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Factors Influencing Elementary and High-School Aged Cochlear Implant Users

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INTRODUCTION

Teaching a child with a profound sensorineural hearing loss (SNHL) of 90 dB HL or greater to use spoken communication as their primary mode of communication represents a significant clinical challenge. When profound SNHL occurs within the early years of life, children are deprived of critical auditory stimulation during time periods associated with substantial development of the neural architecture of the auditory system. Auditory system development appears to be associated not only with laying the foundation for processing speech signals to form language constructs but also with laying the foundation for producing speech signals that are understood by other listeners who interact with the speaker with a SNHL (Kent, Weismer, Kent, & Rosenbek, 1989; Tobey et al., 2000). Exactly how auditory feedback influences the development of intelligible speech in children with profound SNHL remains elusive in the detail of how it stimulates and refines spoken output—yet, the diminished or absent auditory information during early formative years results in a wide array of poor spoken outputs. Spoken outputs from children with profound SNHL range from utterances understood by familiar and unfamiliar listeners to communications enhanced by sign systems--such as Signing Exact English or Cued Speech--or languages such as American Sign Language (Tobey & Geers, 1995). The challenge of providing spoken communication to children with profound SNHL continues to command clinical attention since the majority of SNHL children have normal hearing families who desire their children to participate in their “family communities” (Geers & Brenner, 2003).

In the early 1990’s, cochlear implants (CI) were approved by the Food and Drug Administration (FDA) as an intervention process for children with profound SNHL. In the ensuing years, criteria for candidacy for a CI shifted from very conservative considerations of residual hearing and chronological age to less stringent criteria incorporating greater degrees of residual hearing and implantation at younger ages (Clark, 2003). Yet, questions remain regarding the relatively long-term impact of CIs on spoken communication. Spoken communication involves a bidirectional interaction between a speaker and a listener. Spoken

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communication is often evaluated using rather global methods such as judgments of speech intelligibility or the "degree to which a speaker's intended message is recovered by the listener" (Kent et al., 1989). Measures of speech intelligibility in young children with severe-profound SNHL who use conventional hearing aids hover around 20% (Smith, 1975). Speech intelligibility in young children with severe-profound SNHL who use CIs improves with increasing experience with plateaus of 80-90% intelligibility around 8 to 10 years post implantation (Chin, Tsai, & Gao, 2003; Mondain et al., 1997; Peng, Spencer, & Tomblin, 2004; Uziel et al., 2007). Greater changes in speech intelligibility accuracy also are associated with changes in the evolving sophistication of the CI technology: speech intelligibility is higher for children using the newest technology and whose audiologist's maximize auditory performance through appropriate mapping techniques (Tobey et al., 2000; Tobey & Geers, 1995). Improvement in speech intelligibility occurs regardless of whether the speech intelligibility is measured with minimal pair words (Monsen, 1981), key words in sentences (McGarr, 1981), rating scales (Nikolopoulos, Archbold, & Gregory, 2005) or calculating the total words correctly identified (Chin et al., 2003; McGarr, 1981; Tobey et al., 2000).

Moreover, studies of children in multiple languages have found that speech intelligibility improves post implantation, suggesting the electrical signal provided by the CIs promotes the development of fundamental speech production actions and their associated feedback consequences (Dawson et al., 1995; Law & So, 2006; Mondain et al., 1997; Nikolopoulos et al., 2005; Peng, Weiss, Cheung, & Lin, 2004; Uziel et al., 2007; Vieu et al., 1998). Changes in speech intelligibility post implantation are fueled by the interactions of these feedback-driven changes on speech gestures and the scaffolding supplied by new auditory-linked opportunities to interface with complex and rich linguistic environments. Inherent in the global speech intelligibility improvements are changes to discrete elements of the spoken message including increased accuracy of consonant and vowel production (Chin, 2003; Chin, 2007; Law & So, 2006; Peng et al., 2004; Serry, Blamey, & Grogan, 1997; Serry & Blamey, 1999; Tobey, Geers, Brenner, Altuna, & Gabbert, 2003; Tomblin, Peng, Spencer, & Lu, 2008), reductions in overall durations of sentences to more nearly normal values (Tobey et al., 2003; Uchanski & Geers, 2003), and use of more nearly normal suprasegmental aspects of speech (Uchanski & Geers, 2003). CI children with poorer levels of speech intelligibility demonstrate greater numbers of substitutions of one sound for another, omissions of sounds in all word positions, and longer sentences composed of elongated syllables and pauses.

Evaluating the rate of speech intelligibility improvement post implantation is often confounded by the interaction of factors related to the age of onset of deafness, the length of deafness, the age of implantation, the amount of residual hearing, and the "hearing" age of child. Newborn hearing screening programs strive to identify and provide intervention early within a child's first years. Short periods of deafness and early implantation are associated with higher speech intelligibility for children implanted within the first few years of life (Chin, Finnegan, & Chung, 2001; Serry & Blamey, 1999; Tobey et al., 2000; Uchanski & Geers, 2003). Speech intelligibility is positively related to residual hearing: higher levels of speech intelligibility are evident in children with greater levels of residual hearing (Smith, 1975; Tobey et al., 2000). Yet, rate of change in speech intelligibility following cochlear implantation is not as steep as the rate of change in speech intelligibility observed in typical hearing children (Chin et al., 2003). Several investigators suggest using a "hearing" age rather than chronological age to tease apart the effects of age of implantation from chronological age effects (Tomblin et al., 2008; Warner-Czyz, Davis, & MacNeilage, 2010). Several studies suggest the greatest growth in speech production occurs within the first six years of use and plateaus of performance are associated with hearing ages of around 8 years in pediatric CI users (Blamey et al., 2001; Blamey, Barry, & Jacq, 2001; Tomblin et al., 2008).

The data reported here address a number of factors associated with how well children with profound SNHL who received CIs within the early FDA approval time period use spoken communication. This report focuses on spoken communication measured at early elementary and high school ages in one of the first, large groups of children to receive CIs after their FDA approval. We focus our attention on their abilities, as teenagers, to be understood by unfamiliar listeners in quiet and noisy situations and to produce sounds correctly as judged by trained listeners. We examine these measures in relation to other critical factors thought to influence levels of spoken communication performance. These factors include student characteristics such as duration of deafness, nonverbal performance intelligence quotient (PIQ), their families' socioeconomic status, family size, and gender. We also take into account their abilities to hear with the CI via their averaged threshold responses, their auditory memory, and how their communication is enhanced by the addition of visually-based signed communication. We extend previous investigations not only by examining a large population with over 10 years experience with CIs but we also evaluate the usefulness of an additional method of measuring speech intelligibility in adolescents. We anticipated high levels of speech intelligibility in the adolescents; therefore, we elected to measure their intelligibility first by using our previous techniques of presenting their spoken sentences in quiet to unfamiliar listeners and then by digitally embedding the sentences in a multispeaker babble background. Multispeaker backgrounds simulate situations where a teenage speaker must convey a message in a noisy situation such as a restaurant, sporting or social event. The multispeaker babble was added "off-line"; thus, allowing us to evaluate the speech without "on-line" adjustments by individual speakers to their rate, intensity, and clarity. Previous studies indicate speech intelligibility is reduced under these conditions but the extent to which it is reduced remains unclear as are the factors related to this reductions (Gould et al., 2001; Tobey, Shin, Geers, & Sundarrajan, 2010).

METHODS AND MATERIALS

Participants

One hundred and ten adolescent users of cochlear implants (CI-HS) who participated in an earlier study conducted when the children were 8 and 9 years of age (CI-E test session) comprise the follow-up sample (Tobey et al., 2000; Tobey et al., 2003). A detailed description of the CI-HS teenagers is contained in this supplement (Geers, Brenner, & Tobey, 2010). The average age of the CI-HS participants was 16.7 years with a range of 15.0 to 18.5 years. Fifty-nine members of the CI-HS sample were female. Mean length of deafness of the CI-E participants was 3.1 years (standard deviation (SD) 1.16 years) with a range between 4 months and 5.4 years. Average experience with the cochlear implant at the CI-HS session was 13.3 years with a range of 10.8 years to 15.7 years. The average family size at CI-E and CI-HS testing was 4.2 and 4.0 members, respectively. Socioeconomic status remained comparable for the participants across the two test sessions. All participants and their families signed consent and assent forms approved by the Institutional Review Board of the University of Texas at Dallas.

Average nonverbal performance intelligence quotient measured by the Wechsler Intelligence Scale for Children-Performance Scale (WISC) (Wechsler, 1991) was 103.2 (SD 14) during the CI-E and 103.1 (SD 15.97) during the CI-HS test session. Speech perception for the teenagers averaged 50.3% and 58.1% on the Lexical Neighborhood Test (LNT) (Kirk, Hay-McCutcheon, Sehgal, & Miyamoto, 2000) when tested at 70 dB SPL in elementary school and high school, respectively. Average scores on the Bamford Kowal Bench (BKB) sentences (Bamford & Wilson, 1979) were 63.2% at CI-E and 80.5% at CI-HS for presentations delivered at 70dBHL. Seventy-three percent of the CI-HS adolescents report using oral methods of communicating (OC) in their environment and 27% of the teens report also incorporating signs into their communication (SC).

Speech Production Measures

Speech Intelligibility at CI-E and CI-HS—DAT and audio recordings were made of thirty-six sentences composed of three-, five-, and seven syllable sentences (McGarr, 1981). Each sentence contained a key word selected from a pool of words that predicted speech intelligibility in deaf children. The eighteen words that ranked the lowest in intelligibility occurred in sentences designated as “low” context and the eighteen words that ranked the highest occurred in sentences designated as “high” context. Participants were shown a card with the sentences written out, prompted with a verbal or sign elicitation of the sentence and encouraged to repeat the sentence orally. The microphone was placed a foot in front of the participants’ mouths. Recorded stimuli were edited under computer control to form individual files and to calculate the overall duration of the sentences. In addition, the individual sentences produced by the CI-HS participants were embedded in multispeaker babble (MSB) produced by a male and female speaker reading passages (Tobey et al., 2010). Duration of the babble varied across the samples in order to present three seconds of babble before the target sentence and two seconds of babble after the sentence. A brief .2 sec 1k Hz tone was presented prior to the sentence. Measures derived without the background babble are referred to as quiet (Q). Samples were collected during both CI-E and CI-HS test sessions.

Judgments of the stimuli were acquired from normal hearing adults who were allowed to hear a sentence and any given child speaking once. Judges were instructed to write down as much of the sentence as they understood. Three judges provided responses to each sentence rendering a total of 108 judgments contributing to the score. Judges were recruited from the student population of the University of Texas at Dallas and members of the Dallas community. All judges signed consent forms approved by the Institutional Review Board of the University of Texas at Dallas. The total number of key words was calculated (36 key words × 3 judges) and served as the dependent variables.

Duration Measures at CI-E and CI-HS—Stimuli were initially analyzed using a waveform display to identify the initial and final zero crossings associated with the sentences. Dependent variables used in the analyses of this report were the average durations of the 12, 7-syllable sentences from the high and low context sentences.

Consonant Accuracy at CI-E and CI-HS—Speech language pathologists transcribed the speech intelligibility sentences following procedures previously reported (Serry & Blamey, 1999; Shriberg & Lof, 1991; Tobey et al., 2003). Comparisons of the phonemic transcriptions produced a phoneme accuracy score derived in a software program, CASALA (Computerized Aided Speech and Language Analysis) (Blamey et al., 2001). Dependent variables of consonant correct were generated from reports using a percent correct consonant-revised (PCC-R) criterion (Campbell, Dollaghan, Janosky, & Adelson, 2007). Substitutions and omissions were counted as errors and allophonic variations or distortions were counted as correct. A similar measure was adopted for vowels correct (a percent vowel correct-revised) reflecting allophonic variations as correct. Periodic calibration of transcribers occurred to reduce transcriber “drift.”

Use of Speech Questionnaire at CI-E—Parents of CI-E participants completed a “use of speech” questionnaire during the elementary school test session (Tobey et al., 2003). Parents indicated on a 5-point scale (ranging from completely understood to never understood) how well their child was understood by familiar and unfamiliar listeners. A speech usage score was acquired by averaging the item scores.

Measures of Sign Enhancement

Test results at CI-E and CI-HS were used to create metrics reflecting the extent to which a student's language improved when sign language was added to spoken language (i.e., sign enhancement). A complete description of these metrics are contained in this volume (Geers et al., 2010), **Language Samples—CI-E:** An estimate of sign enhancement for the CI-E group was derived from two spontaneous language samples obtained at age 8 or 9 (Geers, Nicholas, & Sedey, 2003). Each child was videotaped in two different semi-structured interviews with an unfamiliar female adult. One interview was conducted in an OC-only mode and the other interview was conducted in SC. Word-for-word transcriptions were created using the CHAT format developed by the CHILDES (MacWhinney, 2010). Four dependent variables were calculated. *Number of words per utterance* served as a measure of utterance length. *Number of words per minute* served as a measure of lexical diversity. *The Index of Productive Syntax (IPSyn): Noun Phrases* and *Sentence Complexity* scores served as measures of syntactic complexity. Sign enhancement was estimated by determining the ratio of each of these language scores obtained in the OC interview to those obtained the SC interview. The average value is referred to as the "CI-E Sign Enhancement Ratio". Sign enhancement ratios below 1.0 indicate better performance on language outcome measures in the SC as compared to the OC interviews. Ratios close to or above 1.0 indicate that better language occurred in the OC interview or there were no differences in language use across the two conditions.

Peabody Picture Vocabulary Test-III (PPVT)

(Dunn & Dunn, 1997) Difference Score—CI-HS—The PPVT, was used to assess one-word receptive vocabulary at the CI-HS session. Examiners provided a label and the student selected the picture designating the label. Form IIIA was administered using standard administration of spoken stimulus words (OC administration). Form IIIB was administered using sign or finger spelling to accompany the spoken word (SC administration). Dependent variables were standard scores based on a normative sample of typically-developing children (NS-TD). The standard scores from the PPVT administered with SC were subtracted from the standard scores from the PPVT administered with OC to form the Adolescent Sign Enhancement variable.

Working Memory

Digit Span Measure—Short-term information processing/storage capacity was measured with the digit span subtest of the WISC-III at both the CI-E and CI-HS sessions (Pisoni & Cleary, 2003). Administration followed established guidelines for the WISC III test procedures (Wechsler, 1991). The task requires students to repeat lists of digits spoken by an experimenter at a rate of approximately one digit per second. The face of the clinician was visible to the student. The lists began with two digits and increased in length until a student was unable to correctly repeat two lists of a given length. Both forward and backward spans were obtained. A detailed description of these variables is contained within this volume (Pisoni, Kronenberger, Roman, & Geers, 2010). Dependent variables were the longest series correctly repeated forward at least once, the total raw score for digits forward, the WISC Scaled Score relative to the normative sample, and total raw score for digits repeated forward and backward.

Speech Perception

Video Game Test of Speech Pattern Contrast Perception (VIDSPAC) (Boothroyd, 1997)—CI-E—This test provides a non-linguistic measure of a child's ability to discriminate specific phoneme contrasts. The test requires a participant to detect a feature contrast change in two syllables. One of the syllables serves as a standard stimulus that forms a repeating background. The participants respond by pressing a key when the different stimulus occurs. The VIDSPAC stimuli consisted of two vowel contrasts, tee/too and tee/taa; two place contrasts, daa/gaa and saa/shaa; two voicing contrasts, daa/taa and saa/zaa and two manner contrasts, daa/zaa and saa/taa. VIDSPAC scores were adjusted for random responding and the following corrected scores constituted the dependent variable: a) total contrasts (i.e., consonants and vowels) correctly detected, b) consonant contrasts correctly detected, c) vowel contrasts correctly detected, and 4) consonant manner contrasts correctly detected.

Aided Threshold Average—CI-HS—Aided sound-field detection thresholds were obtained using frequency modulated tones at octave frequencies from 250-4,000 Hz . A detailed description of the methods is contained in this monograph (Davidson, Geers, Blamey, & Tobey, 2010).

RESULTS

Table 1 describes the mean, SDs and range of performance associated with each of the dependent variables as a function of test session (CI-E versus CI-HS) and gender. Speech intelligibility in quiet at both CI-E and CI-HS test conditions revealed higher performance for key words in high context than low context sentences for both genders [F(1,214)=14.35, p<.0001]. The high context advantage disappeared during the MSB conditions at CI-HS with equivalent intelligibility scores between high and low contexts evident. Higher performance was evident for female participants for each intelligibility measure obtained at each time period [F (1,214) =7.09, p<.008]. Consonant correct performance was significantly higher at the CI-HS than the CI-E time period [F (1,214)=122.12, p<.0000]. Sign enhancement at CI-E indicated ratios from .8 to .96 for the language samples while Adolescent Sign Enhancement was 3.7 and 3.1 for females and males, respectively. Parents reported similar ratings of speech use for both genders at the CI-E session. VIDSPAC scores were higher for females relative to males for all CI-E values except vowels. As reported in detail elsewhere in this monograph (Davidson et al., 2010), average performance on the LNT and BKB sentences presented at 70 dB SPL was higher at the CI-HS session than the CI-E session. The average aided threshold was 30.4 with a SD of 9.6. Duration of the intelligibility sentences was significantly reduced at the CI-HS session relative to the CI-E session for both the total durations and the duration of the 7-syllable items [F (1,214)=100.63, p<.0000]. Forward digit span increased two items on average for the participants in the CI-HS session and a detailed description is contained in this volume (Pisoni et al., 2010).

Table 2 provides the intercorrelation matrices summarizing five sets of measures. The high correlation coefficients associated with each set of measurements suggested the measurements could be reduced to single standardized variables using principal component analyses (PCA). In the first set of speech production measures acquired at the CI-E test period, we examined how normal hearing listeners judged the accuracy of high and low context words in the sentences, consonant accuracy, and parental consideration of how their child used speech. As indicated by the values in Table 3, all coefficients were highly significant suggesting these variables could be reduced to a single variable, "Early Speech Production" using PCA. We also examined how the accuracy of consonant production and judgments of normal hearing listeners for the high and low context words in the McGarr sentences under optimal, quiet conditions and in degraded listening conditions with multispeaker babble were related at the CI-HS test session. The highly significant coefficients suggested these variables could be reduced to a single variable, “Adolescent Speech Production” using PCA. Four measures representing the ratio of OC to SC performance (words per utterance, different words per minute, noun phrases and sentence structure scores) at the CI-E session also were highly related and were reduced to a single variable, “ Early Sign Enhancement.” The four measures acquired on the VIDSPAC at the CI-E test session (total, vowel, consonant and manner contrasts) were highly related and reduced to a single variable, “Early Speech Perception.” CI-E performance on memory measures (raw score for forward span, total scaled score, longest forward digit span and raw score for forward and backward spans) also were highly related and reduced to a single component, “Early Working Memory.” A single component “Adolescent Working Memory” was obtained from the highly related measures associated with the same digit measures collected at the CI-HS test session.

The Adolescent Speech Production variable was evaluated using multiple regression analyses with variables associated with the characteristics of the participants and their families as predictor variables. These variables included two measures which remained constant across the two test sessions, duration of deafness and gender, as well as three variables which may change across the CI-E and CI-HS test sessions, nonverbal PIQ, family size, and socioeconomic status. In addition, we considered the impact of three additional measures acquired at the CI-HS test session. These measures included the average aided thresholds, the Adolescent Sign Enhancement variable, and the average duration taken to produce the 7-syllable sentences of the sentences at each test session.

Is Adolescent Speech Production related to participant, family and performance measures observed during the elementary school age?

Ten variables were used as predictors of the Adolescent Speech Production variable. These variables included duration of deafness, gender, nonverbal PIQ, family size, socioeconomic status, Early Sign Enhancement, Early Speech Perception, Early Working Memory, Early Speech Production and the duration of producing 7-syllable sentences. First, we evaluated duration of deafness, gender, nonverbal PIQ, family size and socioeconomic status. As shown in Table 4, these variables accounted for nearly 13% of the variance associated with the Adolescent Speech Production component. Two variables, family size and socioeconomic status, provided significant independent contributions to the Adolescent Speech Production variance. We next added to these variables the values associated with the PCA generated variables of Early Working Memory, Early Sign Enhancement, and Early Speech Perception. These variables, in combination, accounted for nearly 56% of the variance in the Adolescent Speech Production scores. Addition of these variables eliminated the independent contribution of family size and socioeconomic status; however, gender, the Early Sign Enhancement and Early Speech Perception components became significant independent contributors to the Adolescent Speech Production variance. Finally, we added in the contributions of duration of producing 7-syllable sentences and the Early Speech Production variable. The cumulative effect of all the variables accounted for 66% of the variance in the Adolescent Speech Production. Once all the variables were included, two components, Early Sign Enhancement and Early Speech Production, made robust independent contributions to the Adolescent Speech Production component. Data indicated higher levels of Adolescent Speech Production were associated with smaller families, higher socioeconomic status, and females at the early elementary, CI-E test session. Once these variables are accounted for, Adolescent Speech Production was strongly related to Early Speech Production and Early Speech Perception proficiencies. Children with the lowest

Adolescent Speech Production scores demonstrated a greater reliance on sign enhancement at the CI-E session.

Is Adolescent Speech Production predicted by participant, family and performance measures obtained at the adolescent test session?

Nine variables obtained at the CI-HS session were considered as predictors for the Adolescent Speech Production component (see Table 5). These variables included the non-changing variables from CI-E to CI-HS testing of duration of deafness and gender, the child and family measures of PIQ, family size, socioeconomic status acquired during the CI-HS test session and the measures of aided thresholds, Adolescent Sign Enhancement), the Adolescent Working Memory Component, and duration of the 7-syllable sentences at CI-HS. In comparable analyses to those described in the above paragraph, we first evaluated the influence of the child and family variables, duration of deafness, gender and CI-HS measures of PIQ, family size and socioeconomic status. These variables accounted for 6.9% of the variance in the Adolescent Speech Production component. In this initial consideration, gender served as an independent contributor to the Adolescent Speech Production component. In the second pass, we evaluated the child and family variables in combination with the average aided thresholds, the Adolescent Sign Enhancement variable and the Adolescent Working Memory component. These variables accounted for an additional 30.4% of the variance observed in the Adolescent Speech Production components. The analysis revealed independent contributions to the variance were evident in the gender and Adolescent Sign Enhancement variables. Finally, we included the child, family, average aided thresholds, and Adolescent Working Memory variables with duration of the 7-syllable sentences acquired in the CI-HS session. Inclusion of the 7-syllable duration variable further accounted for 11.7% of the variance with three variables, gender, Adolescent Sign Enhancement and sentence duration at CI-HS, independently contributing to the variance. Nearly 50% of the Adolescent Speech Production component is accounted for overall by these variables. During adolescence, speech production is more accurate in females and teenagers who produce sentences at faster durations. Children who rely less on sign for their receptive vocabulary also demonstrate higher Adolescent Speech Production performance.

Is Adolescent Speech Production predicted by participant, family and performance measures obtained at both the elementary age and adolescent test sessions?

In order to evaluate how the CI-HS variables accounted for variance over and beyond that accounted for by the CI-E variables, we examined eight child and family variables acquired at both test sessions in conjunction with average aided thresholds, Adolescent Sign Enhancement, Adolescent Working Memory and duration of 7-syllable sentences acquired during the CI-HS session. As shown in Table 6, duration of deafness and gender in combination with PIQ, family size and socioeconomic status at the CI-E test session accounted for 12.5% of the Adolescent Speech Production variance. Family size and socioeconomic status at the CI-E session provided independent contributions to the variance. Evaluation of these variables in conjunction with comparable measures at CI-HS of PIQ, family size and socioeconomic status revealed an additional 5.9% of the variance of Adolescent Speech Production component was accounted for. Family size measured at both CI-E and CI-HS remained an independent contributor to the variance of Adolescent Speech Production. Socioeconomic status at CI-E remained an independent contributor to the overall variance; however, socioeconomic status at CI-HS did not independently contribute to the variance in Adolescent Speech Production. Consideration of the child and family variables with measures acquired at CI-HS of average aided thresholds, Adolescent Sign Enhancement, and Adolescent Working Memory accounted for an additional 21% of the variance associated with the Adolescent Speech Production. There is a tendency for family size and gender to remain important contributors to variance. However, once child and family variables measured at the two times are accounted for, only average aided thresholds and the Adolescence Sign Enhancement variables provided independent contributions to the variance. In the final step, we included the child and family variables, aided thresholds, Adolescent Sign Enhancement, Adolescent Working Memory, and the 7-syllable CI-HS duration of the sentences. Inclusion of the sentence duration variable accounted for an additional 10.3% of the total variance. Gender and family size at the CI-HS test session tended to move towards independent contributions to the variance but failed to reach significance. Strong independent contributions to the overall variance were made by the Adolescent Sign Enhancement and 7-syllable CI-HS duration variables.

The model incorporating the child and family variables from both test sessions accounted for nearly 18% of the overall variance. Adolescent Speech Production was higher for participants from smaller families and higher socioeconomic status but these variables were no longer significant once aided thresholds and Adolescent Sign enhancement were introduced into the model. Higher aided thresholds and greater Adolescent Sign Enhancement were associated with less accurate Adolescent Speech Production. There was a tendency for females to achieve more accurate levels of performance relative to males. Adolescent Working Memory and 7-syllable durations reduced the influence of aided thresholds. Higher Adolescent Speech Production was evident in teenagers who displayed little difference in their OC and SC receptive vocabulary scores and who produced 7-syllable sentences with short durations.

DISCUSSION

Continued experience with a CI into adolescence results in substantial improvements in several speech production measures. Consonant production improved from an average of 71% correct during the CI-E test session to 93.8% correct during the CI-HS session—nearly a 22% improvement. Increased consonant accuracy was accompanied by roughly 22% increases in the accuracy of unfamiliar listeners in identifying keywords contained in high and low context sentences. Variability in performance for speech intelligibility measures decreased by nearly 10% in the CI-HS test session. Contextual effects remained evident in the CI-HS values with higher accuracy associated with keywords contained in high context sentences. Differences in accuracy were reduced relative to the effects observed during the elementary school test session suggesting sentential context played less of a role during adolescence than when the children were younger. These high levels of speech production performance are remarkably striking when compared to previous reports of speech intelligibility in children with profound SNHL using conventional hearing aids averaging 17 to 21% (Monsen, 1981; Smith, 1975). Improvements in consonant accuracy with increased auditory experience with a CI also are in agreement with several previous reports examining smaller sets of participants' speech production after implantation (Blamey et al., 2001; Blamey et al., 2001; Chin, 2003; Chin, 2007; Mondain et al., 1997; Peng et al., 2004; Serry et al., 1997; Serry & Blamey, 1999; Tomblin et al., 2008; Uziel et al., 2007; Vieu et al., 1998; Warner-Czyz et al., 2010).

In an attempt to model normal speaking conditions where a speaker must convey their message in environments with competing talkers such as in an active classroom discussion or a restaurant, we also evaluated the speech intelligibility of the teenagers by embedding their McGarr sentences in a multispeaker background babble condition. This condition allowed us to assess the impact of multispeaker babble while also controlling for any "on-line" adjustments to rate, intensity, and clarity. Speech intelligibility for keywords in multispeaker babble conditions was reduced by approximately 20%--a finding resembling previous reports (Tobey et al., 2010). Moreover, equivalent intelligibility was observed for keywords in high and low context sentences. Thus, any advantage sentential context played under normal, quiet listening conditions was eliminated when listeners were forced to understand spoken communications under less desirable situations. On the surface, this observation is perplexing given the nearly 100% consonant correct scores associated with the CI-HS productions. Closer examination, however, suggests several reasons for this observation. First, the multispeaker babble condition intentionally does not assess how the speakers adjust their articulation and speech “on-line” when speaking in a noisy background. Controlling for this aspect of adjustment allows us to obtain a “baseline” measure of intelligibility under quiet and less ideal listening conditions. Second, in order to make consonant correct comparisons across the two test sessions, we used a PCC-R measure which counted substitutions and omissions as errors but counted distortions or allophones as correct. We initially chose this measure to use for the CI-E data because it appeared to adequately capture the types of errors (substitutions versus omissions) and emerging consonants of the young CI population. The PCC-R averages observed in this study are similar to the 88 – 91% values reported for CI pediatric users with 8 – 10 years of device experience using similar broad transcription techniques. Narrow transcriptions used to evaluate phonetic inventories suggest phonetic development slows between the 5th and 6th years post implant (Blamey et al., 2001). Such limitations may signal constraints on the underlying responsiveness of the nervous system as children grow and move through the sensitive periods associated with spoken communication. The consequences of using PCC-R in evaluating the CI-HS productions are evident in the multispeaker babble. In less ideal listening conditions, allophones or distortions which failed to adversely influence a listener’s ability to understand the teenagers in quiet situations appear to come into play and reduce intelligibility of keywords to an extent that any additional information conveyed by the sentence context is neutralized. Thus, equivalent intelligibility is observed for keywords in high and low contextual sentences. Further evaluation will be needed to determine how a speaker adjusts their speech “on-line” to multispeaker babble conditions and if equivalent intelligibility continues in high and low context sentences.

Close examination of the factors influencing the high levels of performance associated with the Adolescent Speech Production measures reveal several interesting observations. First, we evaluated how characteristics observed during the elementary school ages associated with the child and family, Early Sign Enhancement, Early Speech Perception, Early Working Memory, Early Speech Production and duration of 7-syllable sentences predicted the adolescent speech production. More accurate speech production in adolescence was associated with female speakers, teenagers who demonstrated higher levels of speech production accuracy during elementary school ages, and teenagers who demonstrated high levels of performance on the VIDSPAC measures at the CI-E session. Once Early Working Memory also was taken into account, Adolescent Speech Production was most strongly predicted by the Early Sign Enhancement and Early Speech Production variables. Higher Adolescent Speech Production performance was associated with teenagers who displayed higher performance during OC than SC language sampling in elementary school. These data suggest early exposure and reliance on listening and speaking continues to impact speech production accuracy in adolescence.

Adolescent Speech Production also was influenced by several factors observed in the CI-HS session. Higher consonant accuracy and speech intelligibility in quiet and multispeaker babble was associated with female rather than male speakers. Higher Adolescent Speech Production also was associated with teenagers whose one-word receptive vocabularies were equivalent or higher in OC relative to SC administrations. Consonant accuracy and the ability of unfamiliar listeners to understand keywords was higher for teenagers who also produced sentences in shorter periods of time. When all the variables associated with the CI-E and CI-HS analyses were combined, family size and gender remain important contributors to Adolescent Speech Production performance. Teenagers from smaller families demonstrated higher speech production skills. Although socioeconomic status is commonly reported as an influential variable (including in the initial report of the current study population at elementary school ages (Tobey et al., 2003)), its influence is diminished once similar variables acquired at adolescence were taken into account. Higher average aided thresholds were associated with lower Adolescent Speech Production but its importance diminishes as Adolescent Working Memory and abilities to produce more nearly normal length 7-syllable sentences come into play.

Adolescents whose communication relies more on OC than SC demonstrate higher speech production skills at elementary and high school ages. As discussed in this volume (Geers et al., 2010), we created a PC variable reflecting the OC to SC ratios of performance on words and syntax used in language samples collected during the CI-E test session. Early Sign Enhancement suggested teenagers with higher levels of speech intelligibility also were children whose ratios approached one or higher during the elementary test session. Support for the importance of early experiences incorporating speaking and listening are found in the Adolescent Sign Enhancement measures. When all other child, family, and perception measures were accounted for, Adolescent Sign Enhancement accounted for nearly 10% of the variance in production performance observed at adolescence. These two findings underscore the continuing importance of early experiences and their impact on later speech production performance.

Overall, data from this study indicate speech intelligibility continued to improve from elementary through the high school years, although the study is limited to assessing speech intelligibility at only two test sessions. Such a limitation restricts our ability to estimate at what ages the high levels of intelligibility are acquired and whether or not they are representative of a “plateau.” High levels of speech intelligibility are reduced under demanding listening situations when multiple speakers are in the background. Reductions in overall speech intelligibility in the presence of competing signals suggest the high levels of consonant accuracy determined by trained listeners in quiet conditions may be constrained by underestimating distortions, allophonic variations and the possible use of speech sounds in nonambient languages through the use of a PCC-R measure. Several previous reports detail instances where the speech of CI children is regarded as highly intelligible but also perceived as displaying a foreign accent (Gulati, 2003; Teoh & Chin, 2009). As Toeh and Chin recently noted, “small subtle speech errors are the most challenging to address in therapy” (p. 389, Teoh & Chin, 2009). These small, subtle errors also are evident in the temporal characteristics of sentences produced by CI speakers. Sentences with more nearly normal temporal relationships are judged more intelligible. Collectively, these observations reinforce the importance of balancing narrow and broad transcription techniques for monitoring speech production acquisition. High correlations between the responses acquired on a questionnaire asking parents how other listeners understand their child’s speech and accuracy of consonant production and speech intelligibility measured with keyword accuracy suggests parent ratings of their child’s speech intelligibility might be useful for monitoring speech production acquisition in the early stages following cochlear implantation, in a manner similar to the commonly used Minimal Auditory Integration Scale (Osberger, Geier, Zimmerman-Phillips, & Barker, 1997). Speech intelligibility appears strongly associated with exposure to environments where speaking and listening are included as integral pieces of the therapeutic regime.

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References

Bamford, J.; Wilson, I. Methodological considerations and practical aspects of the BKB sentence lists. In: Bench, J.; Bamford, JM., editors. Speech-Hearing Tests and the Spoken Language of Hearing Impaired Children. Academy Press; London: 1979.

Blamey PJ, Barry J, Bow C, Sarant J, Paatsch L, Wales R. The development of speech production following cochlear implantation. Clinical Linguistics and Phonetics. 2001; 15:363–382.

Blamey PJ, Barry JG, Jacq P. Phonetic inventory development in young cochlear implant users 6 years postoperation. J.Speech Lang Hear.Res. 2001; 44:73–79. [PubMed: 11218111]

Boothroyd, A. Video game test of speech pattern contrast perception. Graduate Center, City University of New York; New York: 1997.

Campbell TF, Dollaghan C, Janosky JE, Adelson PD. A performance curve for assessing change in Percentage of Consonants Correct Revised (PCC-R). J.Speech Lang Hear.Res. 2007; 50:1110–1119. [PubMed: 17675608]

Chin SB. Children's consonant inventories after extended cochlear implant use. J.Speech Lang Hear.Res. 2003; 46:849–862. [PubMed: 12959464]

Chin SB. Variation in consonant cluster production by pediatric cochlear implant users. Ear Hear. 2007; 28:7S–10S. [PubMed: 17496637]

Chin SB, Finnegan KR, Chung BA. Relationships among types of speech intelligibility in pediatric users of cochlear implants. J.Commun.Disord. 2001; 34:187–205. [PubMed: 11409603]

Chin SB, Tsai PL, Gao S. Connected speech intelligibility of children with cochlear implants and children with normal hearing. Am.J.Speech Lang Pathol. 2003; 12:440–451. [PubMed: 14658996]

Clark G. Cochlear implants in children: safety as well as speech and language. Int.J.Pediatr.Otorhinolaryngol. 2003; 67(Suppl 1):S7–20. [PubMed: 14662167]

Davidson L, Geers A, Blamey P, Tobey E. Factors contributing to speech perception scores in long-term pediatric CI users. Ear Hear. (in press).

Dawson PW, Blamey PJ, Dettman SJ, Rowland LC, Barker EJ, Tobey EA, et al. A clinical report on speech production of cochlear implant users. Ear Hear. 1995; 16:551–561. [PubMed: 8747805]

Dunn, LM.; Dunn, LM. The Peabody Picture Vocabulary Test. 3 ed. American Guidance Services; Circle Pines, MN: 1997.

Geers A, Brenner C. Background and educational characteristics of prelingually deaf children implanted by five years of age. Ear Hear. 2003; 24:2S–14S. [PubMed: 12612476]

Geers A, Brenner C, Tobey E. Long-term outcomes of cochlear implantation in early childhood: Sample characteristics and data collection methods. Ear Hear. 2010

Geers AE, Nicholas JG, Sedey AL. Language skills of children with early cochlear implantation. Ear Hear. 2003; 24:46S–58S. [PubMed: 12612480]

Gould J, Lane H, Vick J, Perkell JS, Matthies ML, Zandipour M. Changes in speech intelligibility of postlingually deaf adults after cochlear implantation. Ear Hear. 2001; 22:453–460. [PubMed: 11770668]

Gulati, S. Mental health care of deaf people: A culturally affirmative approach. Erlbaum; Mahwah, N.J.: 2003. Psychiatric care of culturally deaf people; p. 33-107.

Kent RD, Weismer G, Kent JF, Rosenbek JC. Toward phonetic intelligibility testing in dysarthria. J.Speech Hear.Disord. 1989; 54:482–499. [PubMed: 2811329]

Kirk KI, Hay-McCutcheon M, Sehgal ST, Miyamoto RT. Speech perception in children with cochlear implants: effects of lexical difficulty, talker variability, and word length. Ann.Otol.Rhinol.Laryngol.Suppl. 2000; 185:79–81. [PubMed: 11141016]

Law ZW, So LK. Phonological abilities of hearing-impaired Cantonese-speaking children with cochlear implants or hearing AIDS. J.Speech Lang Hear.Res. 2006; 49:1342–1353. [PubMed: 17197500]

MacWhinney, B. The CHILDES project. Erlbaum; Mahwah, N.J.: 2010.

McGarr NS. The effect of context on the intelligibility of hearing and deaf children's speech. Lang Speech. 1981; 24:255–264. [PubMed: 7329194]

Mondain M, Sillon M, Vieu A, Lanvin M, Reuillard-Artieres F, Tobey E, et al. Speech perception skills and speech production intelligibility in French children with prelingual deafness and cochlear implants. Arch.Otolaryngol.Head Neck Surg. 1997; 123:181–184. [PubMed: 9046286]

Monsen RB. A usable test for the speech intelligibility of deaf talkers. Am.Ann.Deaf. 1981; 126:845–852. [PubMed: 7304383]

Nikolopoulos TP, Archbold SM, Gregory S. Young deaf children with hearing aids or cochlear implants: early assessment package for monitoring progress. Int.J.Pediatr.Otorhinolaryngol. 2005; 69:175–186. [PubMed: 15656950]

Osberger MJ, Geier L, Zimmerman-Phillips S, Barker MJ. Use of a parent-report scale to assess benefit in children given the Clarion cochlear implant. Am.J.Otol. 1997; 18:S79–S80. [PubMed: 9391608]

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

Peng SC, Weiss AL, Cheung H, Lin YS. Consonant production and language skills in Mandarin-speaking children with cochlear implants. Arch.Otolaryngol.Head Neck Surg. 2004; 130:592–597. [PubMed: 15148182]

Pisoni DB, Cleary M. Measures of working memory span and verbal rehearsal speed in deaf children after cochlear implantation. Ear Hear. 2003; 24:106S–120S. [PubMed: 12612485]

Pisoni DB, Kronenberger W, Roman A, Geers A. Measures in digit span and verbal rehearsal speed in deaf children following more than 10 years of cochlear implant use. Ear Hear. 2010

Serry T, Blamey P, Grogan M. Phoneme acquisition in the first 4 years of implant use. Am.J.Otol. 1997; 18:S122–S124. [PubMed: 9391628]

Serry TA, Blamey PJ. A 4-year investigation into phonetic inventory development in young cochlear implant users. J.Speech Lang Hear.Res. 1999; 42:141–154. [PubMed: 10025550]

Shriberg LD, Lof G. Reliability studies in broad and narrow phonetic transcription. Clinical Linguistics and Phonetics. 1991; 5:225–279.

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

Teoh AP, Chin SB. Transcribing the speech of children with cochlear implants: clinical application of narrow phonetic transcriptions. Am.J.Speech Lang Pathol. 2009; 18:388–401. [PubMed: 19880945]

Tobey E, Shin S, Geers A, Sundarrajan M. Spoken word recognition in adolescent cochlear implant users during quiet and multispeaker babble conditions. Otol.Neurotol. (in press).

Tobey EA, Geers AE. Speech production benefits of cochlear implants. Adv.Otorhinolaryngol. 1995; 50:146–153. [PubMed: 7610952]

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

Tobey EA, Geers AE, Douek BM, Perrin J, Skellet R, Brenner C, et al. Factors associated with speech intelligibility in children with cochlear implants. Ann.Otol.Rhinol.Laryngol.Suppl. 2000; 185:28–30. [PubMed: 11140993]

Tomblin JB, Peng SC, Spencer LJ, Lu N. Long-term trajectories of the development of speech sound production in pediatric cochlear implant recipients. J.Speech Lang Hear.Res. 2008; 51:1353–1368. [PubMed: 18695018]

Uchanski RM, Geers AE. Acoustic characteristics of the speech of young cochlear implant users: a comparison with normal-hearing age-mates. Ear Hear. 2003; 24:90S–105S. [PubMed: 12612484]

Uziel AS, Sillon M, Vieu A, Artieres F, Piron JP, Daures JP, et al. Ten-year follow-up of a consecutive series of children with multichannel cochlear implants. Otol.Neurotol. 2007; 28:615–628. [PubMed: 17667770]

Vieu A, Mondain M, Blanchard K, Sillon M, Reuillard-Artieres F, Tobey E, et al. Influence of communication mode on speech intelligibility and syntactic structure of sentences in profoundly hearing impaired French children implanted between 5 and 9 years of age. Int.J.Pediatr.Otorhinolaryngol. 1998; 44:15–22. [PubMed: 9720675]

Warner-Czyz AD, Davis BL, MacNeilage PF. Accuracy of consonant-vowel syllables in young cochlear implant recipients and hearing children in the single-word period. J.Speech Lang Hear.Res. 2010; 53:2–17. [PubMed: 20150404]

Wechsler, D. Wechsler intelligence scale for children. 3 ed. Psychological Corporation Harcourt Brace; San Antonio: 1991.

Table 1

Means, standard deviations (SD) and range values are shown for performance of the participants at CI-E and CI-HS test sessions as a function of gender

	Group	Gender	Mean	SD	Minimum	Maximum
Speech Intelligibility--Quiet						
High context sentences	CI-E	Female	78.8	27.5	0.0	100.0
		Male	71.9	26.8	0.0	100.0
	CI-HS	Female	87.9	16.5	25.8	100.0
		Male	84.2	18.9	1.2	98.0
Low context sentences	CI-E	Female	66.7	27.6	1.8	96.3
		Male	57.7	28.7	0.0	94.4
	CI-HS	Female	83.6	17.0	27.4	99.2
		Male	80.8	18.1	15.9	98.4
Speech Intelligibility–MSB [1]						
High context sentences	CI-HS	Female	68.3	23.3	11.1	98.0
		Male	58.9	19.8	13.9	88.5
Low context sentences	CI-HS	Female	67.5	22.4	0.7	94.8
		Male	57.8	19.1	11.9	91.6
Consonants Correct						
Average	CI-E	Female	73.1	17.9	24.9	94.9
		Male	68.9	20.1	9.7	94.2
	CI-HS	Female	95.8	6.9	62.0	100.0
		Male	92.8	12.7	33.0	100.0
Early Sign Enhancement						
Ratio of OC to SC Words/Utterance	CI-E	Female	0.8	0.2	0.3	1.3
		Male	0.8	0.2	0.4	1.2
Ratio of OC to SC # different words/min	CI-E	Female	0.9	0.2	0.3	1.5
		Male	0.9	0.2	0.1	1.4
Ratio of OC to SC IPSyn nouns	CI-E	Female	1.0	0.1	0.3	1.2
		Male	0.9	0.2	0.2	1.4
Ratio of OC to SC IPSyn complexity	CI-E	Female	0.9	0.2	0.1	1.2
		Male	0.9	0.2	0.2	1.5
Speech Perception						

	Group	Gender	Mean	SD	Minimum	Maximum
VIDSPAC[2] Segments	CI-E	Female	67.5	19.1	14.0	97.0
		Male	66.9	20.3	0.0	100.0
VIDSPAC Consonants	CI-E	Female	63.4	19.7	12.0	100.0
		Male	60.7	21.7	0.0	100.0
VIDSPAC Vowels	CI-E	Female	79.5	23.9	10.0	100.0
		Male	85.8	20.5	35.0	100.0
VIDSPAC Manner Score	CI-E	Female	77.8	26.3	−5.0	100.0
		Male	76.2	27.1	0.0	100.0
LNT [3](70 dBHL)	CI-E	Female	50.6	25.3	0.0	94.0
		Male	50.0	24.0	0.0	90.0
	CI-HS	Female	54.5	26.0	0.0	94.0
		Male	61.7	20.2	0.0	92.0
BKB[4] (Quiet)	CI-E	Female	62.4	36.2	0.0	100.0
		Male	63.9	32.1	0.0	100.0
	CI-HS	Female	76.3	30.5	0.0	100.0
		Male	84.7	21.6	0.0	100.0
Sentence Duration						
Duration 7-syllable Sentences (ms)	CI-E	Female	3084.8	1069.6	1669.0	6037.0
		Male	3501.6	1244.0	1900.0	7747.0
	CI-HS	Female	1999.7	457.7	1233.3	3540.7
		Male	2053.3	467.6	1465.0	4024.9
Average Sentence Duration (ms)	CI-E	Female	2238.0	679.5	1301.0	4153.0
		Male	2460.8	787.2	1507.0	5486.0
	CI-HS	Female	1556.0	331.9	1007.0	2555.0
		Male	1567.0	304.0	1143.0	2711.0
Working Memory						
Forward Digit Span Raw Score	CI-E	Female	5.5	1.3	3.0	10.0
		Male	5.1	1.6	1.0	11.0
	CI-HS	Female	7.9	1.9	4.0	12.0
		Male	7.6	1.7	3.0	13.0
Longest Forward Digit Span	CI-E	Female	4.1	0.7	3.0	6.0

	Group	Gender	Mean	SD	Minimum	Maximum
		Male	3.9	0.8	2.0	7.0
	CI-HS	Female	5.4	1.1	3.0	8.0
		Male	5.2	0.9	3.0	8.0
Total Raw Digit Span	CI-E	Female	9.2	2.3	5.0	14.0
		Male	8.4	2.8	2.0	13.0
	CI-HS	Female	13.1	2.9	9.0	23.0
		Male	12.5	2.3	7.0	17.0
Digit Span Scale Score	CI-E	Female	6.8	2.6	2.0	13.0
		Male	6.0	2.4	1.0	12.0
	CI-HS	Female	6.6	2.5	3.0	15.0
		Male	6.1	1.8	1.0	10.0
Use of Speech Questionnaire [5]						
Average	CI-E	Female	4.0	0.7	2.6	5.0
		Male	3.7	0.9	1.3	5.0
Adolescent Sign Enhancement						
OC-SC PPVT[6] Difference		Female	3.7	10.0	−17.0	34.0
		Male	3.1	11.4	−33.0	40.0

[1] Multispeaker Babble Condition (Tobey, Shin, Geers, & Sundarrajan, 2010)

[2] Video Game Test of Speech Pattern Contrast Perception (VIDSPAC) (Boothroyd, 1997)

[3] Lexical Neighborhood Test (Kirk, Hay-McCutcheon, Sehgal, & Miyamoto, 2000)

[4] Bamford Kowal Bench (BKB) sentences (Bamford & Wilson, 1979)

[5] Use of Speech Questionnaire (Tobey, Geers, Brenner, Altuna, & Gabbert, 2003)

[6] Peabody Picture Vocabulary Test (Dunn, Dunn, & Dunn, 1997)

Table 2

Intercorrelations among variables used for Principal Component Analyses are shown.

Early Speech Production

CI-E	High Context	Low Context	Consonants Correct
High Context	1.000		
Low Context	0.914	1.000	
Consonants Correct	0.830	0.822	1.000
Use of Speech Questions	0.735	0.702	0.662

Adolescent Speech Production

CI-HS	Quiet High Context	Quiet Low Context	MSB High Context	MSB Low Context
Quiet High Context	1.000			
Quiet Low Context	0.896	1.000		
MSB[1] High Context	0.700	0.722	1.000	
MSB[1] Low Context	0.029	0.786	0.943	1.000
Consonants Correct	0.522	0.530	0.844	0.794

Early Sign Enhancement

CI-E	# words/utterance	# words/minute	IPSyn Nouns
# words/utterance	1.000		
# words/minute	0.622	1.000	
IPSyn Nouns	0.484	0.617	1.000
IPSyn Complexity	0.591	0.611	0.602

Early Speech Perception

CI-E	Segments	Vowels	Consonants
VIDSPAC[2] Segments	1.000		
VIDSPAC[2] Vowels	0.766	1.000	
VIDSPAC[2] Consonants	0.969	0.603	1.000
VIDSPAC[2] Manner	0.799	0.524	0.808

Early Working Memory

CI-E	Digit Span-Forward	Longest Forward Span	Total Scale Score
Digit Span-Forward	1.000		
Longest Forward Span	0.891	1.000	
Total Scale Score	0.825	0.717	1.00
Forward + Backward	0.827	0.723	0.968

Table 3

Principal component factor loadings are shown.

CI-E Early Speech Production		
	High Context Sentences	0.956
	Low Context Sentences	0.945
	Consonants Correct	0.909
	Use of Speech Questionnaire	0.841
CI-HS Adolescent Speech Production		
	High Context Sentences-Quiet	0.945
	Low Context Sentences-Quiet	0.955
	High Context Sentences-MSB	0.859
	Low Context Sentences-MSB	0.880
	Consonants Correct	0.824
CI-E Early Sign Enhancement		
	Ratio of OC to SC Words/Utterance	0.808
	Ratio of OC to SC # different words/min	0.861
	Ratio of OC to SC IPSyn nouns	0.811
	Ratio of OC to SC IPSyn complexity	0.845
CI-E Early Speech Perception		
	VIDSPAC Segments	0.987
	VIDSPAC Consonants	0.947
	VIDSPAC Vowels	0.794
	VIDSPAC Manner Score	0.872
CI-E Early Working Memory		
	Forward Digit Span Raw Score	0.950
	Longest Forward Digit Span	0.890
	Total Raw Digit Span	0.943
	Digit Span Scale Score	0.945
CI-HS Adolescent Working Memory		
	Forward Digit Span Raw Score	0.953
	Longest Forward Digit Span	0.898
	Total Raw Digit Span	0.948
	Digit Span Scale Score	0.938

Table. 4

Predicting CI-HS Adolescent Speech Production performance from CI-E measures.

	Source	Standardized Regression				
Model		coefficients	df	t-ratio	p	% variance
1	Duration of Deafness	−0.110		−0.119	0.906	
	Gender	0.142		1.485	0.141	
	CI-E PIQ	0.079		0.825	0.411	
	CI-E Family Size	−0.231		−2.360	0.020	
	CI-E Socio-economic status	0.238		2.406	0.018	
	Error		99			
	Percent total variance					12.9%
2	Duration of Deafness	0.001		0.010	0.992	
	Gender	0.152		2.160	0.033	
	CI-E PIQ	−0.001		−0.018	0.986	
	CI-E Family Size	−0.052		−0.696	0.488	
	CI-E Socioeconomic status	−0.100		−0.134	0.893	
	Early sign enhancement	0.522		6.516	0.000	
	Early speech perception	0.245		2.886	0.005	
	Early working memory	0.124		1.634	0.106	
	Error		96			
	Percent total variance					42.6%
3	Duration of Deafness	0.031		0.503	0.616	
	Gender	0.082		1.286	0.202	
	CI-E PIQ	−0.012		−0.190	0.850	
	CI-E Family Size	0.062		0.893	0.374	
	CI-E Socioeconomic status	−0.016		−0.238	0.813	
	Early sign enhancement	0.261		2.989	0.004	
	Early speech perception	−0.013		−0.145	0.885	
	Early working memory	0.067		0.885	0.378	
	Early speech production	0.628		4.811	0.000	
	7 syllable sentence duration	0.032		0.310	0.757	
	Error		94			

Model	Source	Standardized Regression coefficients	df	t-ratio	p	% variance
	Percent total variance					10.3%

Table 5

Predicting Adolescent Speech Production performance from CI-HS measures.

	Source	Standardized Regression				
Model		**coefficients**	**df**	**t-ratio**	**p**	**% variance**
1	Duration of Deafness	−0.053		−0.541	0.590	
	Gender	0.205		2.099	0.038	
	CI-HS PIQ	0.101		0.997	0.321	
	CI-HS Family Size	0.028		0.274	0.785	
	CI-HS Socioeconomic status	0.137		1.326	0.188	
	Error		104			
	Percent total variance					6.9%
2	Duration of Deafness	0.020		0.242	0.810	
	Gender	0.206		2.471	0.015	
	CI-HS PIQ	0.045		0.535	0.594	
	CI-HS Family Size	0.057		0.676	0.500	
	CI-HS Socioeconomic status	0.007		0.083	0.934	
	Aided average thresholds	−0.159		−1.869	0.065	
	Adolescent sign enhancement	−0.480		−5.315	0.000	
	Adolescent working memory	0.066		0.777	0.439	
	Error		101			
	Percent total variance					30.4%
3	Duration of Deafness	0.034		0.452	0.652	
	Gender	0.165		2.173	0.032	
	CI-HS PIQ	−0.006		−0.079	0.937	
	CI-HS Family Size	0.104		1.335	0.185	
	CI-HS Socioeconomic status	−0.022		−0.270	0.788	
	Aided average threshold	−0.093		−1.193	0.236	
	Adolescent sign enhancement	−0.384		−4.547	0.000	
	Adolescent working memory	−0.068		−0.831	0.408	
	7 -syllable sentence duration	−0.417		−4.780	0.000	
	Error		100			
	Percent total variance					11.7%

Table 6

Predicting Adolescent Speech Production performance from early (CI-E) and late (CI-HS) measures.

	Source	Standardized Regression				
Model		coefficients	df	t-ratio	p	% variance
1	Duration of Deafness	−0.018		−0.198	0.844	
	Gender	0.149		1.616	0.109	
	CI-E PIQ	0.062		0.659	0.512	
	CI-E Family Size	−0.219		−2.307	0.023	
	CI-E Socioeconomic status	0.243		2.536	0.013	
	Error		104			
	Percent total variance					12.4%
2	Duration of Deafness	−0.009		−0.094	0.925	
	Gender	0.129		1.307	0.194	
	CI-E PIQ	−0.029		−0.200	0.842	
	CI-E Family Size	−0.425		−3.437	0.001	
	CI-E Socioeconomic status	0.341		2.130	0.036	
	CI-HS PIQ	0.137		0.923	0.358	
	CI-HS Family Size	0.329		2.554	0.012	
	CI-HS Socioeconomic status	−0.167		−0.998	0.321	
	Error		101			
	Percent total variance					5.9%
3	Duration of Deafness	0.033		0.392	0.696	
	Gender	0.170		1.934	0.056	
	CI-E PIQ	0.022		0.176	0.861	
	CI-E Family Size	−0.217		−0.178	0.078	
	CI-E Socioeconomic status	0.140		0.957	0.341	
	CI-HS PIQ	0.041		0.308	0.759	
	CI-HS Family Size	0.205		1.743	0.084	
	CI-HS Socioeconomic status	−0.101		−0.691	0.491	
	Aided average threshold	−0.180		−2.103	0.038	
	Adolescent Sign Enhancement	−0.392		−3.817	0.000	
	Adolescent working memory	0.088		0.996	0.322	

	Source	Standardized Regression				
Model		coefficients	df	t-ratio	p	% variance
	Error		98			
	Percent total variance					21.1%
4	Duration of Deafness	0.041		0.535	0.594	
	Gender	0.152		1.882	0.063	
	CI-E PIQ	0.000		−0.001	0.999	
	CI-E Family Size	−0.138		−1.222	0.225	
	CI-E Socio-economic status	0.051		0.378	0.706	
	CI-HS PIQ	0.003		0.023	0.981	
	CI-HS Family Size	0.194		1.803	0.075	
	CI-HS Socioeconomic status	−0.059		−0.438	0.662	
	Aided average threshold	−0.108		−1.350	0.180	
	Adolescent sign enhancement	−0.334		−3.515	0.001	
	Adolescent working memory	−0.043		−0.497	0.620	
	CI-HS 7-syllable sentence duration	−0.399		−4.448	0.000	
	Error		97			
	Percent total variance					10.3%