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Enduring Advantages of Early Cochlear Implantation for Spoken Language Development

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Abstract

Purpose—To determine whether the precise age of implantation (AOI) remains an important predictor of spoken language outcomes in later childhood for those who received a cochlear implant (CI) between 12–38 months of age. Relative advantages of receiving a bilateral CI after age 4.5, better pre-CI aided hearing, and longer CI experience were also examined.

Method—Sixty children participated in a prospective longitudinal study of outcomes at 4.5 and 10.5 years of age. Twenty-nine children received a sequential second CI. Test scores were compared to normative samples of hearing age-mates and predictors of outcomes identified.

Results—Standard scores on language tests at 10.5 years of age remained significantly correlated with age of first cochlear implantation. Scores were not associated with receipt of a second, sequentially-acquired CI. Significantly higher scores were achieved for vocabulary as compared with overall language, a finding not evident when the children were tested at younger ages.

Conclusion—Age-appropriate spoken language skills continued to be more likely with younger AOI, even after an average of 8.6 years of additional CI use. Receipt of a second implant between ages 4–10 years and longer duration of device use did not provide significant added benefit.

Keywords

cochlear implant; deafness; language; bilateral; children

Spoken Language Advantage of Early Cochlear Implantation over Time

Without question, pediatric cochlear implantation has led to improved spoken language skills for deaf children, with the majority of those who receive a cochlear implant (CI) by age 2 years now scoring within a standard deviation of hearing age-mates after a few years of use (Duchesne, Sutton & Bergeron, 2009; Fitzpatrick, Crawford, Ni & Durieux-Smith, 2011; Geers & Sedey, 2011; Wu et al., 2011). However, while achieving language scores within the average range using spoken language is a remarkable accomplishment for children with profound hearing loss, the preferred goal is for the mean score for groups of children with CIs to reach the mean value for normative samples. The latter goal has not been realized, even when cochlear implantation occurs during early preschool years (Niparko et al., 2010; Fitzpatrick et al., 2011; Geers, Nicholas & Sedey, 2003). Such results confirm that delay associated with early childhood deafness persists throughout preschool and early elementary grades for many children.

One robust finding in the literature is that placement of a CI at the youngest ages tends to improve outcomes in vocabulary (Connor, Craig, Raudenbush, Heavner & Zwolan, 2006; Hayes, Geers, Treiman & Moog, 2009) and expressive or receptive language (Artieres, Vieu, Mondain, Uziel & Venail, 2009; Colletti, 2009; Dettman, Pinder, Briggs, Dowell & Leigh, 2007; Holt & Svirsky, 2008; Nicholas & Geers, 2006, 2007, 2008; Niparko et al., 2010) as well as other related outcome measures such as speech perception and production when children are tested with a relatively brief 1–3 years of CI use. We previously reported results from a nationwide sample of 76 3.5-year-old year children showing a steady increase in language skill for each additional month of CI use after the first 12 months and this advantage became more pronounced over time (Nicholas & Geers, 2006). By the age of 4.5 years, approximately 50% of this sample scored within 1 standard deviation of the normative mean for hearing age-mates in overall language ability. The expected mean score (corrected for other known correlates) for children who received a CI between 12–16 months of age was equal to the mean for the normative sample (Nicholas & Geers, 2008). That finding suggested that language delays due to hearing loss might be ameliorated by age 4.5 in many children who receive their CIs close to their first birthday. This is consistent with other studies reporting that children who receive an implant under 18–24 months of age achieve better spoken language outcomes than those implanted later (Manrique, Cervera-Paz, Huarte & Molina, 2004; Nicholas & Geers, 2007; Niparko et al., 2010; Svirsky, Teoh & Neuburger, 2004).

Despite evidence for short-term advantages, it is unclear whether they are maintained in subsequent years. If maintained into the elementary school years, the likely academic benefits would provide support for promoting the earlier ages of CI surgery. If not, it might lessen the sense of urgency for CI surgery for some parents and allow them more time to adjust to the diagnosis and to learn about communication and technology options.

Also unclear is whether children receiving CIs at somewhat later ages eventually catch up with hearing peers in language once they have accumulated sufficient device experience. Studies based on children with profound hearing loss with hearing aids found that they actually fell farther behind hearing age-mates in subsequent years. This may or may not be the case with children using CIs. Geers and Sedey (2011) reported that a language advantage observed in 8–9 year olds with the shortest period of auditory deprivation before receiving a CI persisted into their teenage years. However, those receiving CIs at younger ages have longer durations of CI use at any given chronological age, making it difficult to determine whether younger age or longer use is more important for language gains. Examination of short-term outcomes between 7 and 45 months of CI use revealed significant effects of duration of CI use as well as age at implantation on language skill (Nicholas & Geers, 2007). In order to control for duration of use, some studies have tested children longitudinally to examine the impact of age at implantation on the rate of language development. Niparko et al. (2010) found that children who received a CI at younger rather than older ages (all before age 5 years) showed significantly faster growth rates in language comprehension and expression. Connor et al. (2006) found that children who received CIs at younger ages exhibited an early “burst of growth immediately following implantation,” a growth pattern not seen in children receiving an implant later in childhood.

Receipt of a Sequential Bilateral CI

The practice of bilateral implantation has increased (Peters, Wyss & Manrique, 2010) based on findings of good speech perception in the second ear and utilization of binaural hearing. However, most studies on these measures report better benefit from simultaneously implanting the two devices rather using a sequential approach, especially when the interval between surgeries gets larger and the age at the second CI surgery moves beyond the preschool years (Galvin, Mok & Dowell, 2007; Peters, Litovsky, Parkinson & Lake, 2007;

Manrique, Huarte, Valdivieso & Perez, 2007; Wolfe et al., 2007). Far fewer studies have been undertaken on the benefits of bilateral implantation specifically for spoken language outcomes, but two recent European studies do report some bilateral advantage. Boons et al. (2012) investigated 25 Dutch-speaking children who received either a simultaneous or sequential bilateral CI before the age of 5 years. A bilateral advantage was seen for scores on two standardized language tests and a negative correlation was found between those scores and the interval between receiving the first and second implants. A second study showed that 9 children who received simultaneous bilateral CIs in the second year of life outperformed 8 children who received unilateral CIs (at a similar surgery age) on lexical production, but the groups did not differ in morphosyntactic production. The large individual variability and small sample sizes caused the authors to conclude that observed differences could have been due to other preexisting variables rather than bilateral CI use (Caselli, Rinaldi, Varuzza, Giuliani & Burdo, 2012). While there are many reasons to believe that simultaneous implantation, early in the preschool years, would provide the best chance of a bilateral advantage for spoken language outcomes, there are currently no conclusive data to support this expectation.

Other important predictors

Not all children benefit equally from early implantation and previously published work shows that there are factors other than the age of CI surgery that influence successful language growth in the elementary school years. Because these factors may not be randomly distributed across the continuum of age of implantation, their influence should be considered. Studies of children with and without hearing loss show that a family's socioeconomic status (SES) affects both the rate of growth and the ultimate level of language achieved (Hart & Risley, 1995; Hoff, 2003; Rowe, Raudenbush & Goldin-Meadow, 2012). Children from higher SES families may be more likely to receive CIs at younger ages, further enhancing their language outcomes. A deaf child's nonverbal IQ is also a strong predictor of language progress (Moeller, 2000; Geers & Sedey, 2011; Dawson, Busby, McKay, & Clark, 2002) as is the communication means (Moog & Geers, 2003; Nittrouer, 2010) and the type and timing of early childhood intervention program (Moog & Geers, 2010; Yoshinaga-Itano, 2003).

Our previous work has shown significant effects of pre-implant *aided* pure-tone-average thresholds (PTAs) on language outcomes (Nicholas & Geers, 2006) and recently Stiles, Bentler and McGregor (2012) have shown that another measure, the (hearing-) aided Speech Intelligibility Index, was a better predictor of vocabulary outcome than unaided PTAs. Even marginally better early acoustic experience may allow children who benefit more from hearing aids to develop spoken language more rapidly than children who received less benefit but who receive a CI at the same age. They also may receive a longer trial with those aids, postponing implantation until slightly older ages. Therefore, not controlling for degree of pre-CI hearing may underestimate the benefits of younger implantation. Language development rate may also be affected by the use of newer CI technologies (Davidson, Geers, & Brenner, 2010). Because the age at implant surgery has become progressively younger, children receiving a CI at the youngest ages may use more recent technology, enhancing their language outcome scores when compared to children implanted at somewhat older ages with earlier technology.

Outcomes for vocabulary versus other language skills

The majority of studies of language outcomes of children with CIs have focused on either vocabulary skills alone or compared only broad measures of receptive versus expressive language. Therefore, it is unclear whether lexical development is more or less susceptible to the influence of age at implantation than other aspects of language, such as grammar. Caselli

et al. (2012) reported that 17 children with CIs who were tested at a mean age of 54-months were not significantly different in vocabulary production than an age-matched group of normally-hearing (NH) age-mates but did produce more errors in grammatical production (on a sentence repetition task). Similarly, in a study of 3–8 year old children who received a CI at 1–2 years of age, Duchesne et al. (2009) showed a larger percentage of children scoring within the average range for receptive and expressive single-word vocabulary (56% and 86%, respectively) than for comprehension of morphemes (42%) or comprehension of syntactic constructions (35%). Finally, Geers, Moog, Biedensten, Brenner and Hayes (2009) reported that when tested at age 4–5 years, the AOI associated with an expected standard score of 100 (average for NH age-mates) ranged from 12–18 months for tests that included complex language skills. However, those who received a CI as late as 36 months could be expected to achieve age-appropriate levels on vocabulary tests. These outcomes underscore a possible difference in the difficulty of achieving skills comparable to NH peers for different aspects of language.

Objectives of the study

The primary objective of this study was to determine whether our previous finding of a significant advantage for young children receiving a CI before 24 months of age persists into the mid-elementary school years. Secondary objectives were: (a) to discover whether the addition of a second (bilateral) CI between ages 4–10 confers an outcome advantage for language skills, and (b) to assess whether the age at first implantation differentially affected lexical, as compared with global, language skills. Changes with age in the proportion of children who score within the average range and individual differences in growth between the two test ages were also examined.

METHOD

Participants

Initial recruitment—The sample for this study was recruited from participants in a previous study of preschoolers who had received a CI between their 1st and 3rd birthdays (Nicholas & Geers, 2006). Children were identified by auditory-oral preschools and speech therapy practices across North America. Candidate children were excluded if there was evidence of previously normal hearing or a progressive loss, preschool developmental testing indicated delayed nonverbal learning abilities, or if the family did not primarily speak English at home. The inclusion criteria restricted the sample to those with oral communication mode, no additional disabilities, and presumed deafness from birth, thus eliminating some potential sources of outcome variability. All children identified as meeting the inclusion criteria were invited to participate in the study.

Participants in this follow-up study—All (76) children in the previous study were invited to participate in the follow-up study and 60 accepted. The sample was geographically diverse, representing 25 different states and 1 Canadian province. Ethnicity was as follows: Caucasian (N = 46), African-American (1), Asian (5), Hispanic (2), multiple ethnicities (3) and other ethnicity (3). Etiology of deafness was: Unknown-congenital (31), genetic (26), ototoxic drug use (1), and maternal CMV infection (1).

Summary statistics of demographic characteristics of the children and their families, as well as audiological factors, can be found in Table 1. The mean chronologic age of participants was 10.5 years ($SD = 0.8$, range 9.1 – 12.7 years) and they will be referred to in this paper as “10.5 year olds”. There were equal numbers of boys and girls in the sample (30 each). The average highest education level completed by either parent was listed as a college degree (coded as grade 16). Parents rated their income in one of 8 categories and 60% of the

families checked the highest category, indicating a family income over \$95,000. A composite variable, “Parent Education/Income” (PEI) was created by summing the highest grade-level completed with the combined family income rating. This composite variable yielded values from 19–30 and was used in subsequent analyses in which PEI was considered a potential correlate or predictor. Nonverbal intelligence was estimated using the Perceptual Reasoning (PR) Scale of the Wechsler Intelligence Scale for Children (Wechsler, 2003). These nonverbal scores are presumably not influenced by language impairment due to hearing loss and provide a fair representation of learning ability relative to NH children. The mean PR Quotient (PRQ) of 105 reflects the higher nonverbal skills of this more advantaged group of children compared to the normative mean of 100.

The age at initial CI surgery was distributed within the 12–38 months range as follows: 12–18 months ($N=22$), 19–24 months ($N=16$) and 25–38 months ($N=22$). Average pre-CI aided PTAs were lower (better) for children implanted at older ages, ranging from 72 dB for children implanted under 18 months of age to 56 dB for children implanted after their 2nd birthday. All of the participants initially received just one CI and by the time of this follow-up study (mean test age 10.5), 29 of the 60 children had received a second CI. A “bilateral CI rating” was assigned to each participant based on duration of use of a 2nd CI: 0 for no years ($N=31$), 1 for < 1 year ($N=14$), and 2 for > 1 year ($N=15$).

Three children had experienced a re-implant surgery. Only 2 of the unilateral CI users also wore a hearing aid and neither had used it continuously. Fifty-five of the 60 children had received an upgrade in speech processor technology in at least one ear between initial implantation and follow-up testing. In order to examine the effects of these upgrades on language development, processors were rank ordered by generation of technology for analysis, with higher rankings indicating newer technologies. For example, processors manufactured by Cochlear Corporation were rated as follows: 1- Spectra, 2- ESPrit 22, 3- Sprint or ESPrit 3G, or 4-Freedom. Processors by Advanced Bionics were rated as follows: 2- PSP or BTE Platinum, 3-Auria BTE, or 4- Harmony BTE.

Responding via questionnaires, all parents reported that their child used their CI(s) “all the time” during waking hours. The vast majority of children chose to communicate through speech alone, and they were perceived by their parents to do so with relative ease. School grades just completed were: 3rd grade (25%), 4th grade (55%), 5th grade (17%) and 6th grade (3%). Participants were enrolled in a variety of educational settings, although 85% were placed in a full-day mainstream classroom with hearing age mates. Most of the children were mainstreamed by kindergarten. On average, they spent 38% of grades completed in private school settings and 47% in classrooms with more than 20 students.

Questionnaire items asked parents to indicate what special services their children received each year. The percentage of grades completed during which such services were provided was calculated for each participant. The children received individual therapy, on average, for 78% of elementary school years completed, used a teacher aide or resource room 37% of grades completed and used FM systems 73% of school years.

Sixteen of the original 76 preschool children either declined the invitation to participate in the follow-up study or were unable to be contacted. Mean audiologic, socio-economic and early language scores of participants were compared with those of non-participants using *t*-tests contrasting means. None of the differences reached statistical significance, indicating no sample selection bias in those returning for follow-up on the characteristics measured at age 4.5. Follow-up questionnaires sent to the 16 non-attending families yielded 7 responses with all families reporting continued full-time use of a CI.

Study Design and Data Collection

In the years 2000–2005, test administrators from this laboratory visited the children's school or therapy center to collect language samples and parent ratings when children were 3.5 and 4.5 years of age (± 2 months). Formal language testing conducted at age 4.5 provides the preschool assessment for the current study (Nicholas & Geers, 2007). Follow-up language testing for 60 of these children took place at a mean age of 10.5 years (range 9.1 – 12.7 years). The mean test interval between the age 4.5 and age 10.5 test sessions was 5.9 years and the range was 4.6 to 8.1 years.

Participants in this follow-up study attended a 2-day “research camp” on the campus of Washington University in St. Louis. The study paid for travel and all expenses of attendance for the participant child and one parent. Families were encouraged to attend whether or not the child was still using their CI and regardless of the child's perceived communicative or academic success. The testing sessions occurred over two mornings, with the test battery administered by experienced clinicians and teachers of the deaf. The protocol was approved by the Human Research Protection Office of Washington University in St. Louis.

In summary, these 60 participants were a relatively advantaged group of CI recipients. They received their first CI at a very young age (1 or 2 years), they received auditory-oral intervention from trained professionals during the preschool years, and many continued receiving special services into the elementary years. Family education and income were well above average and parents were motivated to help their own child and the field of deaf education as evidenced by their willingness to accompany their child to a research camp some distance from their home for several days.

Language Assessment and Analysis

Measures were included at each test age to assess the child's mastery of vocabulary and more global language skills. At age 4.5 the *Peabody Picture Vocabulary Test, 3rd Edition* (PPVT-III; Dunn & Dunn, 1997) was the vocabulary measure and the *Preschool Language Scale- 3rd Edition* (Zimmerman, Steiner & Pond, 1992) at age 4.5 (± 2 mos) estimated global language skills, including syntax. At age 10.5 year they received two vocabulary measures: the *PPVT-III* and the *Expressive One-Word Picture Vocabulary Test* (EOWPVT—III; Brownell & Martin, 2000). The Clinical Evaluation of Language Fundamentals, 4th Edition (CELF-4; Semel, Wiig & Secord, 2003) measured global language skills, including syntax. Receptive Language subtests included: Concepts and Directions (understanding oral commands of increasing length and complexity), Word Classes (understanding semantic relationships between words) and Understanding Paragraphs (understanding the message conveyed by a set of related sentences). *Expressive Language* subtests included: Recalling Sentences (repeating increasingly complex sentences), Formulated Sentences (constructing a sentence using stimulus words), and Word Classes (expressing semantic relations between words).

The Verbal Comprehension Scale of the WISC-IV (Wechsler, 2003) was also administered though it does not assess language skills *per se*. Rather, subtests of this Scale provide an estimate of verbal reasoning ability: Similarities (expressing likenesses between concrete objects, substances, facts or ideas), Vocabulary (providing definitions of words) and Comprehension (responding to questions requiring practical knowledge and social judgment).

Scores on each of the norm-referenced language tests administered were expressed as standardized scores. Normative samples represent “typical” language development and sample selection uses stratification to insure that family socio-economic status, educational background and additional handicapping conditions are represented in proportion to the

general population. Higher mean scores would be anticipated from more select groups of children. To the extent that the CI participants in this study represent families with higher levels of income and education than the general U.S. population, more intensive early education, and fewer other disabilities, standardized scores may underestimate their true potential. Nevertheless, standardized norm-referenced scores provide age-appropriate comparisons and are typically used to make clinical decisions regarding candidacy for special educational services and readiness for educational mainstreaming.

RESULTS

Presentation of the results begins with a reporting of scores on each language measure administered at the two test ages. The next section shows how scores were affected by the age at which children received a first CI. Then the relation among language measures is examined and factors associated with higher performance at age 10.5 years are identified. Finally, scores are compared with normative samples of typically-developing age-mates and change over time is examined in relation to these samples. Where test age 4.5 scores are included they have been previously reported (Nicholas & Geers, 2008) and are provided here for reference, comparison, and examination of growth.

Average Performance at Two Test Ages

Composite standard scores and subtest scaled scores relative to a normative sample of hearing children of the same age are presented in Table 2. When this sample of children was tested at 4.5 years of age, mean standard scores on the PLS and the PPVT were more than 1 *SD* below the mean of the age-appropriate normative sample (i.e., 85). In the present testing, ~6 years later, mean scores were within a standard deviation of NH age-mates on all measures. Scores obtained at 4.5 years of age were highly correlated with language performance at 10.5 years: $r(\text{PPVT}) = 0.75$; $r(\text{PLSrec/CELFrec}) = 0.69$; $r(\text{PLSexp/CELFexp}) = 0.66$.

CELF subtest scores at age 10.5 ranged from 7.12 for Concepts and Following Directions to 9.85 for Formulated Sentences. All subtest means except Formulated Sentences were significantly below the normative mean of 10 ($SD = 3$). Subtest scores were highly correlated with the overall Core Language Score ($r = .79$ to $.92$). Receptive subtest scores were well correlated ($.64$ to $.82$) indicating that they all measured a similar underlying skill. Expressive subtest score inter-correlations ranged from $.61$ to $.64$.

At Age 10.5, scores on vocabulary measures were significantly higher than those obtained for overall language: PPVT vs CELF rec ($t(1, 59) = 4.0, p < .001$), EOWPVT vs CELF exp ($t(1, 59) = 5.2, p < .001$). This vocabulary advantage was not apparent at the age 4.5 test session (PPVT vs PLS-AC ($t(1, 59) = 1.2; p = .244$)). This result confirms previous findings that vocabulary skills are somewhat easier for CI children to acquire than other aspects of language.

The average WISC Verbal Comprehension Quotient (VCQ) of 95.5 was within 0.5 *SD* of the normative mean (100) and was significantly lower than the PRQ score of 105 ($t(59) = 4.40, p < .0001$), indicating that verbal abilities were not on par with nonverbal abilities, reflecting a continuing delay in cognitive skills that are of a verbal nature.

Language Scores as a Function of Age at Implantation

The primary question of this study was whether age of 1st cochlear implantation (AOI) occurring in the 12–36 months age range still exerted a significant influence on language scores in the mid-elementary school years. Correlation coefficients were calculated for AOI and the various language outcome measures (Table 3). Since earlier analyses with this group

of children found these relations were mediated by pre-CI aided PTAs (Nicholas & Geers, 2006), partial correlations among the same predictors with the influence of this variable removed are also provided. Significant correlations were observed between AOI and language score for all tests administered at both test ages, and these correlations increased when pre-CI aided PTAs were partialled out, thus controlling for the benefit of early aided hearing for children who received a CI somewhat later. Proportion of variance in language accounted for by the combination of AOI and pre-CI aided PTA ranged from 30–38% for measures collected at age 4.5 to 18–28% for measures collected at age 10.5. In order to examine whether age of implantation differentially affects the development of vocabulary versus more global language skills, the difference between the correlations of AOI with PPVT and CELF-Core scores was tested and found to be not significant ($t = 0.05$, $p > .05$).

Addition of a Second, Sequentially-Acquired CI

Approximately half of the participants in this study had received a second (bilateral) CI some time between the Age 4.5 and Age 10.5 test session. At Test Age 10.5, the mean PPVT-III standard score was 90.48 ($SD = 22.72$) for those with unilateral CIs and 101.10 ($SD = 20.16$) for those with bilateral CIs. A two-tailed t -test revealed no significant differences between these means ($t(1, 58) = 1.91$, $p = .061$; $d = 0.495$). For the CELF-4 Core standard score, the mean for children with unilateral CIs was 85.52 ($SD = 21.94$) and for those with bilateral CIs it was 93.10 ($SD = 17.67$); these means were also not significantly different ($t(1, 58) = 1.469$, $p = .147$; $d = 0.383$).

The Effect of Other Predictors

In addition to age at implantation, the next analysis sought to identify other factors contributing to language performance during the elementary school years. The first step was to determine the number of distinct language skills represented in this test battery (e.g., vocabulary, syntax, verbal reasoning) and this was accomplished through Principal Components (PC) analysis. The analysis resulted in a single-factor solution, indicating that the test scores could be combined into a single metric that would better represent language outcome than any one isolated test score. Table 4 presents Pearson correlation coefficients among test scores as well as the principal component loadings for language outcomes at ages 4.5 and 10.5. The component loadings are quite high for all PC factors ($>.90$), indicating substantial common variance within each set of language measures. Therefore, the most parsimonious approach to identifying predictors of language outcome uses PC scores in place of individual test scores and will be referred to hereafter as Language (for Age 10.5 testing) and Age 4 Language.

A series of correlational analyses were conducted to explore the extent to which child, family, audiologic and educational characteristics were associated with language level achieved at the two test ages (as estimated from the PC scores) and coefficients are listed in Table 5. Better language users at age 4.5 maintained their advantage at age 10.5. In addition, better language users at age 10.5 were those who earned the higher nonverbal intelligence scores as measured by the WISC PRQ. Higher language outcome scores at both test ages were associated with younger age at 1st CI, greater parental education/income, younger entry into mainstream classrooms, and use of more recent generations of CI technology. Correlation coefficients between these predictors and language outcome score were remarkably similar at the two test ages. However the correlation coefficient between duration of CI experience and language outcomes was significant only at preschool ages. By age 10.5 the amount of accumulated device use was no longer associated with language levels achieved. Language outcome at age 10.5 was significantly better for children who had lower aided PTA thresholds with their CI device. For the 29 children with a second (sequential) CI, there were no significant correlations between Language outcomes and age

at 2nd CI surgery, duration of use of 2nd CI, or the length of the interval between CI surgeries.

Seven predictor variables were entered into a hierarchical multiple regression analysis to determine their independent contributions to the overall PCA score that combined measures of vocabulary, global language and verbal reasoning. The “bilateral CI rating” was used in place of Duration of 2nd CI, in order to include this variable in the multiple regression analysis and allow for a value to be assigned to children with unilateral CIs. Results are summarized in Table 6. In the initial step, Age at implantation, Parent education/income (PEI), Nonverbal IQ (PRQ), and Pre-implant aided PTA accounted for 38% of variance in the Age 10 Language score, with all but PEI reaching statistical significance. After the influence of these variables was removed, none of the current device characteristics (i.e., CI-aided PTA, bilateral CI rating, generation of speech processor) accounted for significant independent variance. Together, all of these predictors accounted for 44% of language outcome variance. Children with the highest language outcome at age 10.5 were those with better-aided pre-implant hearing, those who received a CI at the youngest ages, and those with the highest nonverbal IQ.

Language Growth Relative to Typically-Developing Age-Mates

Table 7 summarizes the percentage of children scoring within or above 1 SD of the normative mean for their age at the 4.5 and 10.5 test sessions. Marked increases were observed for each language measure, with over half of the sample achieving scores within the average range for hearing age-mates at Age 10.5 testing. The percentage of children scoring within the average range on the entire test battery increased from 27% to 48% between test ages. Of children who received their 1st CI by the age of 18 months, 73% scored within the average range on the entire test battery.

Children who were making expected progress over this interval (equal to that of hearing peers) would be expected to maintain approximately the same standard score over time. Figures 1, 2 and 3 depict change in individual standard scores over time. The PPVT was administered at both test sessions, permitting a direct estimate of receptive vocabulary growth between preschool and elementary grades. In addition, scores on the receptive and expressive subscales of the PLS at age 4.5 and the CELF at age 10.5 were compared to provide an indirect estimate of overall language growth.

Receptive vocabulary scores are plotted in Figure 1. At age 4.5, more than half (59%) of these data-points are 85 or higher, within one *SD* of hearing age-mates. Rather than making normative-typical progress in vocabulary acquisition (i.e., maintaining the same standard score as age increased) these children exhibited significant improvement in standard scores over time, from a mean standard score of 84 at age 4.5 to a score of 95 at age 10.5 ($t(58) = 6.28, p < .0001$). Eleven of the 23 children (43%) who scored below the average range at 4.5 scored within the average range at age 10.5. On the other hand, only 3 of the children who scored within the average range at 4.5 scored below average at 10.5. The correlation between length of test interval and the amount of gain in the PPVT standard score was non-significant ($r = .19, p = .142$), indicating that the magnitude of standard score improvement was not associated with the years elapsed between the first and second test sessions.

Individual and mean standard scores for receptive and expressive language on the PLS at age 4.5 and the CELF at age 10.5, are shown in Figures 2 and 3. Of the 33 children who scored below average for receptive language on the PLS at age 4.5, 11 (33%) scored within the average range on receptive language on the CELF at age 10.5. For expressive language, of the 44 children scoring below the average range on the PLS at age 4.5, 29 (66%) scored within the average range on the CELF at age 10.5. While four of the children who scored

within the average range at age 4.5 in receptive language fell below-average at age 10.5, none did so in expressive language.

DISCUSSION

The primary question asked in this study concerned whether the clear advantages of younger cochlear implantation age for spoken language outcomes were maintained into mid-elementary school. We found convincing evidence that this is the case. This crucial advantage, first manifested in testing at 3.5 and 4.5 years of age (Nicholas & Geers, 2006, 2007, 2008), was maintained in all aspects of spoken language tested in this follow-up study. Furthermore, duration of CI use no longer predicted significant variance in language outcome at age 10.5 as it had at age 4.5, indicating that the benefits of early implantation are more enduring than those attributed to longer duration of CI experience.

In addition to the language advantage imparted by a younger age at 1st implantation, better pre-implant aided hearing and higher nonverbal intelligence were also associated with better language at age 10.5. Children with some aided hearing may receive a CI somewhat later due to time spent in hearing aid trial. These results indicate that ensuring both optimal hearing aid benefit and promoting their use before CI surgery is worthwhile and may promote subsequent benefit from a cochlear implant. It initially appeared that language achievement was enhanced for children who received an upgrade from their original speech processor to the most recent technology, especially if this resulted in lower aided thresholds with their CI. However, that effect was no longer significant once age at 1st implantation, nonverbal intelligence and pre-CI aided hearing were controlled. On the other hand, it should be noted that most children had received a technology upgrade, so the range on this variable was restricted, which may have attenuated any possible effects.

There were no significant differences shown in mean performance between children who did and did not receive a second implant in the interval between testing. The effect of a second, bilateral implant deserves further study, however, since the average age of second implantation was 7.7 years and only 14 of the 29 children with bilateral implants had more than one year of 2nd CI experience at the Age 10.5 testing. A longer time period would likely be required for bilateral hearing to affect language outcome scores. These findings would also not be generalizable to children with earlier and/or simultaneous bilateral CIs.

With regard to educational influences on language, there did not appear to be any language advantage to private school placement or greater use of FM systems. Likewise, children with greater use of individual therapy, teacher aides or resource rooms did not exhibit faster language development (possibly because those with greater language learning difficulties needed more of these services). Age upon first entering mainstream classes with hearing age-mates was significantly related to language outcome. Early mainstream placement was likely a result rather than a cause of spoken language proficiency, since children entering the mainstream earlier were those with the best language at age 4.5. While early mainstreaming may not have been the source of this language advantage, it did not seem to interfere with language growth.

Comparison of scores in vocabulary with global language results revealed a significant vocabulary advantage at age 10.5 that was not apparent at age 4.5 (see Table 2). This finding suggests that vocabulary skills may be somewhat easier for children with CIs to acquire. The proportion of children reaching age-appropriate levels in receptive vocabulary exceeded that in receptive language by 14% at age 4.5 and 20% at age 10.5. This vocabulary advantage was observed for only 5% of 10.5 year-olds when expressive skills were compared. The global language measures (PLS, CELF) include substantial assessment of syntactic abilities,

which some studies have shown to be relatively more delayed than vocabulary in children with CIs (Caselli et al., 2012; Duchesne et al., 2009; Geers et al., 2009; Nicholas & Geers, 2008; Szagun, 2000). Language instruction of children with hearing loss may focus more heavily on vocabulary comprehension than on syntax, perhaps contributing to these results.

A strong predictor of language skills at age 10.5 years was the language level exhibited in preschool ($r = .73$). This finding reinforces the importance of achieving language goals early, before the gap between deaf and hearing children becomes too wide. Strong language skills in preschool lead to higher language levels during elementary grades, skills essential for successful literacy and academic achievement. In fact, the accelerated language progress compared to hearing age-mates seen in a substantial number of these children with CIs may have been facilitated by learning to read.

The implications of these findings may be restricted to children with characteristics represented in this sample. Participants all received early listening and spoken language intervention and cochlear implantation before or shortly after they turned three. Children with additional disabilities were not included in this study. The mean parental education and income levels were higher than the average for the general American population and the mean nonverbal intelligence quotient of this sample (105) was slightly higher than the normative mean (100). Therefore, these children might be expected to score somewhat above the normative mean on standardized language tests and achieving within 1 SD of the normative mean does not imply that these children are “caught up” with similarly advantaged NH age-mates.

Conclusions

The current study documents a language advantage for children who received a CI at younger ages that was maintained well into their elementary school years for both lexical skills and for overall receptive and expressive language. Most of the children in this nationwide sample gained language skills at a rate that was similar to, or above, the rate documented for hearing children. Language outcomes relative to hearing age-mates increased between the ages of 4.5 and 10.5, though not as dramatically in the domain of overall receptive language (probably syntax) as compared to receptive vocabulary or all expressive skills. At this stage we do not know whether this process of accelerated growth will continue, with more children catching up as they become older. Nevertheless, this result represents a dramatic improvement over gains reported for children with profound hearing loss before the advent of CIs, a time when the gap between language skills of deaf and hearing children typically increased, rather than decreased, with age. These findings provide new evidence that recommending implantation as early as possible within the 12–36 months window of time (for those who choose it) provide the best chance of achieving and maintaining age-appropriate spoken language skills into and through the elementary school years.

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Figure 1. Individual standard scores on the **Peabody Picture Vocabulary Test** are plotted for 60 participants at two test ages. Ordered data points depict scores at an average age of 4.5 years. Columns depict scores of the same children at an average age of 10.5 years.

Figure 2.

This figure depicts scores for **Receptive Language**. Individual standard scores are plotted for 60 participants at two test ages. Ordered data points depict scores on the Preschool Language Scale at an average age of 4.5. Columns depict scores on the Clinical Evaluation of Language Function for the same children at an average age of 10.5.

Figure 3.

This figure depicts scores for **Expressive Language**. Individual standard scores are plotted for 60 participants at two test ages. Ordered data points depict scores on the Preschool Language Scale at an average age of 4.5. Columns depict scores on the Clinical Evaluation of Language Function for the same children at an average age of 10.5.

Table 1

Characteristics of Participants at Mean Age 10.5

Child & Family Variables	Metric	Mean	SD	Range	N
Chronologic age at testing	Years	10.5	0.8	9.1–12.7	60
WISC Perceptual Reasoning	Standard Score	105.2	12.9	71–135	60
Highest parent education level	Number of Years	16.4	1.8	12–20	58
PEI (Years of Educ + Income [*])	Composite Score	25.3	2.6	19–30	60
Family size	Number	4.6	1.2	3–10	60
Audiological Variables					
Age at diagnosis	Months	10.4	8.2	1–30	60
Age first HA	Months	11.6	8.02	1–31	60
Age at 1 st CI	Months	22.7	7.7	12–38	60
Unaided PTA	dB, HL	108.0	10.9	77–120	60
Pre-CI Aided PTA	dB, HL	65.0	15.1	32–80	60
Current CI-PTA	dB, HL	21.5	7.3	8–48	60
Duration since 1 st implant	Years	8.6	1.0	6–11	60
Age at 2 nd implant	Years	7.7	1.7	4–10	29

* Family Income Rating:

4	10–24,999	3
5	25–49,999	5
6	50–79,999	9
7	80–95,000	6
8	95,000+	36
	NR	1

Table 2

Language Scores for 60 CI Users at Chronologic Ages 4.5 and 10.5 Years

Test Name	Age 4.5 Testing		Age 10.5 Testing		Norm Sample	
	Mean	SD	Mean	SD	Mean	SD
PLS - Auditory Comprehension	82.23	19.32			100	15
PLS - Expressive Language	74.22	21.06			100	15
PPVT-III Standard Score	83.56	18.88	95.62	22.0	100	15
EOWPVT Standard score			100.58	19.56	100	15
CELF -Core Language Standard Score			89.19	20.19	100	15
CELF -Receptive Language Standard Score			88.42	17.01	100	15
Concepts and Following Directions			7.12	3.47	10	3
Word Classes – Receptive			8.73	3.22	10	3
Understanding Spoken Paragraphs			8.23	3.88	10	3
CELF -Express Language Standard Score			92.48	20.38	100	15
Recalling Sentences			7.47	3.80	10	3
Formulated Sentences			9.85	4.21	10	3
Word Classes – Expressive			8.95	3.15	10	3
WISC : Verbal Comprehension Scale (VIQ)			95.52	18.45	100	15
Similarities			10.33	2.93	10	3
Vocabulary			8.73	3.84	10	3
Comprehension			8.73	3.71	10	3

Table 3

Correlation and Partial Correlation (with Pre-CI PTA removed) between Age of 1st Implantation and Test Scores at Ages 4.5 and 10.5 years. N = 60

Test	Correlations			Partial Correlations		
	AOI	<i>p</i> -value	R ²	AOI, controlling for Pre-CI Aided PTA	<i>p</i> -value	R ²
Express Language, Age 4.5 (PLS-EC)	-.492	<.001	.24	-.619	<.001	.38
Recep Vocabulary, Age 4.5 (PPVT)	-.396	.002	.16	-.580	<.001	.34
Recep Language, Age 4.5 (PLS-AC)	-.340	.008	.15	-.552	<.001	.30
Express Vocab, Age 10.5 (EOWPVT)	-.431	.001	.14	-.525	<.001	.28
Combined Language, Age 10.5 (CELF-Core)	-.396	.002	.16	-.507	<.001	.26
Express Language, Age 10.5 (CELF-Exp)	-.393	.002	.15	-.503	<.001	.25
Recep Language, Age 10.5 (CELF-Rec)	-.374	.003	.14	-.467	<.001	.22
Recep Vocabulary, Age 10.5 (PPVT)	-.320	.013	.10	-.429	.001	.18
Verbal Comprehension, Age 10.5 (WISC)	-.344	.007	.12	-.419	.001	.18

Table 4

PC Loadings and Inter-Correlations for Language Scores at (Mean) Age 10.5 Years.

Variable	PC loadings	1	2	3	4
Age 10.5 testing					
1. PPVT-III ss	.951	1.0			
2. EOWPVT-III ss	.944	.871	1.0		
3. Verbal IQ ss	.943	.875	.848	1.0	
4. CELF Core ss	.929	.835	.836	.829	1.0
Total Variance accounted for = 89%					
Age 4.5 testing					
	PC loadings	1	2	3	
1. PPVT-III ss	.918	-	.831	.711	
2. PLS-3 receptive ss	.949		-	.792	
3. PLS-3 expressive ss	.902			-	
Total Variance accounted for = 85%					

PPVT-III = Peabody Picture Vocabulary Test

EOWPVT-III = Expressive One-Word Picture Vocabulary Test

CELF = Clinical Evaluation of Language Fundamentals

PLS-3 = Preschool Language Scale

ss = standard score

Table 5

Correlation of Age 10.5 Language Principal Components score with child, family, educational, and audiologic variables

	Test Age 4.5		Test Age 10.5	
	Language (PC score)	<i>p</i> -value	Language (PC score)	<i>p</i> -value
Variable				
Age 4.5 Language PC score	-	-	.729	< .001
WISC Perceptual Reasoning	-	-	.406	.001
Age at 1 st CI	-.483	< .001	-.396	.002
Family education level + income composite	.218	.100	.384	.001
Age child entered a mainstream school	-.527	< .001	-.602	< .001
Recency of technology	.371	.004	.367	.004
Duration of 1 st CI use	.480	< .001	.184	.083
Current CI-PTA	-	-	-.461	< .001
For N = 29 with a 2nd CI:				
Age received 2 nd CI	-	-	-.085	.66
Duration of use of 2 nd CI	-	-	.228	.23
Interval between CI surgeries	-	-	-.078	.69

Table 6

Hierarchical multiple regression analysis, predicting Language PC score at Age 10.5

Predictor	Step 1				Step 2			
	β	p	sr ²	R ²	β	p	sr ²	R ²
Age at CI	-0.40	.003	.112		-0.32	.018	.067	
PEI	0.20	.092	.034		0.13	.301	.012	
PRQ	0.31	.008	.088		0.32	.006	.091	
Pre-CI aided PTA	-0.33	.013	.078		-0.26	.052	.044	
Current CI-PTA					-0.17	.206	.018	
Bilateral CI rating [*]					0.09	.453	.006	
Speech Processor					0.10	.477	.006	
Explained Variance				.381				.063
Total Explained Variance								.444

^{*} 0 = none; 1 = less than one year; 2 = more than one year

Table 7

Percentage of Children Scoring within or above 1 SD of Normative Mean

Abilities tested	Age 4.5 testing			Age 10.5 testing		
	Test Name	%	1 SD*	Test Name	%	1 SD
Overall language	PLS	32%		CELF	68%	
Receptive language	PLS	45%		CELF	52%	
Expressive language	PLS	27%		CELF	77%	
Receptive vocabulary	PPVT	60%		PPVT	72%	
Expressive vocabulary	-	-		EOWPVT	82%	
Verbal reasoning	-	-		WISC-VCS	80%	

* Percentage of children in the group with standard scores at least within 1 SD of the normative mean for hearing age-mates.