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Long-term outcomes of cochlear implantation in the preschool years: From elementary grades to high school

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Key Words

Cochlear implants
Adolescents
Speech perception
Language
Reading

Abbreviations

BKB: Bamford-Kyle-Bench sentence test
FS: Factor score
OC: Oral communication
LNT: Lexical neighborhood test
PIQ: Performance intelligence quotient
SES: Socio-economic status
TC: Total communication

Abstract

The objective of this study was to document the development of speech, language, and reading skills between primary and secondary school ages in children who received cochlear implants during preschool years. Subjects were a sample of 85 North American adolescents recruited from a larger sample of 181 participants from a previous investigation. Students were first tested in early elementary school (ages eight to nine years) and were re-evaluated in high school (ages 15–18 years) for this study. The methods used were: performance on a battery of speech perception, language, and reading tests. These were compared at both test ages and significant predictors of outcome level identified through multiple regression analysis. Speech perception scores improved significantly with long-term cochlear implant use. Average language scores improved at a faster than normal rate, but reading scores did not quite keep pace with normal development. Performance in high school was most highly correlated with scores obtained in elementary grades. In addition, better outcomes were associated with lower PTA cochlear implant threshold, younger age at implantation and higher nonverbal IQ. In conclusion, early cochlear implantation had a long-term positive impact on auditory and verbal development, but did not result in age-appropriate reading levels in high school for the majority of students.

Sumario

El objetivo de este estudio fue documentar el desarrollo de habla, lenguaje y habilidades para la lectura entre los años de la primaria y la secundaria en niños que fueron implantados en edad preescolar. Los sujetos fueron una muestra de 85 adolescentes norteamericanos seleccionados de una amplia muestra de 181 participantes de una investigación previa. Los estudiantes fueron primero examinados en la escuela elemental temprana (edad de ocho a nueve años) y fueron revalorados en la preparatoria (edad de 15–18 años) para este estudio. Los métodos usados fueron: rendimiento con una batería de percepción del habla, lenguaje y pruebas de lectura. Estas fueron comparadas en ambas edades de prueba y se identificaron predictores significativos de niveles de respuesta por medio de un análisis de regresión múltiple. Las puntuaciones de la percepción del habla mejoraron significativamente con el uso del implante coclear a largo plazo. Las puntuaciones promedio de lenguaje mejoraron a una tasa más rápida que la normal pero las puntuaciones en lectura no mantuvieron el ritmo del desarrollo normal. El rendimiento en la preparatoria se observó en su mayoría correlacionado con las puntuaciones obtenidas en los grados elementales. Además, los mejores resultados se asociaron con umbrales PTA más bajos con el implante coclear, edades de implantación menores y CI no verbal más alto. En conclusión, la implantación coclear temprana tiene un impacto positivo a largo plazo en el desarrollo auditivo y verbal, pero no determina niveles de lectura apropiados para la edad, en la escolaridad preparatoria, en la mayoría de los estudiantes.

Multi-channel cochlear implants provide critical information regarding an auditory-speech system, previously unavailable to children with profound deafness (ASHA, 2003). The advent of cochlear implant technology has dramatically affected educational and communication options available to these children. The proportion of children educationally mainstreamed with hearing age-mates reportedly increases with each year of cochlear implant use (Geers & Brenner, 2003). However, the extent to which improved auditory access has affected the academic achievement of children with hearing loss, particularly their development of reading comprehension, is still under investigation.

Most normal-hearing children are competent language users when they begin to map reading onto existing phonological, syntactic, and semantic skills. Children with prelingual deafness demonstrate average delays of four to five years in language development by the time they enter high school (Blamey et al, 2001). The frequently reported low literacy levels among students with severe-profound hearing impairment are, in part, due to the discrepancy between their incomplete spoken language system and the demands of reading a speech-based system (Perfetti & Sandak, 2000). As a result, many of these children suffer from what teachers refer to as the 'fourth grade problem', meaning that they fail to make progress beyond identification of a limited number of words (Scarborough, 2001). Children with prelingual deafness approach reading with a more limited vocabulary than their hearing age-mates and the greater the hearing loss, the larger the delay (Boothroyd et al, 1991).

The improved auditory access provided by a cochlear implant may serve to reduce the magnitude of the reading gap. Vocabulary development appears to proceed more rapidly following cochlear implantation (Dawson et al, 1995), especially when implant surgery occurs at preschool age (Connor et al,

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2000, 2006). Unlike grammar, which is fairly complete in hearing children by 4–5 years of age, meanings of words are concepts that must be learned individually and vocabulary skills are continuously refined throughout development. The vocabulary advantage associated with cochlear implantation at an early age has a positive effect on reading comprehension, resulting in more age-appropriate literacy skills (Connor & Zwolan, 2004). Higher reading scores are also associated with early speech perception and production skills in children with cochlear implants (Spencer & Oleson, 2008). Early access to sound may help these children build better phonological processing skills, a component of early literacy.

It has been reported that almost four times as many children who had used a cochlear implant for at least two years attained a reading level above the fourth grade barrier when compared to children of similar age and hearing loss before the advent of cochlear implants (Spencer et al, 1997). A study of children enrolled in a private oral education setting following cochlear implantation reported that 70% scored within the average range on standardized reading tests in elementary school (Moog, 2002). However, the lag in reading development in children with hearing loss appears to widen with age (Kroese et al, 1986). An assessment of reading comprehension levels in 91 cochlear implant users at an average age of 11 years revealed that, on average, they were not reading as well as their peers with normal hearing (Connor & Zwolan, 2004). Whether deaf children who receive cochlear implants in preschool and exhibit reading levels commensurate with their hearing age-mates in elementary school will maintain these typical reading levels into adulthood has yet to be determined.

This study summarizes long-term outcomes from children who received a multi-channel cochlear implant between two and five years of age. The sample includes some of the first preschool-aged children to receive a multi-channel cochlear implant. Outcome data are examined at two points in time: during the early elementary grades when the children were eight or nine years old, and again in secondary school when the children were between 15–18 years of age. In this report, we briefly summarize our previous findings when the children were in elementary school, and present preliminary results from a subset of this group who have been retested in high school. The speech perception, language and academic levels achieved after long-term use of a cochlear implant will be described, and the factors that influence outcome levels will be examined.

Summary of outcomes in primary grades

A sample of 181 cochlear implant users was tested between 1996 and 2000 when they were in the first three primary grades (Geers & Brenner, 2003). The sample was geographically diverse, containing children from 29 different states in the USA and five Canadian provinces. Characteristics known to affect outcomes were controlled by sample selection criteria to restrict variability. All participants were eight or nine years old. Most children (77%) were deaf from birth, and the remainder became deaf before their third birthday. Age at implant activation ranged from just under two years to just following the fifth birthday, with the majority receiving an implant between two and three years of age. None of the participants had any additional disabilities and all came from a monolingual English-speaking home environment. All children received their cochlear implants between 1990 and 1996, with the majority of children implanted between 1992 and 1994. All but two of the children used the Nucleus-22 device from Cochlear Corporation. The children were assumed to have no useful pre-implant hearing because they were implanted when candidacy criteria specified that implant recipients receive no measurable benefit from hearing aids (Staller et al, 1991).

Educational placement was allowed to vary as much as possible in order to sample the wide variety of educational settings available for deaf children across North America. Information about each child's educational history over the first five years of cochlear implant use was gathered from questionnaires completed by parents, teachers, and therapists. At the time of implantation 75% of the children were enrolled full time in a special education setting. When they were tested at age eight or nine, 83% were enrolled in mainstream classrooms with normal hearing age-mates for at least part of the day. The communication methodology used in the children's classroom was rated on a six-point scale depicted graphically in Figure 1. Programs were categorized as 'total communication' (TC) if at least some signs or sign language was used, and as 'oral communication' (OC) if no sign language was used for communication. Communication systems were determined by assigning three levels of total communication (1 = sign emphasis, 2 = equal speech and sign emphasis, 3 = speech emphasis) to the TC group, and three levels of oral communication (4 = cued speech, 5 = auditory oral, and 6 = auditory verbal) to the OC group. To obtain an overall summary of communication mode, ratings were averaged over the first five years of cochlear implant use. About half of the children were placed primarily in TC and half in OC programs. The percentage of students enrolled in TC programs decreased from 49% prior to cochlear implantation to 46% in early elementary grades. The percentage using spoken language exclusively increased from 51% to 54% over the same time period.

Outcome data were collected in a series of 12 research camps with about 15 children per camp. A comprehensive battery of tests was administered by audiologists, teachers, psychologists, and speech-language pathologists. The test battery was organized into four overall outcome areas: speech perception, speech production, language, and reading. Several tests were

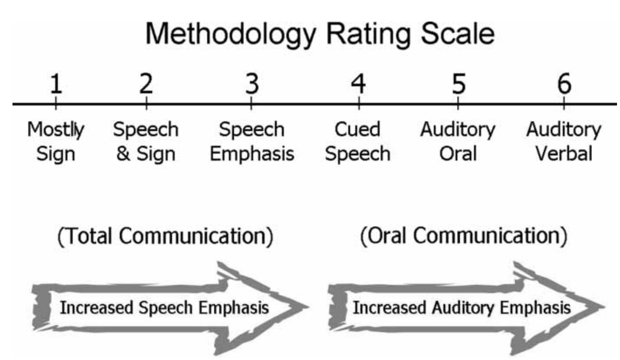

Figure 1. Rating scale used to identify a student's educational methodology as total communication or oral communication, and to quantify the amount of emphasis on speech and auditory skills in each student's classroom

administered in each area and the scores were combined into a weighted factor score using principal components analysis. In addition, a variety of intervening variables thought to affect outcomes were quantified, including: family characteristics (e.g. parent education, family size), cochlear implant characteristics (e.g. number of active electrodes, type of speech processor, mapping variables), and child characteristics (e.g. age at onset of deafness, age at implantation, nonverbal performance intelligence quotient: PIQ). Rehabilitation variables included quantified communication methodology (Figure 1), duration of mainstream placement, number of hours of individual therapy, and the relevant experience of the therapist. Data analyses focused on sources of variability in the speech, language, and reading outcomes. Multiple regression analysis was used to estimate the amount of outcome variance accounted for by rehabilitation characteristics after first removing the variance associated with the child, family, and cochlear implant variables.

A three-stage multiple regression analysis was conducted for each of the four outcome areas (Moog & Geers, 2003). The first stage examined the contributions of child and family characteristics to performance in these areas. Nonverbal PIQ and family socio-economic status (SES measured as combined rating of family income and parents' education level) were highly significant predictors of all outcomes. In addition, smaller family size was associated with higher scores on speech perception, speech production, and language measures; and female gender with higher scores in speech production, language, and reading. Age at test contributed significantly to reading scores, with nine-year-olds scoring better than eight-year-olds. Age at onset of deafness was positively related to both language and reading scores, with later onset associated with higher scores. Surprisingly, age at implantation failed to contribute significant independent variance to any of the measured outcomes. Total outcome variance accounted for by child and family characteristics ranged from 27% for language to 22% for speech perception and speech production outcomes.

Once variance due to the child and family characteristics was removed, the second stage of the analysis examined the contribution of cochlear implant characteristics. Cochlear implant characteristics accounted for between 12% of added variance in reading outcome and 23% of added variance in speech perception outcome. The majority of children had been programmed initially with the M-PEAK coding strategy and were later upgraded to the SPEAK strategy. The number of months they had used the SPEAK coding strategy and the size of the dynamic range represented on the implant map predicted significant variance in all outcomes. The number of active electrodes and growth of loudness also were significantly associated with all outcomes except for reading.

The third stage of the analysis examined rehabilitation factors. After variance due to child, family, and implant characteristics had been removed, two rehabilitation factors accounted for between 6% of added variance for reading outcome and 13% for speech production outcome. Children who had spent more time in mainstream classrooms had higher speech production, language, and reading skills. With this variance removed, children with higher communication mode averages (e.g. those in oral settings), scored significantly higher in speech perception, speech production and language. This finding indicates that after all variance attributed to native intelligence, family socio-economic status, implant characteristics, and classroom placement had been removed, children in oral education programs exhibited a significant speech and language advantage over those from programs with sign language (Moog & Geers, 2003;Tobey et al, 2004). Further analysis of the relation between communication mode and test scores indicated that better speech and language outcomes both resulted from, and contributed to, placement in oral classrooms (Geers 2004).

This initial study concluded that better performance outcomes in primary school were predicted by characteristics the child brings to the learning environment (such as higher native intelligence and family support), characteristics of the implant (such as an up-to-date processing strategy and a well-fitted map), and educational characteristics, especially an emphasis on speech and auditory skill development in the classroom.

The current project focuses on recruiting a large proportion of the 181 primary school students to return for follow-up testing when they are in high school. Beginning in 2004, testing camps were held in St. Louis, Missouri for groups of adolescents who had participated in the study described above. The following preliminary results include students who have participated as of 2007. This is an ongoing study, with the goal of recruiting at least 120 of the original 181 participants.

Table 1. Subject characteristics

Variable	*Mean*	*St. dev*	*Minimum*	*Maximum*
Age at onset of deafness (months)*	4.0	9.0	0	36
Age at implantation (years; months)	3;6	0;10	1;11	5;4
Communication mode rating over first five years of CI use (Figure 1)	3.92	1.45	1.8	6.0
Aided PTA with CI (0.5, 1, 2, 4, 8 kHz, HL)	31.74	9.63	13	48**
Age at first test (years; months)	9;1	0;6	7;11	9;11
Age at second test (years; months)	16;8	0;7	15;0	18;4
Duration of implant use at second test (years; months)	13;2	0;12	10;10	15;7
WISC PIQ at first test	103.24	14.23	65	133
WISC PIQ at second test	102.66	16.28	55	136

*66 had onset of deafness at birth
** One subject, who had experienced a dramatic decrease in hearing with the CI, is not represented in this maximum: this subject's aided threshold average at time of testing was 72 dB, HL.

Table 2. Comparison of follow-up participants (returned) with those who had not returned for follow-up.

Variable	*Returned (N = 85)*		*Not returned (N = 99)*		
	Mean	*SD*	*Mean*	*SD*	*F**
Implant age (years)	3.5	0.8	3.4	0.9	1.93
WISC-PIQ	103.2	14.2	101.3	14.8	0.80
Com. mode rating	3.9	1.4	3.8	1.6	0.43
Speech perception (BKB% correct)	58.4	34.9	55.8	38.2	0.23
Reading (PIAT standard score)	88.0	16.3	84.4	16.9	2.23

*None of the F-ratio values are significant at $p < .05$

Methods

Participants

Follow-up data collection has been completed for 85 of the original sample of 181 participants: 39 boys and 46 girls. Sample characteristics are summarized in Table 1. Communication mode average is based on the rating scale depicted in Figure 1. Aided threshold average was based on responses in the sound field with a cochlear implant at 0.5, 1, and 2 kHz at the second test session. Analyses of variance comparing characteristics of the 85 follow-up participants with the 99 students who had not yet been tested as teenagers revealed no significant differences. Table 2 presents mean values for speech perception (BKB sentences), nonverbal intelligence (WISC-PIQ) at age eight to nine years, communication mode rating (as depicted in Figure 1), age at implantation, and standard score on the reading subtests of the Peabody individual achievement test (Dunn & Markwardt, 1989). Results indicate that students returning for follow-up are comparable to non-returning students.

The implant processors worn by the children were upgraded between the first and second test sessions as new technologies became available. Seven students had received a second device in the other ear. At ages eight to nine years, most of the children used a Nucleus-22 implant (nine children were programmed with a MSP, and 75 with a SPECTRA speech processor). One child had received a Clarion implant from Advanced Bionics Corporation. Most adolescents had upgraded their speech processor by the follow-up testing. Eleven of the students experienced a device failure and were re-implanted. Ten students still used SPECTRA, one student used SPRINT, 22 students used Esprit-22, 46 students used Esprit 3G, and five students had received a Nucleus-24 electrode array and used a Freedom speech processor. The students returning for follow-up represented a broad geographical distribution (28 different states and four Canadian provinces) and included the full range of early communication modes depicted in Figure 1. The histogram in Figure 2 presents the communication mode average over the first five years of cochlear implant use for each of the follow-up participants and demonstrates approximately equal numbers of children whose early education was in TC settings and in OC settings. At follow-up assessment, the teenagers were asked to report the communication mode they used in school. Data points in Figure 2 indicate each student's response. The majority of students (62%) reported that they relied exclusively on speech, while 38% of the students reported using both speech and sign in school.

Figure 3 summarizes the type of classroom in which participants were enrolled at each test session. In the primary grades, 59% of the students were fully mainstreamed with hearing age-mates. By the time they were in high school, 77% of the students were fully mainstreamed, with an additional 19% of the students mainstreamed for part of the school day, and only 4% of the students still in full-time special education classrooms. Figure 4 plots current grade placement by chronologic age. Most students were in an appropriate grade for their age. The ninth graders were 15 years old, 10th graders were 15 and 16, 11th graders were 16 and 17, and 12th graders were 17 and 18 years old. This represents a positive trend for deaf students in the USA, who have been frequently placed with hearing students who were one to three years younger than the deaf students when in mainstream classes.

Procedures

Evaluation of progress

Students were assessed in their preferred communication mode at both test ages. Follow-up data collection used a similar methodology to that employed with the children at ages eight to nine years. However language assessment at eight to nine years was based primarily on language sample analysis while the adolescent test battery was comprised of standardized language tests. A direct estimation of progress between primary and secondary grades was possible only for those measures that were included in both test sessions.

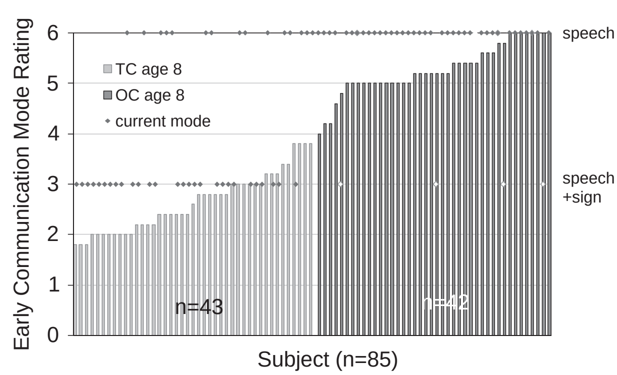

Figure 2. Bars represent individual classroom communication mode ratings averaged over the first five years of cochlear implant use for the 85 participants; data points represent current report from teenagers regarding their use of 'speech only' or 'speech and sign' to communicate in school.

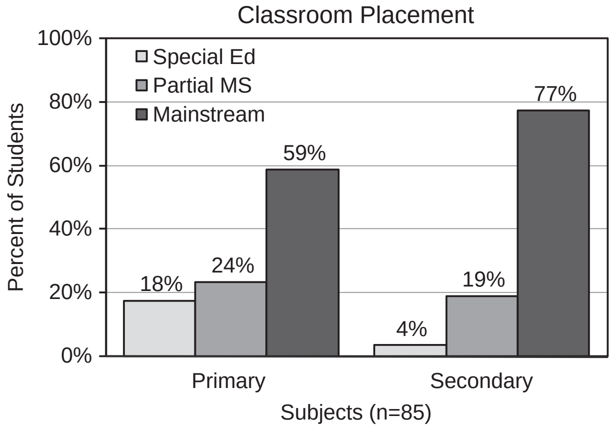

Figure 3. Percent of students (N = 85) enrolled in full-time special education, partial mainstream (MS), and full mainstream classrooms in primary and secondary grades

Tests administered at both elementary and high school ages included:

1. The Lexical Neighborhood Test (LNT) (Kirk et al, 1995) consisting of 50 recorded monosyllabic words delivered in an open-set format. Each list contains 25 'easy' words that are high in frequency of occurrence in English and have few lexical neighbors, and 25 'hard' words that are low in frequency and have many lexical neighbors. Recorded stimuli were presented in the sound field at 70 dB, SPL. Scores are expressed as the percentage of words correctly imitated.
2. The Bamford-Kyle-Bench (BKB) sentence test (Bamford & Wilson, 1979) consisting of 16 recorded simple sentences presented in an open-set format. The sentences include vocabulary, grammar, and sentence length appropriate to the linguistic abilities of most hearing-impaired eight-year-olds. Recorded stimuli were presented in the sound field at 70 dB. Scores are expressed as percentage of key words correctly imitated.
3. The Wechsler Intelligence Scale for Children (WISC) (Wechsler, 1991) provides a global measure of nonverbal intelligence (performances) and verbal achievement (verbal scale). Three performance subtests (picture completion, picture arrangement, and block design) were administered at both primary and secondary test sessions and used to calculate a prorated performance IQ. Two verbal subtests were also administered at both sessions: digit span and similarities. Digit span provided an estimate of auditory memory span. Similarities provided a global language measure, requiring a combination of vocabulary, world knowledge, and verbal abstract reasoning. Subtests scores were expressed as scaled scores, with values between 7 and 13 representing the average range in relation to the normative sample.
4. The Peabody Individual Achievement Test (PIAT) (Dunn & Markwardt, 1989) is a wide-range individually-administered achievement test that includes a reading component consisting of reading recognition and reading comprehension. The reading recognition subtest presents single words that the student reads aloud (using speech and/or sign). The reading comprehension subtest presents one sentence at a time followed by a page with four illustrations. The student selects the picture that best represents the meaning of the sentence. Number of items correct on both subtests are combined and then transformed into a standard score based on performance of hearing age-mates in the normative sample. The average standard score for hearing age-mates is 100 with a standard deviation of 15, thus standard scores of 85 or higher are age-appropriate. Raw scores can also be expressed as grade-equivalent scores based on hearing norms.

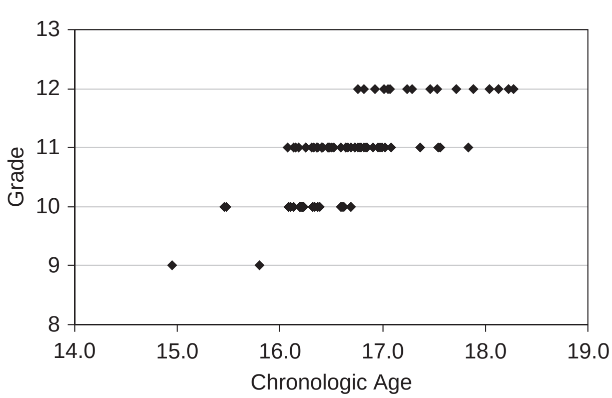

Figure 4. Current grade placement of 85 participants is plotted by chronological age at time of testing.

Outcome predictors

The battery of tests administered in each skill area was reduced to a summary factor score using principal components analysis (Strube, 2003). Principal components analysis forms summary factor scores (FS) by creating a weighted linear combination of test scores. The weights are derived to ensure that the principal component preserves as much of the original score variance as possible. These values are thought to reflect the common ability that is measured by the tests comprising each battery. Speech perception FS was derived from percent correct on two administrations of the BKB sentence test (Bamford & Wilson, 1979) and the LNT words (Kirk et al, 1995). In addition to administering both of these tests in quiet at a loud conversational level of 70 dB SPL (also used at age eight to nine), alternate forms of these two tests were administered in degraded listening conditions. A BKB sentence list was presented in +10 dB S/N and an LNT word list was presented at a level of soft speech (50 dB). The language FS was derived from combining the verbal IQ on the Wechsler intelligence scale for children (Wechsler, 1991) with standard scores on the Expressive One-Word Picture Vocabulary Test (EOWPVT) (Gardner, 2000), the Peabody Picture Vocabulary Test (PPVT) (Dunn & Dunn, 1997), and the Clinical Evaluation of Language Fundamentals (CELF) (Semel-Mintz et al, 2003). The reading FS was derived from combining the total reading standard score on the PIAT (Dunn & Markwardt, 1989), the word attack subtest raw score on the Woodcock Reading Mastery Test (WRMT) (Woodcock, 1987), and the total reading standard score on the Test of Reading Comprehension (TORC) (Brown et al, 1995). A similar principal components analysis of the test batteries administered in the original study had already been completed for speech perception (Geers et al, 2003), language (Geers et al, 2003), and reading (Geers, 2003).

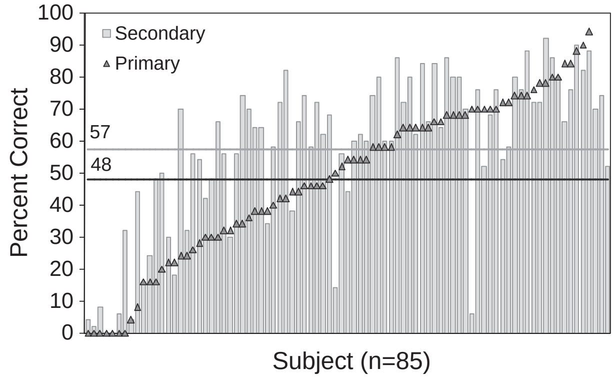

Figure 5. Percent correct score on the LNT word list for 85 participants in primary grades (data points) and secondary grades (columns). Horizontal lines represent group means. Three columns to the far right are missing data at primary grades.

The resulting weighted values were comparable to those used in this study and represent outcome levels measured in elementary grades. These values and are referred to as primary-FS.

Correlation coefficients were calculated between high school FS and predictor variables including primary FS, age at test, age at onset of deafness, age at implantation, duration of implant use, nonverbal IQ, highest education level achieved by either parent, early classroom communication mode as depicted in Figure 1 and aided threshold average (0.25, 0.5, 1, 2, 4 kHz) with a cochlear implant. Finally, multiple regression analyses were conducted to identify variables that contributed independently to performance outcomes in each skill area, when the remaining predictor variables were controlled.

Results

Evaluation of progress

LNT scores obtained by individual participants in primary and secondary school are plotted in Figure 5. Speech perception scores on the LNT improved for 67% of the sample, with a significant increase in the mean score from 48% to 57% correct ($t = 4.74$; $p < .0001$). Two children showed a dramatic decrease in their speech perception skills. One child experienced problems with the implant device and one child experienced difficulties related to auto-immune issues that arose between test sessions. Variability in speech perception outcome in the population remained high across both test sessions, with scores ranging from 0 to 95% correct.

Figure 6 displays speech perception results for the BKB sentences. Word recognition was generally higher when a sentence context was provided relative to the monosyllabic words presented in the LNT. It is likely that BKB sentence scores better reflect speech perception in the real world, where the listener rarely identifies words in isolation. There was an average improvement of almost 20 percentage points on the BKB, from 58% correct at ages eight to nine years to 77% correct at follow-up ($t = 6.75$; $p < .0001$). Only 14 of the 85 children scored below 50% in keyword recognition scores at the most recent test and two thirds of the sample scored 80% or higher.

Figure 7 depicts the changes on the WISC-III similarities subtest. The data points in Figure 7 depict individual scaled scores in primary grades, where 60% of the sample scored within one standard deviation of hearing age-mates (i.e. scaled score > 7), with an average scaled score of 7.6. In order to maintain this scaled score over time, the deaf child must make language progress at the same pace as his/her hearing age-mates. In order to improve this score, the deaf child must gain language skills faster than hearing age-mates. Therefore, the mean scaled score might be expected to decrease somewhat between primary and secondary grades. However, 61% of the students showed an improved scaled score in secondary grades over their performance in primary grades. This relative improvement is greater than would be expected and reflects a closing of the verbal gap between deaf and hearing age-mates. The average scaled score increased from 7.6 to 9.0 ($t = 4.37$; $p < .0001$). In high school, 77% of the sample scored within one standard deviation of age-mates with normal hearing.

Figure 8 depicts the reading standard score on the PIAT. Scores between 85 and 115 are within one standard deviation of age-mates with normal hearing. Forty-four percent of the students obtained standard scores within the average range for hearing students their age, fewer than did so at age eight to nine

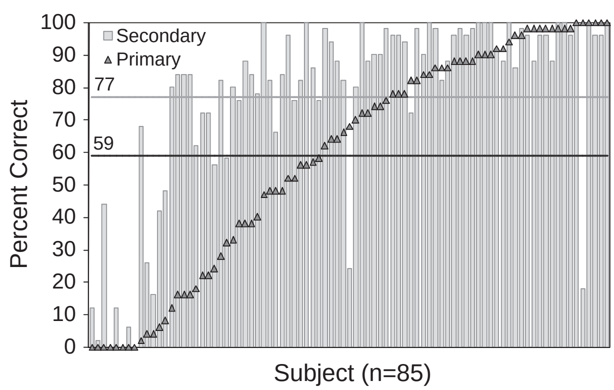

Figure 6. Percent correct key-word scores on the BKB sentence test for 85 participants in primary grades (data points) and secondary grades (columns). Horizontal lines represent group means.

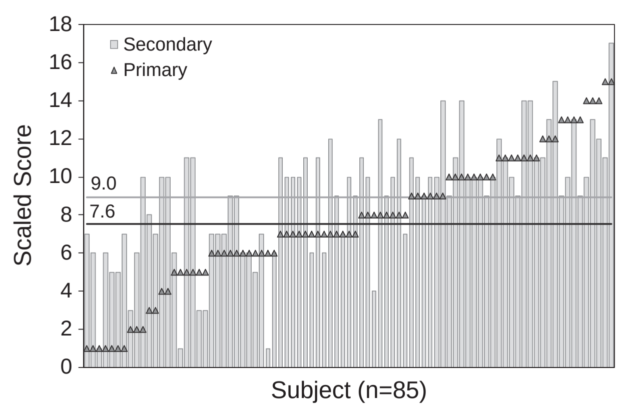

Figure 7. Scaled scores on the WISC similarities subtest for 85 participants in primary grades (data points) and secondary grades (columns). Horizontal lines represent group means.

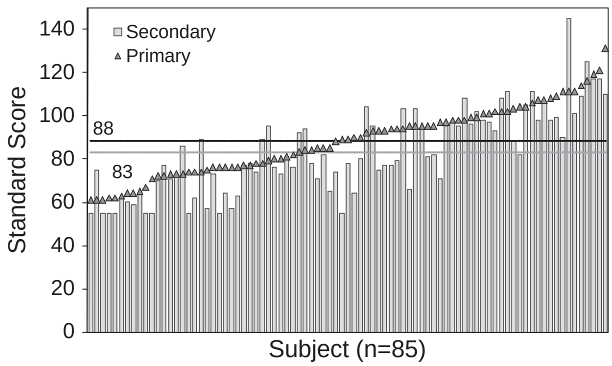

Figure 8. Standard scores on the PIAT reading scale for 85 participants in primary grades (data points) and secondary grades (columns). Horizontal lines represent group means.

(i.e. 56%). The average standard score in primary grades was 88, falling within the low average range for chronological age. This standard score was expected to decrease over time, since it has been frequently documented that students with profound deafness experience a gap in reading achievement relative to typical, hearing children that increases as they get older. Standard scores in secondary grades were significantly lower, with an average score of 83 ($t = -4.19$; $p < .0001$), indicating that, as a group these students failed to keep pace with scores from typical normal-hearing children. However, 20% of the sample gained reading skills at the expected rate and therefore showed no change in standard score. An additional 20% of the children actually increased their reading performance relative to hearing age-mates. On the other hand, 60% of the students failed to keep pace with hearing age-mates and exhibited decreases in standard scores.

Reading improvement between elementary school and high school is better reflected in grade equivalent scores, which are plotted by age at test in Figure 9. Sample growth functions are plotted for three individuals, who all showed a decrease in standard score (relative to hearing age-mates) but an increase in their reading grade equivalent. The dashed line represents an individual who made minimal reading progress and scored at the second grade reading level in both elementary and high school. This student showed a dramatic decrease in standard score from 75 to 57 over this time period. The intermediate gray solid line represents a student who made fair reading progress, from third to sixth grade between 9 and 16 years of age. This level of progress was associated with a smaller decrease in standard score from 95 to 82. The top solid line represents a student who scored at third grade at the age of nine and eleventh grade at 17 years of age, resulting in a small decrease in standard score from 101 to 97.

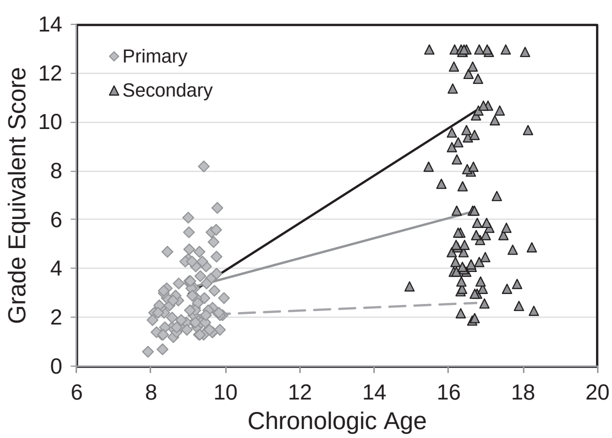

Figure 9. PIAT reading grade equivalent scores are plotted by chronologic age for 85 participants in primary grades (diamonds) and secondary grades (triangles). Growth lines are drawn for three subjects to represent different levels of improvement in reading over the test-retest interval.

Outcome predictors

Table 3 (a) lists correlations among predictor variables. Some predictors correlated significantly with one another. Students with longer duration of implant use tended to have older age at test and younger age at implantation ($r = .508$ and $-.776$, respectively; $p < .001$). Those with later onset of deafness tended to have younger test ages ($-.245$; $p < .05$). Students with higher IQs tended to have more highly educated parents ($r = .368$; $p < .001$), and those who received a spoken language emphasis in their early educational program tended to also have better (i.e. lower) aided thresholds with their implants ($r = .291$; $p < .01$).

High school factor scores (FS) derived from the three test batteries (i.e. speech perception, language, and reading) were used as outcome measures. Table 3 (b) lists correlations between predictor variables and outcome factor scores. The highest correlations were observed between FSs at primary grades (age eight to nine) and those measured in high school, with *r* ranging from .709 for language to .911 for speech perception. In general, the best performers in elementary school maintained this advantage in high school. Age at test and duration of implant use showed no significant correlation with any outcome FSs. Younger age at implantation was moderately associated with better language ($r = -.216$) and reading ($r = -.236$) outcomes, as was older age at onset of deafness ($r = .227$ and $.231$). Nonverbal intelligence strongly associated with language and reading levels in high school ($r = .430$ and $.348$, respectively). Highest level of parent education was not strongly associated with any outcome, though its correlation with language level reached significance ($r = .236$). Aided PTA threshold with the implant showed a substantial correlation with speech perception outcome ($r = -.454$). Finally, communication mode average over the first five years of cochlear implant use showed a strong relation to speech perception outcome ($r = .450$), and a moderate relation with language outcome ($r = .215$). This relation suggests a lasting benefit from oral education that occurs early in the child's life.

Multiple regression analysis was used to determine the independent contribution of each of the predictor variables to outcome FSs in each area. The regression summary presented in Table 4 lists the ten predictor variables included in each analysis. The contribution of each predictor variable to outcome FS was examined with all other predictors controlled, essentially removing shared variance associated with significant relations cited in Table 3 (a). A number of the significant correlates listed in Table 3 (b) did not contribute significant independent variance to skills measured in high school, after the substantial amount of variance associated with performance at age eight to nine years

Table 3. (a) Correlations among predictor variables. (b) Correlations of predictor variables with outcome factor scores (FS)

(a)

	Age at CI	*Age at onset*	*Duration CI use*	*PIQ*	*Parent ed.*	*Aided PTA*	*Mode average*
Test age	.116	−.245*	.508***	−.055	.069	−.105	−.039
Age at CI		−.160	−.776***	−.167	−.050	.091	.087
Age onset			−.034	.021	.194	.033	−.147
Dur CI use				.129	.091	−.134	−.047
PIQ					.368***	−.113	.098
Parent ed.						−.061	.157
Aided PTA							−.291**

(b)

Predictor	*Speech perception*	*Language*	*Reading*
Primary FS	.911***	.709***	.820***
Test age	−.173	−.091	−.062
Age at CI	−.111	−.216*	−.236*
Age onset	−.050	.227*	.231*
Dur CI use	−.028	−.020	.011
PIQ	.132	.430***	.348**
Parent ed.	.102	.236*	.177
Aided PTA	−.454***	−.163	−.093
Mode average	.450***	.215*	.152

*p <.05; **p <.01; ***p <.001

(i.e. primary FS) was removed. Four predictor variables contributed significant independent variance to one or more of the outcomes: Primary grades factor score, implant age, nonverbal IQ, and cochlear implant threshold average. Six of the variables entered into the regression analysis did not contribute significant variance to any of the three outcomes: age at test, age at onset of deafness, gender, highest parent education, communication mode over the first five years of implant use, and type of speech processor. The r^2 value at the bottom of each column indicates the total percentage of variance in FS accounted for by these predictors.

In the area of speech perception, the predictor variables accounted for 87% of total variance, with the majority (84%) associated with the primary speech perception FS. An additional 3% of variance was accounted for by the student's cochlear implant threshold level. This finding suggests that improved threshold levels achieved with newer cochlear implant processors provide added speech perception benefit over levels achieved with previous technology. Because implant age and test age were highly correlated with duration of implant use, these variables could not be included in the same analysis. The regression analysis was repeated with the variables age at test and age at implant replaced by duration of implant use. The total percentage of variance accounted for was not affected by this change and variance accounted for by duration of implant use did not reach statistical significance ($t = .432$).

In the area of language, the predictors accounted for 69% of variance in the FS. The primary language FS accounted for 50% of variance in high school FS, with 17% of added variance accounted for by implant age and nonverbal intelligence. This result suggests that students with greater learning ability and younger age at implantation were able to achieve somewhat

Table 4. Regression analyses of predictors of high school skill level

	Speech perception			*Language*			*Reading*		
Parameter	*β*	*t*	*p*	*β*	*t*	*p*	*β*	*t*	*p*
Primary grades factor score	**.855**	**12.515**	**.000**	**.651**	**7.790**	**.000**	**.807**	**11.623**	**.000**
Implant age	−.047	−.920	.361	−.157	−1.994	.051	**.136**	**−2.331**	**.022**
Nonverbal IQ	−.049	−.893	.375	**.336**	**4.035**	**.000**	**.215**	**3.155**	**.002**
CI-PTA threshold	**−.123**	**−1.988**	**.050**	.005	.053	.958	−.023	−.305	.761
Age at test	−.047	−.875	.385	.041	.502	.617	−.004	−.057	.954
Age at onset	−.037	−.743	.460	.050	.607	.546	.067	1.016	.313
Gender	−.025	−.495	.622	.009	.117	.907	.067	1.055	.295
Parent educ.	.046	.797	.428	.079	.896	.373	.095	1.316	.193
Comm. mode	.022	.379	.706	.010	.123	.902	.129	1.858	.068
CI processor	.019	.341	.734	.022	.261	.795	.007	.099	.921

higher language levels in high school than might be expected based on their performance in elementary school. The regression analysis was repeated with the variables age at test and age at implant replaced by duration of implant use. The total percentage of variance accounted for was not affected by this change and variance accounted for by duration of implant use did not reach statistical significance ($t = 1.669$).

Finally, 79% of the total variance in high school reading scores was predicted, with reading level in elementary school accounting for 67% and implant age and nonverbal intelligence contributing the remaining 10% of explained variance. The analysis was repeated to examine the independent contribution of length of implant use when age at test and age at implant were eliminated from the analysis. In this case, length of use was a significant predictor of reading outcome variance ($t = 2.223$; $p < .030$). Therefore, for the reading factor, it appears that students with longer implant experience and those with greater learning ability made more progress in reading than would have been expected based on their performance in elementary grades.

Conclusions

These data constitute a preliminary analysis of outcomes in a group of 85 teenagers who received a cochlear implant between two and five years of age. These students were recruited from a sample of 181 children who participated in a nationwide study when they were eight or nine years old. Background characteristics of the 85 students who returned for follow-up did not differ from those 96 who had not yet returned. These teenagers exhibited long-term benefits from cochlear implantation that extended into their high school years. Increases were observed between elementary and high school in the number of students who attended mainstream classrooms and in the number of students using primarily spoken language. Most of the teenagers were placed at an age-appropriate grade level in high school.

In general, the strongest predictor of student performance in high school was skill level measured in elementary school. Children who performed well at age eight or nine years also tended to score among the highest as teenagers. In addition, sample characteristics that predicted significant outcome variance in elementary grades (e.g. nonverbal IQ, family SES, age at onset, gender, speech processing strategy, communication mode) were examined again to asses their contribution to achievement in high school. Individual correlations between these characteristics and high school outcomes reflected the continued importance of these underlying factors. However, the contribution of these factors to total variance in the regression analyses was often suppressed by the inclusion of the factor score representing performance in primary grades. Regression analyses did identify some factors that contributed variance to outcomes measured in teenagers, even after earlier performance was controlled. The ability to build on earlier performance to achieve high performance in teenage years depends on an overlapping, but not identical, set of factors that are summarized below for each outcome skill.

Speech perception

Two tests of auditory speech perception were administered at both primary and secondary grades. There was significant long-term improvement on both measures. This result contrasts with relatively short-term gains observed over time in adult cochlear implant users and may reflect a combination of cognitive, linguistic, and auditory skill development in school-aged children. Lower CI thresholds provided a speech perception advantage that was apparent in high school, even after controlling for earlier speech perception scores, and the efforts of implant audiologists to achieve and maintain such thresholds should be encouraged. Correlations confirmed the positive effect of early oral education on speech perception outcome that had been documented in elementary school (Geers et al, 2003). However, multiple regression results indicate that the relative speech perception advantage of oral students did not increase over the ensuing years between elementary and high school.

Language

Language progress between elementary and high school was measured with the similarities subtest of the Wechsler intelligence scale for children. A significant increase was observed in age-referenced standard scores over this time period, indicating that verbal development was faster than would have been expected based on hearing norms. This is an extremely exciting result that represents a dramatic departure from the previously documented gap between language skills of deaf and hearing children that increased with age. An overall language factor score was determined from a battery of standardized tests administered at the high school test session. Although the language outcome was most strongly predicted by language performance in elementary grades, children with higher nonverbal IQs and younger age at implant made greater than expected gains in language over the school years. Correlations confirmed the positive effect of early oral education on language outcome that had been documented in elementary school (Geers et al, 2003). However, multiple regression results indicate that the relative language advantage of oral students did not increase over the ensuing years between elementary and high school.

Reading

Average reading growth between primary and secondary grades, as measured by repeated administration of the PIAT, was only slightly below the expected normal rate for hearing children. Forty-four percent of high school students achieved age-appropriate reading levels in high school, compared to 56% doing so in early elementary grades. This confirms previous results indicating some increase in the reading gap between children with hearing loss and their hearing peers as they get older. However the range of reading levels was quite large, and most of the teenagers surpassed the well-documented fourth grade barrier, many by a substantial margin. Nevertheless, a significant minority of students continued to struggle with reading in high school. Low readers tended to be students who received a cochlear implant at an older age and those with lower nonverbal IQs. It is intriguing that age at implantation accounts for significant variance in high school reading scores, even after early reading levels are controlled. Other studies have also demonstrated that children who receive a cochlear implant at younger ages tend to have higher reading comprehension scores (Connor & Zwolan, 2004). However, implant age was highly correlated with duration of implant use, which accounted for a similar amount of variance when duration replaced age at implant in the regression analysis.

Future research

It will be important to verify the results reported here with analysis of a larger follow-up sample, which awaits completion of planned testing for 120 of the original sample of 181 participants. Reading development remains an area of concern, in view of the large number of children with substantial delays. When this study is complete, skills underlying reading, including nonverbal cognitive skills, working memory, and phonological processing skills will be analysed. Furthermore, outcomes associated with quality of life, such as self-esteem, independence, and cultural identification will be documented. This is a new generation of profoundly deaf children who are growing up with the assistance of cochlear implants. We anticipate that long-term use of this beneficial technology will affect both academic and social opportunities for these individuals.

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