Published in final edited form as:
Ear Hear. 2008 April ; 29(2): 270–280.

Early Listening and Speaking Skills Predict Later Reading Proficiency in Pediatric Cochlear Implant Users

Linda J. Spencer[1] and **Jacob J. Oleson**[2]

[1]Department of Otolaryngology-Head and Neck Surgery, The University of Iowa Hospitals and Clinics, Iowa

[2]Department of Biostatistics, The University of Iowa College of Public Health, Iowa

Abstract

Objectives—Previous studies have reported that children who use cochlear implants (CIs) tend to achieve higher reading levels than their peers with profound hearing loss who use hearing aids. The purpose of this study was to investigate the influences of auditory information provided by the CI on the later reading skills of children born with profound deafness. The hypothesis was that there would be a positive and predictive relationship between earlier speech perception, production, and subsequent reading comprehension.

Design—The speech perception and production skills at the vowel, consonant, phoneme, and word level of 72 children with prelingual, profound hearing loss were assessed after 48 mos of CI use. The children's reading skills were subsequently assessed using word and passage comprehension measures after an average of 89.5 mos of CI use. A regression analysis determined the amount of variance in reading that could be explained by the variables of perception, production, and socioeconomic status.

Results—Regression analysis revealed that it was possible to explain 59% of the variance of later reading skills by assessing the early speech perception and production performance. The results indicated that early speech perception and production skills of children with profound hearing loss who receive CIs predict future reading achievement skills. Furthermore, the study implies that better early speech perception and production skills result in higher reading achievement. It is speculated that the early access to sound helps to build better phonological processing skills, which is one of the likely contributors to eventual reading success.

Introduction

Emerging research in prelingually deaf children who receive a cochlear implant (CI) reveals that many attain higher reading achievement levels than their profoundly deaf peers who use hearing aids (HAs) (Connor & Zwolan, 2004; Geers, et al., 2003; Spencer, et al., 2003). Furthermore, investigators are beginning to describe what factors are associated with and account for these higher reading achievement levels. For example, Spencer et al. (2003) found that the language and literacy skills of prelingually deaf CI users were related. Additionally, Geers (2003) reported that a considerable amount of the variance in reading scores of children who use CIs could be accounted for by child and family variables as well as speech and language variables. Studies also find that the CI provides better access to speech for most children, and this access results in improved speech perception and production (Mildner, et al., 2006; Peng, et al., 2004; Tobey, et al., 2003).

Address for correspondence: Linda J. Spencer, 200 Hawkins OR 21200 PFP, UIHC, Iowa City, IA 52242. linda-spencer@uiowa.edu..

Many factors [e.g., sociocultural characteristics, teaching methodology, language skill, and phonological awareness (PA)] contribute to the development of the ability to read in children with normal hearing (Stone, 2004). A number of these same factors seem to be related to the reading skills of profoundly deaf children who use CIs. The present study will specifically elaborate on the relationship of listening and speaking skills to later reading achievement in children who use CIs. The assumption is that children with CIs will follow a pattern similar to hearing children in that listening and speaking skills provide an important foundation for eventual skills such as language and phonology that are related to reading. It is reasonable to predict that the improved auditory input provided by the CI contributes to reading comprehension.

The Relationship of Listening Skills and Reading Skills

In children with normal hearing there is a strong, predictive relationship between PA and early reading skills. PA is a complex concept composed of compound abilities. In brief, PA is defined as the ability to abstract and manipulate segments of spoken language (Bentin, 1992; Liberman, et al., 1974; Mattingly, 1972). In hearing children, evidence indicates that the ability to discriminate sounds to form word boundaries supports the development of spoken language, which later contributes to reading development. There is disagreement about whether the unit of organization is the phoneme or the syllable (Chomsky & Halle, 1968; Lindblom, et al., 1984). In spite of this disagreement, Fowler (1991) proposed that it is the developmental changes in phonological representations "set the stage" for the development of phoneme awareness, and eventually reading. Specifically she proposed that in early childhood, vocabulary is represented at a holistic level that gradually becomes arranged in terms of phonemic segments. Others have supported this notion, finding that as vocabulary expands, phonological representations restructure and become more specialized (Jusczyk, 1993; Metsala & Walley, 1998; Werker & Tees, 1999). Swan and Goswami (1997) proposed that when we assess PA in hearing children we measure how well the underlying phonological representations are organized.

We do not know whether deaf or hard of hearing children have access to the same phonetic information that hearing children have. Additionally, we are just beginning to assess PA in deaf children. In the case of profoundly deaf children who use HAs, there is limited or at best, variable access to many sounds of language. For example, they may have difficulty in hearing low-intensity sounds such as /m, n, ng/ or high frequency sounds such as /s, z, f/ (Bench, 1992; Erber, 1972). Kishon-Rabin et al. (1997) investigated four children who had bilateral, profound hearing loss with aided pure-tone, free-field testing averages of 48 dB HL (frequencies 500, 1000, and 2000 Hz). Results indicated that they were unable to discriminate between consonant contrasts (e.g., /f/ versus /v/, or /t/ versus /d/). Children with profound hearing loss cannot make fine-grained distinctions between sounds, yet we know that better hearing is associated with better reading skills. Geers and Moog (1989) found that there was a relationship between the use of residual hearing and literacy development in children with profound hearing loss who used HAs. In this study, the participants had better-ear speech frequency pure-tone averages for 500, 1000, and 2000 Hz that were greater than 85 dB.

On the other hand, we know that children with prelingual, profound hearing loss who use CIs tend to perform better on closed and open set word-identification tasks than their peers with profound hearing loss who use HAs. (Meyer, et al., 1998; Vermeulen, et al., 1997) Additionally, children with CIs are more accurate at syllable-counting tasks in spoken words than their peers with HAs, (Fryauf-Bertschy, et al., 1997). However, it remains difficult for these children to discriminate between finergrained stimuli. For example, after nearly 3 yrs of CI experience, they were only 25% accurate in discriminating between rhyming constants (e.g., dee versus me, versus tee) in an auditory-only condition (Tye-Murray, et al., 1995a).

The children were able, however, to identify acoustic features, especially nasality, frication, and place of articulation. Although we can see that input from the CI is beneficial for word, phoneme, and even feature discrimination, it is unclear whether the auditory information provided by the CI is sufficient to contribute to the developmental changes in phonological representations that "set the stage" for the development of phoneme awareness, and eventually reading.

The Relationship of Speech Sound Development and Reading

In children who have normal hearing, research links speech sound disorders (articulation disorders or phonological disorders) with later reading deficits (Catts, et al., 1999; Scarborough & Dobrich, 1990; Snowling, et al., 2000). Most children who are born deaf who receive CIs do not necessarily have a fully resolved speech sound production system by the time they begin to read; however, they display much better speech production skills than their peers with profound hearing loss who do not use CIs (Geers, et al., 2002; Tobey, et al., 2003). Additionally, Spencer and Bass-Ringdahl (2004) found that children who were between 12.8 and 27 mos at time of implantation and who had 36 mos of CI experience produced 69.5% of their phonemes accurately in a sentence repetition task. Similarly, Peng et al. (2004) found that listeners were able to understand 71.5% of the connected speech of prelingually deaf children after they had 84 mos of CI experience. Conversely, Smith (1975) found that children born with profound hearing loss using Has, who were aged 10 or more, only produced 20% of their phonemes accurately. Thus, there are differences in speech production skills between children with profound hearing loss who use HAs and children who use CIs; CI children have greater facility with speech production than their peers with profound hearing loss who use HAs. If speech production skills are indeed related to reading skills, it would be reasonable to predict that use of a CI should yield an advantage with respect to the phonological skills related to reading.

Rationale

CI users are known to have better speech production, speech perception, English language, and reading skills than their prelingually, profoundly deaf peers who use HAs (Geers, 2003; Spencer, et al., 1997). Investigators are just beginning to understand the complex relationship between these factors and how they might contribute to the higher reading achievement levels observed in CI users. The goal of this study was to closely examine the role of two factors, early listening and early speaking skills on the eventual reading achievement in CI users. The rationale for investigating these specific factors is to build a foundation for future studies to document the chain of relationships between several skills (phonology, language comprehension, and production) that are believed to play an important role in literacy development in hearing children. Thus, this study was designed to ascertain whether it is possible to account for the variance in eventual reading skills by looking at early speech perception and speech production skills. The hypothesis is that there will be a positive and a predictive relationship between earlier speech perception, production, and subsequent reading comprehension.

Materials and Methods

Participants

Retrospective speech perception and production data from 72 pediatric CI users (38 females, 34 males) after 48 mos of CI experience were examined. Reading data were collected on average after 89.5 mos (SD 30 mos) of CI experience. At time of CI surgery, participants were between 1.1 and 7.3 yr of age with a mean age of 3.6 yrs (SD 1.6 yrs). All participants had prelingual, bilateral hearing loss with no other identified cognitive or learning disability, and none of the children had repeated a grade in school. Additionally, all participants

underwent CI surgery at the University of Iowa Hospitals and clinics. Etiologies of deafness included unknown, nonspecific heredity component, and identified GJBT mutation (Connexin 26), meningitis, cytomegalovirus, cochlear malformation, Waardenburg's Syndrome, Ushers Type 1, and complications from receiving ototoxic drugs. The type of CI processors used by the participants at the 48 mos collection time point included Nucleus 22-channel WSP, Nucleus MSP, Nucleus Spectra, Nucleus Sprint, and Nucleus 3-G. Processing strategies at the 48 mo interval included Nucleus F0F1F2, Nucleus MPeak, Nucleus Speak, and Nucleus ACE. Appendix A contains the demographic data for the participants in the study. Data for this analysis were collected under the NIH grant (2 P50-DC 00242) from the National Institute of Health and approved by the University of Iowa Institutional Review Board.

Test Measures

Speech Perception Measures—Data from the following auditory comprehension tests were used. The Vowel Perception Test requires the identification of a monosyllabic word from a closed set of four words (e.g., toe, toy, tie, two) varying only in vowel content (place and height). The Consonant Perception Test requires the identification of the correct letter/word from a set of 10 choices (D, T, P, B, V, Z, C, me, knee, key) varying only in consonant content. The Phonetically Balanced-Kindergarten Word Test (PBK) requires the identification of a word presented in an open-set condition. The participants' responses on PBK test are reported in percent words correct and percent phonemes correct. The children repeated or signed the words after they were presented and the production was phonetically transcribed Scoring followed the procedure outlined by Fryauf-Bertschy et al. (1997). Finally, the Word Identification by Picture Identification (WIPI) test was administered. This test requires the child to listen to a word and chose the correct word that was presented from a choice of six words. The percent score for the auditory only condition was used for all tests.

Speech Production Measures—Speech production measures included the Short–Long Sentence Repetition Task (Short–Long) and a Story Retell task as measures of speech production. The procedures followed those described by Tye-Murray et al. (1995b). Short-Long sentence repetition required the participants to repeat 14 sentences each after hearing an examiner's model, which was presented in speech and sign (e.g., How are you going to get there? Please stop making so much noise). Each sample was transcribed using a target transcription to compare with the actual production. A research assistant tallied the transcriptions using a target transcription to yield a short-long percent phonemes produced correct score.

For the Story Retell task, the participants listened and watched the examiner tell each of six short stories in speech and Signed English based on a four-picture sequence. After each story presentation the children repeated the story. For 42 children, responses were recorded on a Panasonic VHS professional/industrial video camera with a Realistic tie-pin microphone input. In the year 2000, the video recording equipment was upgraded to a Panasonic AG-1330 ¾-inch videotape system coupled to a Panasonic WV CP234 surveillance camera with a Tamron 69YE zoom lens and a wall mounted microphone that was situated 24-in from the participant. Data were collected for the speech samples from the remaining 30 children using this set-up.

The author transcribed the children's productions. A research assistant scored or tallied the accuracy of productions using a target transcription. A comparison of the phonemic transcription and the gloss yielded a Story Retell-phonemes score (i.e., accurate number of phonemes produced in proportion to the number of glossed phonemes). The percent

phoneme correct measure was the index of mastery of speech sound production (Tye-Murray, et al., 1995a,b). Additionally, the phonetic transcriptions yielded Story Retell-vowels score, which was the percent vowels produced correctly, and the Story Retell-consonants score, which was the percent consonants produced correctly.

Transcription and Reliability

A phonemic gloss for the intended words, based on the participant's signed and spoken utterances, was made in conjunction with the contexts of the stories. Only the initial 100 spoken words were phonemically transcribed to approximately equalize sample size from each participant, yet there were some children who produced less than 100 words. The mean number of phonemes produced for the sample was 295.75 (SD = 95) with a range of 51 to 405.

To demonstrate insignificant transcriber bias, interjudge reliability measures were periodically performed on randomly selected Story Retell speech production samples in the NIH data set. The last reliability check was completed in the year 2005 when 27 of 224 Story Retell samples (12%) were checked via a retranscription procedure. Two separate research assistants (transcribers A and B) who were native speaker of American English and who were familiar with the speech of children with hearing impairments completed the reliability procedure. The retranscriptions were scored with regard to point-by-point phoneme accuracy after a training session. The average interjudge agreements for the original transcriptions and the retranscriptions by transcribers A and B were 78.58% (SD = 7.04%) and 79.05% (SD = 8.87%), respectively, across the selected samples. The interjudge agreements for both transcribers were considered to be within the acceptable range as typical interjudge reliability for phonemic transcription can range from mid-60% to mid-high-90% (Shriberg & Lof, 1991).

Finally, subjective listener ratings were used to measure speech production skills. A set of 10 raters were asked to listen to an audio recording of the child telling two of the six stories. The listeners rated how well they were able to understand the story on a scale of 1 to 10. The total score for the Story Retell-listener rating was tallied, and possible rating totals were between 0 and 100.

Word Comprehension and Passage Understanding Tests

Two subtests from the Woodcock Reading Mastery Tests Revised Form (WRMT; Woodcock, 1987) were used. Data from the most recent postimplant follow-up visit (between 48 and 144 mos post-CI) were collected. The average postimplant interval was 89.63 mos (SD 30.16 mos). The Word Comprehension subtest consisted of three tasks. First, the child read a word and supplied a word that meant the opposite of the word read. Second, the child read a word and supplied a synonym for the word. The final task required the child to read a series of words to complete an analogy (e.g., big is to small as sweet is to …). All tasks continued until the child achieved a ceiling score (five incorrect responses).

The reading comprehension measure was the Passage Comprehension subtest from the WRMT. This is a modified cloze procedure that assessed a child's ability to comprehend a short passage that was two or three sentences in length. The child had to comprehend the entire passage to complete the sentence with the correct word. The participants answered using sign only responses, voice and sign, or voice only responses. The norms provided from the test were used to convert the raw score to a standard score based on the child's grade in school.

Socioeconomic Status

Socioeconomic status (SES) tends to be a powerful predictor for many language-related skills including vocabulary and reading level (Hart & Risley, 1995; Hoff, 2003; Huttenlocher, et al., 1991, 2002). Unless a family is in extreme poverty, mother's educational level seems to be the best predictor of the parenting skills that are felt to contribute to language and literacy development (Bornstein, et al., 2003; Hoff, et al., 2002). For this reason a measure of SES for each participant was collected by determining the highest level of education of the mother of each participant (Hoff & Tian, 2005). We used the following scale: 1 = completed grades kindergarten through grade 8, 2 = completed grades 9 to 12, 3 = graduated from high school, 4 = completed some post high-school programming, 5 = completed a 4 yr-college degree, 6 = completed a postgraduate college degree.

Challenges of Working With a Clinical Data Set

One of the issues of working with a retrospective data set that contains longitudinal, clinical data is that of missing data. Data points can be missing due to a variety of reasons including fatigue of the child, clinician error, and equipment error. Additionally, in this study some missing data were attributed to protocol changes. For example, at a particular point in time a test may not have been a part of the experimental protocol, or alternatively the test was removed from the protocol. The typical analytic approach to missing data is to drop the cases with the missing test or tests. Only 16 of the 72 participants in our data set have a complete set of records. This sample size would be too small to adequately test our research question. If the absence of data is due to only one variable in particular, then that variable is often excluded from the analysis. Our data set, however, has multiple variables with varying degrees of missing values (see Table 1). Analyses when missing data are present can result in biased estimates and loss of power.

An alternative approach to alleviate the missing data problem is data imputation using appropriate statistical methodology. An imputed data point is an observation that is not observed, but rather a reasonable value is generated that is conditional on all of the values that have been observed. With an imputed data set one is allowed to take advantage of the rich original data set that preserves as much information as possible.

The method of imputation used by the authors was multiple imputation (MI) (Rubin, 1978). The steps used to complete the MI procedure are outlined briefly in the paragraphs below. For more detail in the MI approach see Little and Rubin (2002).

In MI, each of the missing values are imputed *m* times. These imputed values are generated by using the information from the observed values. Thus *m* completed data sets are created. Then each of the *m* completed data sets are analyzed using standard complete-data procedures.

The variables are all assumed to be normally distributed for this MI approach. We made transformations on three variables to better satisfy the normality assumption. The Story Retell-listener rating task was log transformed, the Story Retell-vowels correct for the task was square transformed and Vowel Perception Test was cubic transformed. In the imputation procedure, we chose the usual Markov Chain Monte Carlo (MCMC) method for imputation. The results of the Expectation-Maximization algorithm were used to start the MCMC process, whereas the means and standard deviations from available cases in the original data set were used as the initial estimates for the Expectation-Maximization algorithm. Once the initial values are set, imputed data are randomly generated from the distribution of the missing variable conditional on all other variables. This process is performed for every variable in the data set and repeated 1000 times. The first 200

replications were removed to increase stability. The imputed value is then the average of the remaining 800 replications. This process is repeated to generate $m = 5$ imputed data sets resulting in five "complete" data sets. The MIs were carried out through PROC MI in SAS 9.1.

Note that the variables in this analysis are percentages that range from 0 to 100. The MI procedure was not always able to restrict within these bounds when the observed percentages clustered too closely to 0 or 100. Our resulting data set has all the imputed values set to 100 if they exceeded 100 and set to 0 if they are less than 0.

Regular statistical procedures can then be performed on each of the imputed data sets. Results from each of the individual data sets are then combined according to Rubin (1978) using PROC MIANALYZE in SAS 9.1. One advantage of this procedure is that it accounts for additional variability that will be inherent in imputing values where they were not observed. One disadvantage is the inherent multicollinearity in the data set. When two or more predictor variables are highly correlated their standard errors are inflated making it harder to find statistical significance of the affected predictors. Predicted values are unaffected, however. Model selection under multicollinearity will potentially lead to an underfit model. That is, fewer variables are likely to be selected than are potentially useful.

Results

Means for Speech Perception, Production, and Reading Tests

Table 1 presents the means and standard deviations for the speech production and perception variables as tested at the 48-mo postoperative interval using the data set without imputation, and from the fifth imputed data set presented as the italicized values. The means from both the nonimputed and the imputed data sets are very close, thus the imputed data set will be reported in the narrative. The averages for perception scores were highest for the Vowel Perception Test accuracy at 83.21%, followed by the PBK-phoneme accuracy (57.74%) then PBK-word accuracy (38.51%). The percent phonemes correct for the Short Long and the Story Retell-all phonemes task were similar, 67.27 and 63.88%, respectively. Regarding production accuracy, Story Retell-vowels produced higher (74.12%) than Story Retell-consonants produced (58.35%). The Story Retell-listener rating score was 44.42 where 100 would be the highest possible score.

Table 2 presents the means and standard deviations of the standard scores obtained on Word Comprehension and Passage Comprehension reading measures. Average standard score for the Word Comprehension measure was 93.38, and the average standard score for the Passage Comprehension measure was slightly lower, at 88.05.

The rest of the results are reported based on the imputed speech production and perception data. The intercorrelations between each of the speech perception measures and each of the speech production measures are in Tables 3 and 4. The intercorrelations between the speech perception and speech production measures are in Table 5, whereas the intercorrelations between the speech perception and reading measures plus the speech production and the reading measures are in Table 6.

All the speech perception measures had a Spearman coefficient values above the 0.62 level. The highest correlation was between the PBK-word and the PBK-phoneme measures at $r = 0.98$ ($p < 0.0001$).

All the speech production measures were strongly related to each other and had Spearman coefficient values above the 0.73 level ($p < 0.0001$). The highest correlation was between

the correct Story Retell-phonemes and the correct Story Retell-consonants ($r = 0.97$, $p < 0.0001$). The lowest correlation was between the Story Retell-listener rating and the percent Short-Long phonemes produced correctly ($r = 0.74$, $p < 0.0001$).

All the speech perception and speech production measures were moderately to strongly correlated. Spearman coefficient were lowest between Story Retell-vowels produced correctly and Vowel Perception Test ($r = 0.57$ $p = 0.0001$), with highest correlations between Story Retell-consonant production and percent PBK-words correct ($r = 0.86$, $p < 0.0001$).

The Spearman correlation coefficients for both the reading measures and the perception and production measures were more variable. The Word Comprehension was most closely associated with the Story Retell-listener rating, the Story Retell-phoneme, and Story Retell-consonant task ($r = 0.64$, $p < 0.0001$, $r = 0.52$, $p < 0.0001$, and $r = 0.52$, $p < 0.0001$, respectively), whereas Passage Comprehension was most closely associated with Story Retell-listener rating, Short-Long accuracy, and Story Retell-phoneme tasks ($r = 0.63$, $p < 0.0001$, $r = 0.54$, $p < 0.0001$, $r = 0.53$, $p < 0.0001$, respectively).

Regression Analysis

Ten test measures were considered as predictor variables for each regression analysis. These were Short-Long (percent phonemes correct), Story Retell-all phonemes, Story Retell-vowels, Story Retell-consonants, Story Retell-listener rating, Vowel Perception Test, Consonant Perception Task, PB-K Words, PB-K Phonemes, and WIPI.

Additionally, because SES has been demonstrated to be associated with reading outcome in children with and without CIs (Connor & Zwolan, 2002) the mother's education level as an SES measure was used in this model to account the amount of variance associated with SES. Age at test was considered in the model as well.

With five regression analyses to combine, we chose a model selection criterion rather than a stepwise selection procedure to produce the best model. MI is inherently a Bayesian procedure making the Schwarz information criterion (BIC), an appropriate model selection criterion (Schwarz, 1978). We selected the model with the lowest average BIC across the five imputed data sets. The model selection was realized by using PROC REG in SAS 9.1.

Because of highly correlated predictor variables, we performed multicollinearity diagnostics. There were very few observations in the fully observed data set to compute reasonable values of these diagnostics. For the imputed data sets, the variance inflation factor was approximately 30 and 70 for percent Story Retell phonemes correct and Story Retell listener rating, respectively. In the final selected data set, however, all variance inflation factor values were less than 7 for all imputed data sets. Thus, mulitcollinearity does not play a role in the final selected model. There is a chance, however, that an important predictor variable was not included in the final model. We feel that the R^2 values are high enough where this is not a concern. Caution should always be exercised when analyzing imputed data.

Tables 7 and 8 provide the results from regression analysis that was used to predict the amount of variance (R^2) associated with later Word Comprehension scores and Paragraph Comprehension scores that could be accounted for by the early speech production and perception measures.

For the dependent variable Word Comprehension, the resulting independent variables that entered into the regression analysis were Short Long (percent phonemes produced correctly), Story Retell (percent phonemes produced correctly), Vowel Perception Test,

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Consonant Perception Test, WIPI, and age at testing. The variables yielded an average R^2 = 59%, suggesting that these variables account for 59% of the variability in Word Comprehension.

For the dependent variable Passage Comprehension, the resulting independent variables that entered into the regression analysis were age at testing, Short Long (percent phonemes produced correctly), Consonant Test, WIPI, and PBK-words. These variables yielded an average R^2 = 62%.

We point to the variable Consonant Test in Tables 7 and 8 and the variable PBK-words in Table 8. The beta estimates are negative for these variables in the multiple regression analyses even though the zero-order correlations shown in Table 6 are positive. The negative parameter estimate in the multiple regressions does not necessarily indicate a direct negative relationship with the outcome variable but rather a negative adjustment given that the model already contains the information produced from the other variables in the model.

Discussion

This study examined the speech and hearing skills of children with prelingual, profound hearing loss after 4 yr of listening experience with a CI and the subsequent relationship to Word, and Passage Comprehension skills. The rationale for this investigation was that CI users are known to have better reading skills than their peers who use HAs (Geers, 2003; Spencer, et al., 1997), yet investigators are just beginning to account for the better reading skills. It was hypothesized that the speech production and perception skills after 4 yrs of CI use would have a positive and predictive relationship to subsequent Word and Passage Comprehension.

The hypothesis was based on what is known about how children with hearing learn to read, and what is known about how children who are hard-of-hearing read. Specifically, in hearing children, there is a predictive relationship between PA and subsequent reading skills. For children who are hard-of-hearing, those who have better speech perception and better speech production tend to have higher reading skills.

Results of this study replicated earlier studies of reading skills in CI children in that overall standard reading scores were within the low average range. The mean standard scores on the word and passage comprehension assessments were 93 and 88, respectively. Spencer et al. (2003) reported mean standard scores of 90.13 on the same passage comprehension measure for 16 prelingually deaf children who had almost 6 yrs of CI experience. These 16 children included in the cohort of 72 who participated in the present study, yet their scores may not have been taken at the same test interval. Again the reading scores for CI users are higher than what is typically seen in children with profound hearing loss (Allen, 1986; DiFrancesca, 1972; Traxler, 2000).

The results of this study also indicated that there was a large range in speech perception and speech production skills 4 yrs after CI use. Speech perception scores ranged from 0 to 100%; on average the children perceived vowels with 83% accuracy, consonants with 41% accuracy, and PBK-words in an open-set condition with 40% accuracy, and in a closed-set condition (WIPI) with 70% accuracy. Recall that typically, children with profound hearing loss achieve below 20% accuracy on most such testing. Similarly, speech production scores ranged from 17 to 99% of words produced correctly, (Story Retell) mirroring speech perception trends. On average, after 48 mos of experience, the children with CIs were producing 75% of their vowels and 60% of their consonants accurately, with whole-word production accuracy at 65%. Again these production scores are much higher than those

NIH-PA Author Manuscript

NIH-PA Author Manuscript

scores typically seen in children with profound hearing loss wearing HAs, who average about 20% of their words produced accurately (Smith, 1975).

The correlation and the regression analysis supported the hypothesis. Both speech production and perception skills of 72 children after 48 months of CI use had a relatively strong correlation with later word and passage comprehension. Additionally, the regression analysis revealed that for eventual Word Comprehension, 59% of the eventual variance was accounted by speech production and speech perception skills early on, at 48 months postimplantation. For Passage Comprehension, 62% of the variance was accounted for by speech production and speech perception skills at 48 mos postimplantation. The contribution of speech and listening to reading for these CI children supports the notion of Leybaert and Alegria (1995) that speech intelligibility may be a measure of the "mental model" of speech, and a measure of phonological skills. Additionally, these results support the findings of Raitano et al. (2004) who found that children with normal hearing who have better articulation have better reading skills.

The fact that speech production skills 48 mos after receiving a CI predicts later reading proficiency, suggests that there is a link between how children with CIs map the acoustic signal onto phonological representations. This link is likely related to speech articulation. The results of this study set the stage for the subsequent investigations into the relationship between speaking, listening, PA, and reading. The data from the current study suggest that individual differences in hearing and phonological skills predict later individual differences in reading.

Finally, the results of this study indicate that the children with CIs have access to sound, which helps to build their speech production skills. These early listening and speaking skills play through later phonological processing skills. In turn, the phonological skills support the development of language skills, which help to produce better readers. The present findings indicate that it would be important for future studies to evaluate phonological skills of children with CIs and compare those skills concurrently with reading performance. Future studies of this association can make a contribution to the understanding of the relationship between listening, speaking, language, and reading in children with CIs.

Acknowledgments

The authors thank Kara Zielinski and Sarah Knoll for their work on transcription reliability. One of the authors, Linda Spencer, acknowledges her dissertation advisor and mentor, J. Bruce Tomblin.

This research was funded in part by research grant awarded to the Department of Otolarynology-Head and Neck Surgery, University of Iowa (number 2 P50 DC00242) from the National Institutes on Deafness and Other Communications Disorders, National Institutes of Health; grant RR00059 from the General Clinical Research Centers Program, Division of Research Resources, NIH; the Lions Club International Foundation; and the Iowa Lions Sight and Hearing Foundation.

APPENDIX A. Demographic data for the participants in the study

ID	SEX	Age at implant (yrs)	Months Post-CI at reading testing	SES	Etiology	CI type	Processing strategy
1	M	3.4	60	4	CNX 26	Spectra	SPEAK
2	M	2.8	72	4	CNX 26	Spectra	SPEAK
3	F	2.2	60	5	CMV	Sprint	ACE
4	M	5.5	96	4	Meningitis	Spectra	SPEAK
5	M	3.8	132	5	Unknown	WSP	FOF1F2
6	F	4.1	96	3	Meningitis	MSP	MPEAK
7	F	5.3	120	4	Unknown	MSP	MPEAK
8	M	4.1	96	4	Meningitis	MSP	MPEAK
9	F	5.1	108	3	Meningitis	MSP	MPEAK
10	F	1.3	60	4	Meningitis	3G	ACE
11	F	3.6	96	5	CMV	MSP	MPEAK
12	M	1.6	60	5	Unknown	Sprint	ACE
13	M	1.1	60	5	Unknown	Sprint	ACE
14	M	5.1	60	4	CMV	MSP	MPEAK
15	F	1.3	132	5	CNX 26	Sprint	ACE
16	M	1.6	132	5	Unknown	Sprint	ACE
17	F	2.3	96	2	Unknown	Sprint	SPEAK
18	F	4.7	72	4	Unknown	MSP	F0F1F2
19	M	5.9	72	5	Meningitis	MSP	F0F1F2
20	M	1.1	72	5	CMV	Sprint	SPEAK
21	M	5.1	72	4	Unknown	Sprint	ACE
22	F	5.5	72	3	CMV	MSP	MPEAK
23	M	2.8	120	3	CNX 26	MSP	MPEAK
24	F	1.5	72	6	Unknown	Sprint	ACE
25	M	2.9	96	3	Cochlear Mal	Sprint	ACE
26	M	1.4	84	3	Meningitis	Sprint	ACE
27	M	3.8	96	5	Meningitis	MSP	MPEAK
28	F	6.2	72	5	Her NS	3G	ACE
29	F	5.7	96	5	Unknown	MSP	MPEAK
30	M	5.3	72	5	Unknown	Spectra	SPEAK

ID	SEX	Age at implant (yrs)	Months Post-CI at reading testing	SES	Etiology	CI type	Processing strategy
31	M	4.5	120	3	Waardenburg	MSP	MPEAK
32	M	5.5	120	4	CNX 26	MSP	MPEAK
33	F	5.1	72	5	Unknown	MSP	MPEAK
34	F	1.5	72	5	Unknown	Sprint	ACE
35	F	1.9	60	2	Unknown	Sprint	ACE
36	F	3.4	72	4	Unknown	Sprint	ACE
37	F	1.0	60	3	Her NS	Sprint	ACE
38	F	2.2	84	3	Her NS	Sprint	SPEAK
39	M	5.6	72	4	Meningitis	Sprint	ACE
40	M	3.4	132	5	Meningitis	MSP	MPEAK
41	F	3.4	120	5	Unknown	Spectra	SPEAK
42	F	3.3	72	4	Unknown	Sprint	ACE
43	M	5.4	108	4	Unknown	Spectra	SPEAK
44	M	3.5	72	3	Unknown	Sprint	ACE
45	M	3.3	120	4	CNX 26	MSP	MPEAK
46	F	3.8	132	5	Unknown	MSP	MPEAK
47	F	3.0	72	5	Unknown	Spectra	SPEAK
48	M	5.8	72	3	Unknown	MSP	MPEAK
49	M	3.5	120	4	CNX 26	Spectra	SPEAK
50	M	1.3	72	5	Her NS	Sprint	ACE
51	M	2.5	144	5	Meningitis	MSP	MPEAK
52	M	1.6	72	3	Ototoxicity	Sprint	ACE
53	F	4.3	108	3	Unknown	MSP	MPEAK
54	M	2.7	108	6	CNX 26	Spectra	SPEAK
55	F	5.3	60	4	Anoxic episode at birth	MSP	MPEAK
56	F	6.6	96	4	Unknown	MSP	MPEAK
57	M	2.5	72	5	Her NS	Sprint	ACE
58	F	1.5	60	3	Cochlear Mal	Sprint	ACE
59	M	3.2	72	4	Her NS	Sprint	ACE
60	F	5.0	84	3	Meningitis	MSP	MPEAK
61	F	1.6	72	4	CNX 26	Sprint	ACE

ID	SEX	Age at implant (yrs)	Months Post-CI at reading testing	SES	Etiology	CI type	Processing strategy
62	F	1.6	84	5	Ushers Type 1	Sprint	SPEAK
63	F	4.7	108	4	Unknown	MSP	MPEAK
64	M	4.7	120	3	Unknown	MSP	MPEAK
65	M	6.2	96	5	CNX 26	Spectra	SPEAK
66	M	4.2	60	4	Unknown	3G	ACE
67	F	4.4	108	2	Unknown	MSP	MPEAK
68	F	4.2	120	5	Unknown	Spectra	SPEAK
69	F	7.3	108	2	Ototoxicity	WSP	FOF1F2
70	F	2.7	84	4	Unknown	Spectra	SPEAK
71	F	2.7	60	3	Unknown	MSP	MPEAK
72	F	4.8	120	5	Meningitis	MSP	MPEAK

All Devices were Cochlear Corporation (Nucleus).

CNX 26, GJBT mutation (Connexin 26); CMV, Cytomegalovirus; Her NS, nonspecific hereditary component; Cochlear Mal, cochlear malformation.

References

Allen, TE. Patterns of academic achievement among hearing-impaired students. In: Schildroth, AN.; Karchmer, A., editors. Deaf children in America. Pro-Ed; Austin, TX: 1986.

Bench, RJ. The speech reception of hearing-impaired children. In: Bench, RJ., editor. Communication skills in hearing-impaired children. Singular; San Diego: 1992.

Bentin, S. Phonological awareness, reading, and reading acquisition: a survey and appraisal of current knowledge. In: Frost, R.; Katz, L., editors. Orthography, phonology, morphology and meaning. North-Holland; Amsterdam: 1992. p. 193-210.

Bornstein, MH.; Hahn, CS.; Suwalsky, JT., et al. Socioeconomic status, parenting, and child development: the Hollingshead four-factor Index of social status and the socioeconomic index of occupations. In: Bornstein, MH.; Bradley, RH., editors. Socioeconomic status, parenting, and child development. Lawrence Erlbaum; Mahwah, NJ: 2003. p. 29-82.

Catts HW, Fey ME, Zhang X, et al. Language basis of reading and reading disabilities: evidence from a longitudinal investigation. Sci Stud Read. 1999; 3:331–361.

Chomsky, N.; Halle, M. The sound pattern of English. Harper & Row; New York: 1968.

Connor CM, Zwolan TA. Examining multiple sources of influence on the reading comprehension skills of children who use cochlear implants. J Speech Lang Hear Res. 2004; 47:509–526. [PubMed: 15212565]

DiFrancesca, S. Academic achievement test results of a national testing program for hearing-impaired students. Gallaudet College; Washington, DC: 1972.

Erber NP. Auditory, visual, and auditory-visual recognition of consonants by children with normal and impaired hearing. J Speech Hear Res. 1972; 15:413–422. [PubMed: 5047880]

Fowler, AE. How early phonological development might set the stage for phoneme awareness. In: Brady, SA.; Shankweiler, DP., editors. Phonological processes in Literacy: a tribute to Isabelle Y. Liberman. Lawrence Erlbaum; Hillsdale, NJ: 1991. p. 97-118.

Fryauf-Bertschy H, Tyler RS, Kelsay DM, et al. Cochlear implant use by prelingually deafened children: the influences of age at implant and length of device use. J Speech Lang Hear Res. 1997; 40:183–199. [PubMed: 9113869]

Geers A, Moog J. Factors predictive of the development of literacy in profoundly hearing-impaired adolescents. Volta Rev. 1989; 91:69–86.

Geers A, Spehar B, Sedey A. Use of speech by children from total communication programs who wear cochlear implants. Am J Speech Lang Pathol. 2002; 11:50–58.

Geers AE. Predicting reading skill development in children with early cochlar implantation. Ear Hear. 2003; 514:59S–68S. [PubMed: 12612481]

Geers AE, Brenner C, Davidson L. Factors associated with development of speech perception skills in children implanted by age five. Ear Hear. 2003; 24:24S–35S. [PubMed: 12612478]

Hart, B.; Risley, T. Meaningful differences in the everyday experience of young American children. Brooks; Baltimore: 1995.

Hoff E. The specificity of environmental influence: socioeconomic status affects early vocabulary development via maternal speech. Child Dev. 2003; 74:1368–1378. [PubMed: 14552403]

Hoff E, Tian C. Socioeconomic status and cultural influences on langauge. J Commun Disord. 2005; 38:271–278. [PubMed: 15862810]

Hoff, E.; Laursen, B.; Tardif, T. Socioeconomic status and parenting. In: Bornstein, MH., editor. Handbook of parenting. Erlbaum; Mahwah, NJ: 2002. p. 231-252.

Huttenlocher J, Haight W, Bryk A, et al. Early vocabulary growth: relation to language input and gender. Dev Psychol. 1991; 27:236–248.

Huttenlocher J, Vasilyeva M, Cymerman E, et al. Language input at home and at school: relation to child syntax. Cognit Psychol. 2002; 45:337–374. [PubMed: 12480478]

Jusczyk, PW. How word recognition may evolve from infant speech perception capacities. In: Altmann, GTM.; Shillcock, R., editors. Cognitive models of speech processing: the second Sperlonga meeting. Lawrence Erlbaum; Mahwah, NJ: 1993. p. 22-55.

Kishon-Rabin L, Haras N, Bergman M. Multisensory speech perception of young children with profound hearing loss. J Speech Lang Hear Res. 1997; 40:1135–1150. [PubMed: 9328885]

Leybaert J, Alegria J. Spelling development in deaf and hearing children: evidence for use of morpho-phonological regularities in French. Read Writing. 1995; 7:89–109.

Liberman IY, Shankweiler D, Fischer F, et al. Explicit syllable and phoneme segmentation in the young child. J Exp Child Psychol. 1974; 18:201–212.

Lindblom, B.; MacNeilage, P.; Studdert-Kennedy, M. Self-organizing processes and the explanation of language universals. In: Butterworth, B.; Comrie, B.; Dahl, S., editors. Explanations for language universals. Walter de Gruyter; Berlin: 1984. p. 181-203.

Little, RJA.; Rubin, DB. Statistical analysis with missing data. Wiley; New York: 2002.

Mattingly, IG. Reading, the linguistic process, and linguistic awareness. In: Kavanagh, JF.; Mattingly, IG., editors. Language by ear and by eye: the relationship between speech and reading. Massachusetts Institute of Technology; Oxford, England: 1972.

Metsala, JL.; Walley, AC. Spoken vocabulary growth and the segmental restructuring of lexical representations: precursors to phonemic awareness and early reading ability. In: Metsala, JL.; Ehri, LC., editors. Word recognition in beginning literacy. Lawrence Erlbaum; Mahwah, NJ: 1998. p. 89-120.

Meyer TA, Svirsky MA, Kirk KI, et al. Improvements in speech perception by children with profound prelingual hearing loss: effects of device, communication mode, and chronological age. J Speech Lang Hear Res. 1998; 41:846–858. [PubMed: 9712131]

Mildner V, Sindija B, Zrinski KV. Speech perception of children with cochlear implants and children with traditional hearing aids. Clin Linguist Phon. 2006; 20:219–229. [PubMed: 16428240]

Peng SC, Spencer LJ, Tomblin J. Speech intelligibility of pediatric cochlear implant recipients with 7 years of device experience. J Speech Lang Hear Res. 2004; 47:1227–1236. [PubMed: 15842006]

Raitano NA, Pennington BF, Tunick RA, et al. Pre-literacy skills of subgroups of children with speech sound disorders. J Child Psychol Psychiatr. 2004; 45:821–835.

Rubin, DB. Multiple imputation for nonresponse in surveys. Wiley; New York: 1978.

Scarborough HS, Dobrich W. Development of children with early language delay. J Speech Hear Res. 1990; 33:70–83. [PubMed: 2314086]

Schwarz G. Estimating the dimension of a model. Ann Stat. 1978; 6:461–464.

Shriberg LD, Lof GL. Reliability studies in broad and narrow phonetic transcription. Clin Linguist Phon. 1991; 5:225–279.

Smith C. Residual hearing and speech production in deaf children. J Speech Hear Res. 1975; 18:795–811. [PubMed: 1207108]

Snowling MJ, Bishop DVM, Stothard SE. Is preschool language impairment a risk factor for dyslexia in adolescence? J Child Psychol Psychiatr. 2000; 41:587–600.

Spencer, L.; Bass-Ringdahl, SM. An evolution of communication modalities. In: Miyamoto, RT., editor. International congress series. Elsevier; Indianapolis: 2004. p. 352-355.

Spencer L, Barker B, Tomblin B. Exploring the language and literacy outcomes of pediatric cochlear implant users. Ear Hear. 2003; 24:236–247. [PubMed: 12799546]

Spencer L, Tomblin J, Gantz B. Reading skills in children with multichannel cochlear-implant experience. Volta Rev. 1997; 99:193–202.

Stone, CA. Theoretical and methodological issues in the study of language and literacy disorders. In: Stone, CA.; Silliman, ER.; Ehren, BJ., et al., editors. Handbook of language and literacy: development and disorders. Guilford Press; New York: 2004. p. 3-24.

Swan D, Goswami U. Picture naming deficits in developmental dyslexia: the phonological representations hypothesis. Brain Lang. 1997; 56:334–353. [PubMed: 9070416]

Tobey EA, Geers AE, Brenner C, et al. Factors associated with development of speech production skills in children implanted by age five. Ear Hear. 2003; 24:36S–45S. [PubMed: 12612479]

Traxler CB. The Stanford Achievement Test, 9th edition: National Norming and performance standards for deaf and hard-of-hearing students. J Deaf Stud Deaf Edu. 2000; 5:337–348.

Tye-Murray N, Spencer L, Gilbert-Bedia E. Relationships between speech production and speech perception skills in young cochlear-implant users. J Acoust Soc Am. 1995a; 98:2454–2460. [PubMed: 7593929]

Tye-Murray N, Spencer L, Woodworth GG. Acquisition of speech by children who have prolonged cochlear implant experience. J Speech Hear Res. 1995b; 38:327–337. [PubMed: 7596098]

Vermeulen A, Snik AF, Brokx JP, et al. Comparison of speech perception performance in children using a cochlear implant with children using conventional hearing aids, based on the concept of "equivalent hearing loss.". Scand Audiol Suppl. 1997; 26:55–57. [PubMed: 9428046]

Werker JF, Tees RC. Influences on infant speech processing: toward a new synthesis. Annu Rev Psychol. 1999; 50:509–535. [PubMed: 10074686]

Woodcock, R. Woodcock Reading Mastery Tests-Revised. American Guidance Service; Circle Pines, MN: 1987.

TABLE 1

Speech perception and production performance at 48-mo postimplant where the numbers in italics are the values for the imputed data set

Variable name	Mean	SD	Minimum	Maximum
Vowel test (n = 70,*72*)	83.91, *83.21*	20.54, *20.93*	10	100
Consonant test (n = 33,*72*)	41.43, *47.31*	25.22, *29.80*	0	92
PBK phonemes (n = 69,*72*)	58.00, *57.74*	29.90, *29.46*	0	96
PBK words (n = 69,*72*)	39.46, *38.51*	30.00, *29.80*	0	95
WIPI (n = 46,*72*)	69.98, *63.64*	20.90, *25.84*	22	100
Short long (n = 71,*72*)	67.35, *67.27*	21.30, *21.16*	18	99
Story Retell-all phonemes (n = 69,*72*)	64.72, *63.88*	24.82, *24.64*	17.13	99
Story Retell-vowels (n = 69,*72*)	75.01, *74.72*	21.67, *21.71*	25.21	100
Story Retell-consonants (n = 69,*72*)	58.95, *58.35*	27.58, *27.23*	12.02	99.44
Listener rating (n = 29,*72*)	32.93, *44.41*	26.27, *31.16*	25.21	100

First value for n is for the nonimputed n, second, italicized value is the imputed n.

First five tests are perception tests, remaining tests are production tests.

TABLE 2

Word and passage comprehension standard scores as tested on average 89.5-mo postimplant

	Mean	SD	Minimum	Maximum
Word comprehension (n = 72)	93.38	19.42	46	141
Passage comprehension (n = 72)	88.05	24.02	7	154

NIH-PA Author Manuscript

NIH-PA Author Manuscript

TABLE 3

Spearman correlation matrix of speech perception measures taken at 48-mo postimplant

	Vowels	Consonants	PBK phonemes	PBK words	WIPI
Vowels	1.0	0.62	0.68	0.67	0.74
Consonants		1.0	0.85	0.85	0.75
PBK phonemes			1.0	0.98	0.86
PBK words				1.0	0.85
WIPI					1.0

$p < 0.0001$ for all values.

TABLE 4

Spearman correlation matrix of speech production measures taken at 48 mos postimplant

	Short Long	Story Retell-All phonemes	Story Retell-Vowels	Story Retell-Consonants	Listener rating
Short-Long phonemes	1.0	0.84	0.76	0.85	0.74
Story-all phonemes		1.0	0.93	0.97	0.84
Story-vowels			1.0	0.85	0.80
Story-consonants				1.0	0.82
Listener rating					1.0

$p < 0.0001$ for all values.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

TABLE 5

Spearman correlation matrix of speech perception and speech production measures taken at 48 mos postimplant

	Short Long	Story Retell-All phonemes	Story Retell-Vowels	Story Retell-Consonants	Listener rating
Vowels	0.65	0.63	0.57	0.64	0.65
Consonants	0.85	0.76	0.71	0.77	0.59
PBK phonemes	0.83	0.84	0.77	0.85	0.80
PBK words	0.83	0.81	0.80	0.86	0.68
WIPI	0.79	0.77	0.76	0.76	0.81

$p < 0.0001$ for all values.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

TABLE 6

Spearman correlation matrix between reading measures taken on average 89.5 mos postimplant and speech perception and speech production measures taken 48 mos postimplant

	Word Comprehension	Passage Comprehension
Vowel test	0.23*	0.23*
Consonant test	0.17ns	0.39
PBK phonemes	0.42	0.49
PBK words	0.40	0.47
WIPI	0.47	0.53
Short long	0.45	0.54
Story Retell-All phonemes	0.52	0.53
Story Retell-vowels	0.48	0.51
Story Retell-consonants	0.50	0.53
Listener rating	0.64	0.63

$p < 0.0001$ if unmarked, ns is not significant. First five tests are perception tests, remaining tests are production tests.

*$p < 0.05$.

TABLE 7

Regression results for word reading

Source	Beta	*p* <
Short long	2.62	0.02
Story Retell-All phonemes	2.06	0.05
WIPI	3.75	0.0005
Consonant test	−5.06	0.0002
SES	−1.10	0.31
Vowel test	−1.65	0.14

R^2 for model was 0.59.

TABLE 8

Regression results for passage comprehension

Source	Beta	*p* <
Short long	3.26	0.004
WIPI	3.86	0.001
Consonant test	−2.10	0.05
PBK words	−1.83	0.10
SES	−1.75	0.16

R^2 for model was 0.62.