, there is a trend, especially for children with severe residual hearing loss, to achieve better spoken word recognition and language if they use OC rather than TC. Although our research design does not permit us to infer a cause-and-effect relationship, these results support those of other investigators who have found greater speech and language gains in pediatric CI users with profound hearing loss who use OC compared to those who use TC (Kirk et al., 2002; Osberger et al., 1991; Sommers, 1991). Our results expand upon these findings and suggest that children with more usable hearing might benefit from a rich oral environment that allows them to capitalize on their greater auditory potential. Further research is needed on this population of cochlear implant recipients with more residual hearing to determine if specific communication and educational environments result in better speech and language outcomes.

Effects of Combined Cochlear Implant and Hearing Aid Use

The results from this investigation suggest that after 2 years of CI use, cochlear implanted children with severe hearing loss in the nonimplanted ear demonstrate significantly better word recognition skills when combining a HA on their nonimplanted ears with their CI than when using their HAs alone in quiet listening environments. However, this word recognition benefit does not extend to quiet listening conditions in which they use their CI alone. In contrast, spoken word recognition in background noise is significantly improved by combining a HA with a CI than by using either device alone after 2 years of CI 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). CI+HA PB-K word recognition performance in quiet was between 5-16% higher than CI-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 data from adults with normal hearing, 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 et al., 1986). Despite the differences in mode of auditory stimulation and participant characteristics, these pediatric CI 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 CI experience, 4 of the 8 children and 2 of the 5 children tested on the PB-K, respectively, had significantly higher scores in the bilateral condition than in the CI-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 CI- or HA-only conditions. The HINT-C scores cannot be directly analyzed 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 CI-only condition for 6 of the 8 children tested in quiet on the HINT-C after 1 year of CI experience. The bilateral scores for the two children who failed to show improvement after 1 year of CI use were 6% and 13% lower than CI-only scores, respectively. After 2 years of CI use, 4 of the 5 children tested had higher scores in the bilateral condition than in the CI-only condition. The fifth child already was scoring at ceiling in the CI-only condition and her/his CI+HA score was only 6% below her/his CI-only score after 2 years of CI use.

For the HINT-C in noise, performance was significantly better in the bilateral condition than in either the CI- or HA-only conditions after 2 years of CI use. Two of the 6 children tested after 1 year of CI use had substantially higher word recognition scores in the bilateral condition than the CI-only condition and two others had nearly equivalent CI+HA and CI-only scores. The bilateral scores for the two children who failed to show improvement after 1 year of CI use were 5% and 23% lower than CI-only scores, respectively. The child with the substantial drop in bilateral relative to CI-only performance had much better (42%) bilateral than HA-only performance, however. All five children tested after 2 years of CI use had higher scores in the bilateral condition than in either the CI- or HA-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 CI 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 CI use in the CI-only and the combined CI+HA condition. In other words, children with severe hearing loss in their nonimplanted ears require over 1 year of both CI experience and combined CI+HA experience to begin demonstrating gains in CI-only and combined CI+HA word recognition in both quiet and in the presence of background noise. This finding suggests that experience with both signals is needed before monaural CI-only and bilateral CI+HA 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 CIs for at least 6 months demonstrated better spoken sentence and consonant recognition in quiet and noise when using their CIs and HAs simultaneously than when using their CIs 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 CI 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 HAs 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.

Conclusions

In summary, these results suggest that children with different degrees of residual hearing in their nonimplanted ears (from severe through profound) benefit in their spoken word and sentence recognition and language skills from cochlear implantation. However, the time course of the changes might be different for the two groups. Children with severe hearing loss might require more than 1 year of CI experience to demonstrate gains in their spoken word recognition, whereas children with profound losses appear to show more of their benefit early on. One potential explanation for the different developmental time course is that prior to cochlear implantation children with severe hearing loss receive auditory input, albeit degraded, whereas children with profound hearing loss receive virtually no auditory stimulation. Therefore, the children with profound hearing loss most likely have not experienced any usable auditory stimulation and thus, must learn to use the input from a CI to both develop and access their mental lexicon. In contrast, children with severe hearing loss have experienced acoustic stimulation and likely achieved limited spoken word recognition with it. When they receive a CI, they need to re-map the perceptual categories they have already learned (however crude they may be). This perceptual re-mapping might take longer than simply learning to use auditory stimulation. In contrast, postlingually deafened adult CI recipients typically have much better spoken word recognition skills than prelingually deafened adult CI recipients, even those with newer CIs and speech processing strategies (e.g., Teoh, Pisoni, & Miyamoto, 2004). However, postlingually deafened adults already have well-established categories. Presumably, it takes experience with the new signal before children who have some experience with oral language, but who have less well-developed perceptual categories than adults, to re-map these categories.

For measures in which the groups showed performance differences, the children with severe hearing loss had better speech perception and language skills than did the children with profound hearing loss. Furthermore, children with severe hearing loss in their nonimplanted ears benefit from combining the acoustic input received from a HA in the nonimplanted ear with the electric input received from a CI, particularly in background noise, a very common listening environment. However, the benefit emerges after the children adapt to the novel input from the CI and gain experience combining the two signals from the CI and the HA. 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 CI-only condition. This occurred for one participant on the HINT-C sentences in noise after 1 year of CI experience. Because this participant was not tested again after 2 years of CI 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 HA in the contralateral ear of a cochlear implanted child will cause interference that results in poorer word recognition than when a CI is used alone, even early on when the child is learning to use the novel input from the CI. Indeed, our findings suggest that it is appropriate to encourage children receiving CIs 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 CI in combination with their HA, it might be prudent to arrange training to the novel CI 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 CI 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. Related to this, is a need to better define the role of communication mode and the optimal educational environment for pediatric CI recipients with more residual hearing. Our results certainly do not answer the question of whether this population benefits most from a TC or an OC environment, but they do imply that these children are capable of capitalizing on the hearing that they do have by using primarily oral modes of communication. Finally, research comparing children who use CIs and HAs in contralateral ears to children with bilateral CIs 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 CIs and nonimplanted-ear HA use arguably allows for improved spoken word recognition skills over a CI alone, while simultaneously reducing auditory deprivation in the nonimplanted ear, thereby preserving that ear for future technological advances in cochlear implantation or hearing restoration.

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