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## Neuropsychological Correlates of Vocabulary, Reading, and Working Memory in Deaf Children With Cochlear Implants

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### Abstract

The performance of deaf children with cochlear implants was assessed using measures standardized on hearing children. To investigate nonverbal cognitive and sensorimotor processes associated with postimplant variability, five selected sensorimotor and visuospatial subtests from *A Developmental Neuropsychological Assessment* (NEPSY) were compared with standardized vocabulary, reading, and digit span measures. Participants were 26 deaf children, ages 6–14 years, who received a cochlear implant between ages 1 and 6 years; duration of implant use ranged from 3 to 11 years. Results indicated significant correlations between standard scores on the Design Copying subtest of the NEPSY and standard scores on vocabulary comprehension, reading, and digit span measures. The results contribute to our understanding of the benefits of cochlear implantation and cognitive processes that may support postimplant language and academic functioning.

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Over the past decade, the typical age of cochlear implantation has declined from early school age to infancy. Many profoundly deaf infants are now being implanted at 12 months or younger. The benefits of cochlear implantation for spoken language development, social interaction, and academic achievement have been clearly demonstrated (e.g., Connor, Craig, Raudenbush, Heavner, & Zwolan, 2006; Nicholas & Geers, 2006; Stacy, Fortnum, Barton, & Summerfield, 2006; Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). Age of implantation alone, however, does not account for the wide variability routinely observed among children with implants in speech perception, spoken language, and academic outcome measures. Therefore, research efforts have begun to focus on identifying and measuring processes underlying success with cochlear implants in order to understand individual differences in variability (e.g., Dawson, Busby, McKay, & Clark, 2002; Pisoni, Cleary, Geers, & Tobey, 1999). Identifying sources of variability will be useful in determining implant candidacy, designing new educational programs, and addressing the benefits and limitations of cochlear implantation.

### Benefits of Implantation

Academic functioning, especially reading, has been affected by hearing loss (e.g., Kyle & Harris, 2006; Paul, 2003; Traxler, 2000). Most deaf and hard-of-hearing children perform below grade level on tests of reading comprehension, reading vocabulary, and language when compared with hearing children of the same age (e.g., Traxler, 2000). Kyle and Harris (2006), for example, examined literacy-related skills of 29 prelingually deaf 7- and 8-year-old children with normal nonverbal intelligence (i.e., nonverbal IQ of at least 85), and 31 hearing children matched to the deaf children on reading age ( $M = 6.75$ , range = 5.33 to 8.58 years). For the deaf children, mean performance on productive vocabulary was more than 3 years

below mean chronological age, and mean reading scores were 13 months below mean chronological age.

However, recent reports suggest significant benefit on measures of language and literacy for many deaf children who receive cochlear implants. For example, a large cross-sectional study of 468 children with cochlear implants and more than 2000 nonimplanted deaf children reported significant benefits from cochlear implants, especially for children who received implants before 5 years and used them for more than 4 years (Stacy et al., 2006). In this questionnaire-based study, parents and teachers reported greater enhancements in auditory performance, speech perception, speech intelligibility, academic functioning (i.e., reading, writing, and other academic skills), and quality of life for children with cochlear implants.

Moreover, Svirsky et al. (2000) reported improvement in expressive language quotients after only 6–18 months of cochlear implant use. In this study of preschool and early school-age deaf children assessed before and after receiving a cochlear implant, rate of spoken language growth following cochlear implantation exceeded that expected for nonimplanted deaf children and was in some cases similar to that of hearing children. Nevertheless, for some of the deaf children with cochlear implants in this study, expressive language ability remained severely delayed even after more than 2 years of implant use.

Benefits of cochlear implantation have been reported at even younger ages. For example, Nicholas and Geers (2006) studied expressive language functioning in seventy-six 3.5-year-old children who received a cochlear implant between ages 12 and 38 months and who also scored within the average range on a nonverbal test of intelligence (administered by their school) or on the Daily Living Skills and Motor domains of the *Vineland Adaptive Behavior Scales* (VABS; Sparrow, Balla, & Cicchetti, 1984). In this study, raw scores were calculated from a spontaneous language sample (e.g., number of words), a parent report measure of word and sentence production normed on a younger sample (MacArthur Communicative Development Inventory: Words and Sentences; Fenson et al., 1993), and teacher-completed scales of communication skill normed on deaf and hard-of-hearing children (Scales of Early Communication Skills for Hearing-Impaired Children, SECS; Moog & Geers, 1975). For children who had used their implant for at least 1 year, Nicholas and Geers found a linear relationship between amount of implant experience and language development.

Other recent studies have shown that language and reading gains following cochlear implantation compare favorably with levels reported for hearing children (e.g., Geers, 2003; Geers, Nicholas, & Sedey, 2003; Spencer, Barker, & Tomblin, 2003). For example, several studies have investigated language comprehension and production, verbal reasoning, reading comprehension, and working memory in 8- and 9-year-old prelingually deaf children using measures standardized on hearing children (Geers, 2003; Geers et al., 2003). Deaf children in these studies received cochlear implants by age 5 and had 4–7 years of implant experience at the time of testing. Children who scored below 85 on a standardized measure of performance intelligence were eliminated from the study. More than half of the remaining children with at least average performance intelligence ( $N = 157$ ) scored within the average range for hearing 8- and 9-year-old children on standardized tests of verbal reasoning and nonstandardized measures of narrative ability, lexical diversity, and utterance length (Geers et al., 2003). Moreover, more than half of the children scored within the average range for hearing children on a standardized test of word reading and written sentence comprehension (Geers, 2003).

Taken together, these studies suggest that many deaf children with cochlear implants perform at a level similar to that of hearing children on measures of language and reading whether measured with raw scores, language quotients, or standard scores.<sup>1</sup> Comparing children within and across groups using raw scores or language quotients is difficult. For example, children

functioning 6 months below and those functioning 6 months above age level might both be within the normal range for their age group. These practices were useful in the past because children with cochlear implants were often older than normative populations (e.g., Nicholas & Geers, 2006). Moreover, measures standardized on hearing children were thought to be inappropriate for use with deaf children, and few measures were standardized on deaf and hard-of-hearing children. However, recent evidence indicates that many children with cochlear implants are functioning at or close to the levels of performance observed in hearing peers (e.g., Geers, 2003). For this reason, using measures standardized on hearing children is becoming an appropriate research strategy (see Knutson, 2006). Additionally, standardized measures may be useful in providing a reference for monitoring children's progress following cochlear implantation, addressing educational concerns, and documenting benefits and limitations of cochlear implantation.

## Nonverbal Predictors of Variability

Although more than half of profoundly deaf children in some studies achieve age-appropriate reading and language scores following cochlear implantation, many do not. Several studies have used measures of nonverbal and motor performance to predict outcomes and explain performance variability (e.g., Dawson et al., 2002; Geers et al., 2003; Kyle & Harris, 2006; Myklebust & Brutton, 1953; Nicholas & Geers, 2006). All of these studies have found some benefit to including nonverbal measures. For example, Geers et al. (2003) found that nonverbal intelligence was a significant predictor of language functioning following cochlear implantation. Nonverbal intelligence has also been useful in predicting the potential for deaf and hard-of-hearing children to acquire spoken language in oral education programs (Geers & Moog, 1987). Although several studies have used global measures of nonverbal intelligence as a predictor variable, the specific components of nonverbal functioning that may be important in explaining postimplant functioning have not been identified.

In several recent reports, measures of gross and fine motor performance were used to predict language performance in a group of 37 deaf children followed from before cochlear implantation until 4 years after implantation (Horn, Pisoni, & Miyamoto, 2006; Horn, Pisoni, Sanders, & Miyamoto, 2005). In these studies, the group median standard score from the motor domain of the VABS (Sparrow et al., 1984) was used to divide children into high- and low-motor groups. Although the overall mean standard score was within the normal range (i.e., within 1 *SD* of the test mean), motor scores for at least three children were more than 2 *SD* below the population mean. Significant motor delay, often an indicator of possible neurological impairment, may account for the poor postimplant language performance reported by Horn et al. (2005) for children in the low-motor group as compared with children in the high-motor group.

More recently, Horn et al. (2006) examined gross and fine motor components of the VABS separately using age ratios (i.e., age-equivalent score/chronological age) rather than standard scores. Mean preimplant gross motor (.82) and fine motor (.92) ratios were not significantly different. However, the fine motor measure (but not the gross motor measure) was positively correlated with postimplant expressive language functioning (but not with receptive language or word recognition) 1 and 2 years after implantation.

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<sup>1</sup>That deaf children with cochlear implants often function at a level similar to that of hearing children does not suggest that tests of language and reading necessarily measure similar constructs in both populations. For example, to some degree among deaf individuals, tests of vocabulary comprehension may reflect lip reading skills.

## Descriptive Information

Descriptive information about language and cognitive functioning is important in assessing implant success. Nevertheless, a number of studies of children and adults with cochlear implants report ratios or correlations but do not describe overall language or cognitive performance (e.g., Dawson et al., 2002; Horn et al., 2006; Knutson et al., 1991). In a study of 29 postlingually deaf adults with cochlear implants, for example, Knutson et al. (1991) examined correlations among several experimental cognitive tasks (e.g., visual sequence completion) administered prior to implantation and audiological measures (e.g., phoneme identification) obtained after 18 months of implant experience. Only adults with scores within or above the low-average range on an adult intelligence scale were included. Results indicated that whereas several preimplant cognitive tasks were significantly correlated with postimplant audiological measures, global IQ scores were not. Because IQ scores (full-scale, verbal, and performance) were not significantly correlated with the audiological measures, the authors concluded that standardized measures of intelligence were not useful in predicting audiological outcomes. However, actual performance on cognitive tasks was not reported. Knowing whether participants with average intelligence do well or poorly on specific cognitive tasks would be informative and could provide additional insight into psychological processes underlying audiological outcomes.

In summary, studies that have examined language and reading performance following cochlear implantation have rarely used measures standardized on hearing children and have frequently reported raw scores or age ratios instead of standard scores. Moreover, although previous studies have used nonverbal performance as an inclusion criterion or predictor variable, few have explored the specific components of nonverbal functioning that may be important in explaining postimplant variability. This study examined performance on measures of vocabulary, reading, and short-term memory using tests standardized on hearing children and assessed relations between postimplant performance on these measures and performance on selected nonverbal cognitive and sensorimotor subtests from a standardized neuropsychological assessment. The purpose of this study was to compare the performance of children with cochlear implants with normative standards developed for hearing children and to explore relations between these outcome measures and specific components of nonverbal functioning.

## Method

### Participants

Participants included 26 children (16 males and 10 females), ages 6–14 years ( $M = 9.1$  years,  $SD = 2.5$ ), who received a cochlear implant between ages 1 and 6 years ( $M = 2.5$  years,  $SD = 1.3$ ). Standard scores could not be calculated for an additional child, not included in analyses, whose chronological age was unavailable. Duration of cochlear implant use ranged from 3 to 11 years ( $M = 6.7$  years,  $SD = 2.2$ ); duration of deafness ranged from .5 to 6 years ( $M = 2.3$  years,  $SD = 1.4$ ). Twenty-three children were congenitally deaf, and age of onset for the remaining three children was .5, 1.5, and 3.5 years, respectively. All the children in this study used spoken English to communicate, all were children of hearing parents, and all were enrolled in mainstream educational programs. Etiology of deafness for 17 of the children was unknown; for the remaining nine children etiology included Mondini malformation ( $n = 3$ ), other middle ear malformations ( $n = 3$ ), meningitis ( $n = 1$ ), and genetic etiology ( $n = 2$ ).

### Procedure

Each child was tested individually and videotaped during a single 1.5-hr testing session. Several standardized measures of vocabulary knowledge, reading, and digit span were administered.

Relevant measures, summarized for the purpose of this study, were administered as part of a larger study of reading and phonological awareness in children with cochlear implants (Dillon, 2005; Dillon & Pisoni, 2006). Additionally, five selected standardized nonverbal neuropsychological tests were administered; they included measures of sequential planning, design copying, imitation, and motor speed and dexterity. These measures were selected to assess components of nonverbal functioning and investigate their relation to outcome measures.

**Neuropsychological measures**—Several components of nonverbal functioning were assessed using *A Developmental Neuropsychological Assessment* (NEPSY; Korkman, Kirk, & Kemp, 1998), a measure standardized on hearing children between ages 3 and 12 years. Subtests from two of five NEPSY domains were selected for administration—four subtests from the Sensorimotor Domain and one subtest from the Visuospatial Processing Domain (described below). Each of these subtests contained a motor component, and none required a verbal response. NEPSY results are expressed in standardized scaled scores ( $M = 10$ ,  $SD = 3$ ) for all measures except Visuomotor Precision (VMP), which is expressed in percentile ranks (expected level = 26th–75th percentile).

Two of the children in this study were older than the normative ages of the NEPSY; one child (13.0) was 1 month older and the other child (14.0) was 13 months older. Because standard scores were not expected to be substantially affected by relatively small differences at the oldest ages, these children were included in data analyses. However, data were analyzed both with and without standard scores for these two children.

**Sensorimotor subtests**—The four subtests from the Sensorimotor Domain included: Imitating Hand Positions (IHP), Fingertip Tapping (FTT; repetitive and sequential), Manual Motor Sequences (MMS), and VMP. IHP assessed the ability to imitate hand positions produced by the examiner. FTT assessed finger dexterity for simple movements (rapidly tapping the index finger against the thumb) and complex movements (sequentially tapping each finger against the thumb). MMS assessed imitation of rhythmic hand movement sequences. VMP assessed fine motor skills and eye-hand coordination (drawing a line inside a track as quickly as possible). These motor subtests were administered to obtain nonverbal measures of manual motor imitation, speed, dexterity, sequencing, and coordination.

**Visuospatial processing subtest**—One visuospatial processing subtest was administered, Design Copying (DC). This test of visuomotor integration that assessed the ability to copy two-dimensional geometric figures was administered to obtain a nonverbal measure of motor and cognitive ability (e.g., visuospatial organization and cognitive planning) known to be correlated with performance subtests of nonverbal intelligence (Korkman et al., 1998).

### **Vocabulary, reading, and digit span measures**

**Vocabulary:** Vocabulary knowledge was measured with the *Peabody Picture Vocabulary Test-III* (PPVT-III; Dunn & Dunn, 1997), a test of receptive vocabulary with norms for ages 2–90 years ( $M = 100$ ,  $SD = 15$ ). The PPVT assessed children's ability to identify which of four pictures best represented the meaning of each single word spoken by the examiner.

**Reading measures:** Phonological awareness was assessed using the Lindamood Auditory Conceptualization Test-Third Edition (LAC3; Lindamood & Lindamood, 2004), a standardized measure with normative data for ages 5.0 to 18.9 years. LAC3 subtests assess perception of phoneme and syllable patterns (e.g., number, order, and similarity). The LAC3 total standard score was used in data analyses ( $M = 100$ ,  $SD = 15$ ).



Two subtests of the *Peabody Individual Achievement Test-Revised* (PIAT; Markwardt, 1998) were also administered: Reading Recognition, a test of letter and phoneme awareness and single-word reading, and Reading Comprehension, a test of written sentence comprehension. The combined standard score for both subtests was used in data analyses ( $M = 100$ ,  $SD = 15$ ). Due to the range of ages included in this study, these subtests were administered to assess both early reading skills and sentence comprehension.

Word attack skills were measured using the Word Attack subtest of the *Woodcock Reading Mastery Tests-Revised* (WRMT; Woodcock, 1998;  $M = 100$ ,  $SD = 15$ ). This subtest assessed children's ability to correctly read nonwords and rare words aloud.

**Digit span:** Forward Digit Span (FDS), Backward Digit Span (BDS), and Total Digit Span (TDS) subtests of the Wechsler Intelligence Scale for Children-Third Edition (WISC-III; Wechsler, 1991;  $M = 10$ ,  $SD = 3$ ) were administered to obtain standardized measures of short-term auditory sequential memory and working memory capacity.

**Scoring and reliability:** Three trained coders scored test items either during testing or from the videotapes: One coder scored all reading and vocabulary measures, and the two others scored sensorimotor and visuospatial measures. To calculate interrater reliability for NEPSY scores, 20% of the data (four videotapes) was randomly selected and three sensorimotor subtests from each of the videotapes were independently scored by an additional trained coder (IHP, FTT, and MMS). Interrater agreement for number of correctly imitated hand positions was 100%. Pearson's product-moment correlations for number of seconds to complete finger tapping tasks and for number of correct MMS were .70 and .87, respectively.

## Results

Results reported below include descriptive analyses and analyses of relations between neuropsychological, vocabulary comprehension, reading, and digit span measures.

### Descriptive Analyses

#### Neuropsychological measures

**Sensorimotor subtests:** Table 1 presents a summary of mean scaled scores or standard scores and standard deviations for all measures except MMS, which will be described below. Mean performance on each of the four sensorimotor subtests was within the normal range for hearing children. Looking at individual data, all but one child scored within or above the average range for IHP. This one child whose scaled score was  $> 1 SD$  below the mean, scored above the mean for hearing children on vocabulary comprehension and several reading measures. For the FTT subtest, all but two children scored within or above the average range. The mean scaled score for VMP was in the low-average range. Six children scored more than  $1 SD$  below the mean on this subtest, indicating some difficulty rapidly drawing a path between two lines.

Regarding MMS, all but four children scored within or above the average percentile range (26th–75th). Of the four remaining children, two scored within the borderline percentile range (11th–25th) and two scored within the below-expected-level percentile range (3rd–10th).

Thus, most children performed within or above the average range on the standardized sensorimotor measures. Although a few children scored below the mean on a given sensorimotor subtest, none scored below the mean on all four subtests, and only one child scored below the mean on two of the subtests. That child, however, scored above the mean on vocabulary and reading measures. Thus, none of the children displayed a pattern of global

motor delay across all sensorimotor measures or across sensorimotor measures, vocabulary, and reading measures.

**Visuospatial subtest:** Mean performance on the DC subtest was within the low average range; however, seven children scored  $>1$  *SD* below the mean on this subtest, and only one child scored  $>1$  *SD* above the mean. Thus, 27% of the children had some difficulty planning and accurately reproducing geometric forms.

Inspection of individual data indicated that, across all five NEPSY sensorimotor and visuospatial subtests, none of the children scored below average on more than two subtests; six children scored  $>1$  *SD* below the mean on two subtests. By contrast, six children scored  $>1$  *SD* above the mean on at least one subtest, and one child scored  $>1$  *SD* above the mean on two NEPSY subtests. Of the six children who scored below the mean on two subtests, three scored below the mean on VMP and DC, the pencil-and-paper tasks. DC required cognitive planning with only one opportunity to imitate the examiner. The child who scored  $>1$  *SD* above the mean on two NEPSY subtests scored within the average to low average range on the PPVT-III and reading tests and below average on all three digit span measures. The two children beyond the normative ages of the NEPSY scored within the average range on all NEPSY subtests, except the younger of the two scored 2 *SD* below the mean on VMP only.

### Vocabulary, reading, and digit span measures

**Vocabulary comprehension:** As shown in Table 1, mean performance on the PPVT-III was below average and  $>1$  *SD* below the mean standard score for hearing children. Scores for more than half of the children ( $n = 14$ ) were  $>1$  *SD* below the mean; of those 14 children, 7 scored  $>2$  *SD* below the mean. However, three children scored at or slightly above the test mean (100, 110, and 113, respectively) and one child scored  $>1$  *SD* above the mean (117). The child who received the lowest PPVT-III standard score (40) also scored  $>1$  *SD* below the mean on all of the reading and digit span measures but at or above average on all NEPSY subtests. Only the children with PPVT-III scores of 100 and 113 scored within or above the average range across all measures in this study.

**Reading measures:** Mean standard scores on all tests of reading ability were within the average range for hearing children, although the mean LAC3 score was in the low average range. An examination of individual scores indicated that eight children scored  $>1$  *SD* below the mean and four scored  $>1$  *SD* above the mean on the LAC3. For the WRMT, three children scored  $>1$  *SD* below the mean and 12 children scored  $>1$  *SD* above the mean. Thus, across all three reading measures, performance was best on the word attack measure (WRMT) and poorest on the measure of phonological awareness (LAC3).

**Digit span:** Mean performance on each of the three standardized digit span measures was below average; however, mean FDS standard scores were better than BDS standard scores. Two children scored at or just above the mean standard score for FDS (i.e., 10 and 11, respectively); half of the children ( $n = 13$ ) scored  $>1$  *SD* below the mean. For BDS, two children scored above the mean and 19 children scored  $>1$  *SD* below the mean. For TDS, two children scored above the mean and 21 children scored  $>1$  *SD* below the mean. Only one child scored at or above the mean on all three digit span measures.

Several children in this study were of particular interest because of their demographic profiles: the two children with the oldest ages of implantation (6 and 5.4 years, respectively), the two children with the longest duration of implant use (11.8 and 11.2 years, respectively), and the child with both the oldest age of onset and the shortest duration of deafness before implantation (3.5 years and 6 months, respectively). Of the late implanted children, one child scored  $>1$

*SD* below the mean on most measures; however, the other typically scored within the average range. The two children with the longest duration of implant use differed in similar ways; one child scored within the average range on all measures, the other child scored  $>1$  *SD* below the mean on some measures and within the average range on others. Finally, the child with the shortest duration of deafness before implantation presented a mixed profile; several scores were in the average range, and others (BDS and some reading measures) were  $>1$  *SD* below the mean. Thus, variability was evident even among children who were similar on one or more demographic variables.

We did not find any systematic relation between performance and etiology for the children for whom etiology was known. For example, a history of meningitis was not associated in this study with poor performance on any measures.

## Statistical Analyses

**Demographic variables**—Pearson's product-moment correlations (two-tailed) showed that chronological age was significantly correlated with duration of implant use,  $r = .85, p < .001$ , indicating that, in general, older children had used their implants for longer periods. However, due to variation in age at implantation and duration of implant use, duration of implant use was not significantly correlated with age at implantation,  $r = -.01, p = .95$ . To explore the relationship between age, duration of implant use, and age at implantation, participants were divided into two groups: later-implanted children (i.e., age at implantation  $\geq 36$  months,  $n = 6$ ) and earlier-implanted children (i.e., age at implantation  $< 36$  months,  $n = 18$ ).<sup>2</sup> An independent sample *t*-test showed that mean chronological age (i.e., age at testing) for later-implanted children ( $M = 10.9, SD = 2.0$ ) was significantly greater than for earlier-implanted children ( $M = 8.6, SD = 2.5$ ),  $t(22) = -2.25, p < .05, d = 1.0$ . Thus, older children tended to have received their cochlear implants at later ages. However, mean duration of implant use for the two groups, later-implanted children ( $M = 6.4$  years,  $SD = 2.1$ ) and earlier-implanted children ( $M = 6.8, SD = 2.3$ ), was not significantly different,  $t(22) = .38, p = .70$ . Perhaps for this reason, duration of implant use was not correlated with outcome measures in this study.

Age at implantation was found to be negatively correlated with BDS,  $r = -.52, p < .05$ , indicating that children implanted at older ages had more difficulty on this measure. Chronological age was negatively correlated with LAC3,  $r = -.44, p < .05$ , suggesting that older, often later-implanted children performed more poorly on phonological awareness. A measure of Father's highest level of education (but not Mother's highest level of education) was found to be significantly correlated with PPVT-III scores,  $r = .42, p < .05$ .

**Standardized measures**—Table 2 provides a summary of the correlations among standardized measures.<sup>3</sup> NEPSY measures were not correlated with one another, indicating that, in general, they measured different nonverbal processes.<sup>4</sup> As shown in Table 2, of the NEPSY measures obtained in this study, only DC was significantly correlated with other standardized measures; DC was correlated with PPVT-III, BDS, and LAC3. Thus, cognitive processes underlying the ability to copy geometric designs (e.g., mental representation,

<sup>2</sup>Age at implantation was not reported by parents of two children in this study. Due to the small number of children in the later-implanted group, analyses based on this variable were limited.

<sup>3</sup>MMS percentile ranges were converted to rank-ordered scores in the following manner: percentile scores  $< 2$  (well below expected level) = 1; 3–10 (below expected level) = 2; 11–25 (borderline) = 3; 26–75 (at expected level) = 4; and  $>75$  (above expected level) = 5. Rank-ordered scores were then entered into correlational analyses. Results indicated that MMS scores, coded in this way, were not significantly correlated with vocabulary, reading, or digit span measures.

<sup>4</sup>Psychometric and statistical properties of the NEPSY are such that subtests within a given domain contain some shared variance, but each subtest also measures a unique aspect of that domain (Korkman et al., 1998). For this reason, correlations among sensorimotor subtests in the normative population were weak (i.e., .10–.19), as were correlations between DC and sensorimotor subtests (i.e., .07–.31). Correlations among NEPSY subtests in this study are consistent with these reports.



cognitive planning, monitoring, and memory) may be similar to those that underlie vocabulary comprehension and the sequencing and cognitive manipulation of spoken digits and phonemes. PPVT-III standard scores were significantly correlated with all reading measures and digit span measures. Thus, vocabulary knowledge was correlated with reading and memory. Digit span measures were also correlated with all measures of reading. Results were similar whether analyses were conducted with or without data from the two children who were beyond the NEPSY normative ages; the magnitude of correlations changed slightly but significance levels did not. Therefore, data reported here include both of these children.

## Discussion

This study assessed the performance of deaf children with cochlear implants and compared their scores to standardized data from hearing children to investigate relationships between nonverbal neuropsychological measures and vocabulary, reading, and digit span measures. Mean performance on all neuropsychological measures included in this study was found to be within the average range for typically developing hearing children. However, mean performance on vocabulary comprehension and digit span measures was below average. This finding is consistent with earlier reports that children with cochlear implants perform more poorly than hearing children on digit span measures (Geers, 2003; Pisoni & Cleary, 2003) and on auditory and visual sequential memory tasks that contain verbal stimuli (Dawson et al., 2002).

By contrast, the mean performance of children with cochlear implants on all of the reading measures, measures typically found to be delayed in deaf children (e.g., Traxler, 2000), was within the average range for hearing children. Geers (2003) and Spencer et al. (2003) reported similar results for 8- and 9-year-old children implanted by 5 or 6 years on measures of reading comprehension. Moreover, for children in this study, implanted at a mean age of 2.5 years, vocabulary scores were nearly 1 *SD* higher and reading comprehension scores were nearly 2 *SD* higher than the scores reported by Connor and Zwolan (2004) for children implanted at a mean age of 6.78 years. Thus, the results of this study provide additional evidence of benefit from cochlear implantation for deaf children implanted by 6 years and younger.

The sensorimotor measures obtained in this study were not significantly correlated with vocabulary, reading, or digit span measures. However, DC, the nonverbal visuospatial measure of neuropsychological function, was significantly correlated with PPVT-III, BDS, and LAC3, suggesting that DC and these measures may rely on common underlying cognitive processes. For example, LAC3 and BDS tasks are similar in that both require the ability to cognitively maintain and manipulate information in working memory. Thus, the relationship between performance IQ and language performance reported in some previous studies of children with cochlear implants (e.g., Geers & Moog, 1987; Geers et al., 2003) may be based largely on cognitive rather than sensorimotor components of nonverbal measures. DC more than any of the other nonverbal measures obtained in this study relies on cognitive planning and executive control, including “the ability to synthesize elements into a meaningful whole (visualization) and represent objects mentally” (Korkman et al., 1998, p. 16). Moreover, within the normative, hearing population, the DC subtest of the NEPSY was found to be significantly correlated with two performance subtests of the WISC-III, Picture Completion (.38) and Block Design (.35; Korkman et al., 1998). Thus, DC may utilize executive processes (e.g., visualization, cognitive representation, and cognitive control) that are similar to those associated with these other measures of nonverbal intelligence.

The results of this study indicating a relationship between DC and vocabulary, reading, and digit span are also consistent with several studies which found that global nonverbal performance was a reliable predictor of verbal performance in deaf children with cochlear

implants (e.g., Dawson et al., 2002; Geers, 2003; Geers & Moog, 1987; Geers et al., 2003). For example, Dawson et al. (2002) reported a significant relationship between nonverbal spatial memory and receptive language for children with cochlear implants. Relations between nonverbal and verbal performance in hearing children have been previously documented by a correlation (.82) between WISC-III performance IQ and PPVT-III scores (Dunn & Dunn, 1997). Moreover, the findings of this study are consistent with the results of Holt and Kirk (2005) who found that cochlear implanted children with performance and verbal delays had lower PPVT-III language quotients than did implanted children without cognitive delay.

Further, the relationship between PPVT-III scores and reading measures in this study is consistent with earlier evidence that language competence underlies reading competence (e.g., Connor & Zwolan, 2004; Geers, 2003). Geers (2003), for example, found that language competence was more strongly associated with reading than was speech perception. Note, however, that the relationship between PPVT-III and reading measures is not always consistent. In this study, for example, two children with poor PPVT-III scores performed well above average on phonological awareness, word attack skills, and reading comprehension. Thus, some children apparently do well on some reading tasks despite weak vocabulary knowledge.

Comparing deaf children who use cochlear implants with norms obtained from hearing children has several advantages, even when children with cochlear implants score below hearing norms, as they often do. For example, knowing how deaf children with cochlear implants differ from hearing peers will help to facilitate comparisons among studies that use different outcome measures, identify new directions for education and therapy programs, and contribute to improvements in implant technology. Because discrepancies between neuromotor and language development are possible, however, care should be taken in using nonverbal sensorimotor or visuospatial measures as indicators of overall functioning. For example, low motor functioning can co-exist with normal cognitive functioning in children with cerebral palsy who use cochlear implants (Hood, Firszt, & Kirk, 2006). Note also that some children in this study scored below average on one or two of the neuropsychological tasks but within the average range on others.

The results of this study have contributed to our knowledge of the benefits and limitations of cochlear implantation, variability across tasks, and neuropsychological correlates of vocabulary, reading, and working memory after cochlear implantation. Limitations of this study include a relatively small number of participants and relatively wide differences among participants in chronological age, age at implantation, and years of implant experience. Additionally, two children were beyond the NEPSY age range, and the youngest children were just beginning to learn to read. However, the results of this study demonstrate the usefulness of a nonverbal cognitive measure, DC, in understanding performance variability in children with cochlear implants. The advantages of using a standardized design copying task as a measure of nonverbal functioning include ease of use, relatively short administration time, and appropriateness for a wide range of ages. Additional research with a larger population should assess the usefulness of this and other neuropsychological measures in identifying factors that contribute to the wide variability in performance among deaf children with cochlear implants.

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**Table 1**  
Mean standard score, standard deviation, range, test mean, and test standard deviation for standardized measures

Measure	Standard score	SD	Range	Test Mean	SD
IHP	10.6	2.5	6–15	10	3
FTT	10.7	3.0	2–15	10	3
VMP	7.4	3.4	1–15	10	3
DC	8.0	3.4	1–14	10	3
PPVT	80.5	19.4	40–117	100	15
LAC3	88.2	12.8	55–111	100	15
PIAT	96.1	16.1	63–130	100	15
WRMT	101.0	14.7	70–125	100	15
FDS	6.5	2.0	3–11	10	3
BDS	5.0	2.8	1–14	10	3
TDS	4.9	2.4	1–11	10	3



Table 2

Correlations between standardized tests

	IHP	FTT	VMP	DC	PPVT	LAC3	PIAT	WRMT	FDS	BDS	TDS
IHP	1										
FTT	.20	1									
VMP	.21	.03	1								
DC	.12	.39	.04	1							
PPVT	.20	.25	.34	.56**	1						
LAC3	.13	.14	.23	.51*	.60**	1					
PIAT	.06	.40	.20	.35	.76**	.71**	1				
WRMT	.34	.02	-.08	.36	.70**	.67**	.73**	1			
FDS	.37	.16	.13	.20	.45*	.20	.47*	.58**	1		
BDS	.16	.20	.10	.56**	.44**	.69**	.61**	.38	.38	1	
TDS	.35	.19	.32	.36	.55	.68	.69	.65	.72	.86	1

Note. Pearson correlation coefficients (two-tailed).

\*  $p < .05$

\*\*  $p < .01$ .