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Article 7: Measures of digit span and verbal rehearsal speed in deaf children following more than 10 years of cochlear implantation

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Precis

This paper reports results on the development of immediate memory capacity and verbal rehearsal speed in 112 children with more than ten years of CI use. We found less than half of the sample showed increases in both forward and backward digit spans suggesting disturbances in basic mechanisms related to storage or rehearsal of verbal information. Both spans and verbal rehearsal speeds in elementary school were found to be correlated with speech and language outcomes in high school. These developmental results provide new insights in the elementary neurocognitive information processes associated with high variability in speech and language outcomes.

Introduction

One of our long-term objectives is to understand and explain the enormous variability and individual differences in speech and language outcomes in deaf children who have received cochlear implants. Why are some deaf children very successful with their cochlear implants, often achieving “near-normal” scores within the range of variation observed in typically-developing age-matched normal-hearing peers, while other children struggle and show substantial delays and weaknesses in domains such as speech perception, spoken word recognition, sentence processing, vocabulary, language and reading? Answers to these questions about the underlying factors that are responsible for the variability in speech and language outcomes following implantation have important clinical implications for improving diagnosis and treatment of children with profound hearing loss. Understanding individual differences in outcomes in this clinical population will also be critical for developing new screening methods that can be used to identify those children who may be at high risk for poor outcomes as early as possible so that novel targeted behaviorally-based interventions can be used to help children achieve optimal levels of performance from their implants and reach important speech and language milestones in development.

At the present time, many outcome studies have been published documenting the success of cochlear implants in both children and adults (see Kirk & Choi, 2009). Cochlear implants work well in many hearing impaired listeners. However, they do not work equally well for all children and adults who receive this medical intervention. Moreover, the precise reasons for the enormous variability in speech and language outcomes are still unclear and remain poorly understood at this time, even after many years of clinical research on cochlear implants (see Niparko et al., 2009). Individual differences and variability in speech and language outcomes are not new problems in the field of cochlear implantation. In fact,

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several important issues surrounding the study of variability in outcomes in both children and adults were explicitly addressed and identified as high priority areas of research in the two previous NIH Consensus Conferences on Cochlear implants held more than 15 years ago in 1988 and 1995 (NIH, 1988; 1995). Unfortunately, very little solid progress has been made in identifying the basic fundamental core underlying factors that are responsible for the variability in speech and language outcomes in this clinical population or developing new reliable predictors of outcome that move beyond the traditional routine clinical assessments that have focused almost entirely on conventional demographic, medical, educational and family variables (Pisoni et al., 2008).

Why has there been so little progress in understanding variability and sources of individual differences in patients who receive cochlear implants? Part of the problem is that almost all of the implant centers around the world continue to use the same battery of conventional speech and language tests, with few adjustments based on developments that have taken place in closely related fields of study. These tests were originally selected to measure outcomes and benefits and establish device efficacy for FDA evaluation purposes. Although the current batteries of outcome measures have good face validity, they were not developed to measure the real-world, ecologically-valid effectiveness of cochlear implants or to uncover the underlying sources of variability responsible for the large individual differences in speech and language outcomes in this clinical population. As a result, most tests currently in use today at implant centers are “endpoint” or “product-based” assessments of speech and language skills that are the final result of a long series of complex information processing operations that encompass a wide range of levels from early sensory encoding to short-term storage and processing operations in working memory to executive control processes, response planning and response execution depending upon the specific task demands of the test (Gathercole & Baddeley, 1993). Moreover, these tests were selected without any theoretical or conceptual framework aimed at explaining the process of development following implantation. Their primary focus is on efficacy of CIs using measures of speech perception, spoken word recognition, speech intelligibility, vocabulary knowledge and language comprehension. However, these endpoint measures are all built on more basic elementary information processing operations such as stimulus encoding, phonological storage, verbal rehearsal, processes involving phonological decomposition and reassembly, and retrieval strategies, as well as response planning, selection, organization, attention, concentration, and execution.

Beginning in the late 1990's we began collaborating with Ann Geers and her research group in St. Louis to investigate the utility of using several new “process-based” outcome measures of performance that were developed in the field of Cognitive Psychology to study individual differences in information processing that underlie speech-language development (see Pisoni & Geers, 2000; Pisoni & Cleary, 2003). These new measures were specifically designed to uncover and assess more basic elementary information processing operations that underlie all of the conventional end-point product-based clinical outcome measures that are routinely used to assess benefits and success following cochlear implantation (see Pisoni, 2000). Specifically, speech perception, spoken word recognition, and language processing are all closely linked and are critically dependent on rapid and efficient phonological coding of speech in immediate memory (Conrad, 1979, Gathercole et al., 2004, Gupta & MacWhinney, 1997). Basic information processing operations of immediate memory are used to encode, store, maintain, and retrieve phonological and lexical representations of words in a wide variety of language comprehension and production tasks. Immediate memory operates as the “gateway” or “processing interface” between the initial sensory input in the speech waveform and the listener's stored knowledge of language in long-term memory. Representations of the sound patterns of speech in CI listeners are weakened by degraded auditory input, resulting in underspecified phonological representations in

immediate memory. These underspecified phonological representations may reduce the capacity and efficiency of immediate memory, which in turn would affect speech perception, spoken word recognition, and other language processing operations. Hence, individual differences in capacity and efficiency of immediate memory processes might offer some explanation of the variability of speech and language outcomes in children with CIs (Alloway & Gathercole, 2006).

Digit spans are commonly used as capacity measures of immediate verbal memory. Digit Span tests consist of forward (repeating digits in the same order as they were presented) and backward (repeating digits in the reverse order from which they were presented) conditions, which are related because they share a component of short-term verbal memory (similar to the phonological loop component of working memory, as defined by Baddeley, 2003; see also Alloway, 2007; Alloway & Gathercole, 2006). However, measures of Digit Span Backward require not only rote immediate verbal memory but also include an additional processing component of concurrent mental operations (i.e., reordering). This additional processing component requires divided attention, allocation of multiple mental resources/operations, and active control of conscious attention, which fall under the purview of the central executive (Baddeley, 2003, 2007). For children with CIs, Digit Span Forward may be a more difficult task (relative to norms) than Digit Span Backward because of its emphasis on the phonological loop of memory and sequential processing, both of which have been shown to be at risk in CI samples (Pisoni et al., 2008; Conway et al., 2009). Digit Span Backward, on the other hand, may be less affected because it emphasizes other processes (central executive, attention) in addition to immediate verbal memory and sequential processing.

Verbal rehearsal speed, operationally defined using measures of speaking rate for verbal information such as sentence repetition, provides an additional index of how fast children are able to recode and maintain verbal information in immediate memory for short periods of time (Hulme & Muir, 1985). These processes are critical for efficiency of immediate memory because they keep information active in memory for other more complex linguistic processes such as spoken word recognition, sentence comprehension and language production. Working memory capacity and verbal rehearsal speed are correlated (Cowan et al., 1994, 1998), likely because rehearsal speed is a good measure of the efficiency of maintenance of phonological representations in immediate memory. In addition to verbal rehearsal speed based on measuring speaking rates, in another study we also obtained measures of memory scanning and retrieval of verbal information from short-term memory by acoustically measuring the pause durations between successive digits in the verbal responses of children carrying out the digit span task (see Cowan et al., 1994; 1998; Burkholder & Pisoni, 2003; 2006). We found that deaf children were three times slower than an age-matched group of NH children to correctly retrieve spoken digits from immediate memory in the digit span task (Burkholder & Pisoni, 2006).

Based on expectations that capacity and efficiency of immediate memory for phonological/lexical representations of words may be important underlying processes mediating the relationship between auditory experience and speech-language development in children with CIs, we investigated relation between measures of these constructs (IM Span and Verbal Rehearsal Speed, respectively) and speech-language outcomes in the original sample of 180 children in the initial phase of the St. Louis project when the children were 8 years of age (Pisoni & Cleary, 2003). The first set of findings reported measures of immediate memory capacity using forward and backward digit spans from the WISC III (Wechsler, 1991). As a group, we found that both the forward and backward digit spans from deaf children with cochlear implants were atypical relative to normative data from NH (normal-hearing) children (Pisoni & Cleary, 2003). Furthermore, the digit spans were significantly correlated

with three different measures of spoken word recognition. Children who had longer forward digit spans showed higher word recognition scores on the WIPI, LNT and BKB tests even after other contributing sources of variance such as chronological age, communication mode, duration of deafness, duration of device use, age at onset of deafness, number of active electrodes and speech feature discrimination were removed using partial correlation techniques.

The second set of findings reported measures of verbal rehearsal speed obtained from a sentence repetition task that was originally designed to assess speech intelligibility in deaf children (McGarr, 1983; Tobey et al., 2003). Verbal rehearsal speed, measured from sentence durations reflecting the child's speaking rate, was strongly correlated with forward digit span as well as measures of spoken word recognition. The results of our analyses of the digit spans and verbal rehearsal speeds of the original 180 children in the first phase of the project were revealing both clinically and theoretically in a number of respects. The findings reported in our paper was the first attempt to identify basic elementary underlying neurocognitive information processing factors in deaf children with CIs that were strongly associated with conventional endpoint product measures of speech and language performance (see also Pisoni & Geers, 2000).

In this paper, we report new findings on the development of immediate memory capacity and verbal rehearsal speed after eight years of cochlear implant use. Studying developmental change in memory capacity and verbal rehearsal speed longitudinally in the same group of deaf children with cochlear implants provides a unique and valuable opportunity to investigate the effects of long-term learning and the contribution of activity-dependent experiences on speech and language development in this clinical population. More importantly, with this large dataset we now have the ability to begin identifying novel predictors of developmental change and to understand some of the underlying neurocognitive factors that are responsible for the variability in speech and language outcomes in deaf children who use cochlear implants.

In addition, the availability of normative data from standardized neuropsychological tests with normal-hearing children provides a solid benchmark for comparisons permitting us to document for the first time the strengths, weaknesses and milestones in speech and language skills in this sample of children with cochlear implants. Finally, the findings from this study also provide the empirical and theoretical basis for identifying reliable behaviorally-based markers or "risk factors" for predicting poor speech and language outcomes in deaf children at an early age when novel interventions can be implemented to help ameliorate their delays and disorders.

The key research questions addressed in this study involve (1) comparison of test results of immediate memory span and verbal rehearsal speed to norms obtained from samples of normal hearing children; (2) evaluation of changes in immediate memory capacity and verbal rehearsal speed after 8 years of CI use; and (3) assessments of relations between immediate memory span and verbal rehearsal speed and speech-language outcomes, emphasizing predictive relationships (e.g., immediate memory span and verbal rehearsal speed at 8 years predicting speech and language outcomes at 16 years of age; or change in immediate memory span and verbal rehearsal speed from 8 to 16 years of age predicting speech and language outcomes at 16 years of age).

Methods

Subjects and Procedures

Study participants were drawn from a larger sample of 181 children who received a CI between 1990 and 1996 when they were between 1.8 and 5.4 years of age and participated in a previous research study between 1996 and 2000 when they were between 8.0 and 9.11 years of age (Geers, Brenner, & Davidson, 2003). Children selected to participate in the study at age 8 or 9 years were reported to have no educationally significant diagnosed disabilities in addition to deafness. The group average nonverbal intelligence quotient (PIQ = 102; SD = 14.5) was close to the normative mean compared to either hearing or deaf age-mates. One hundred twelve students returned for follow-up testing between 2004 and 2008 when their average duration of cochlear implant use was 13 years 3 months. All participants and their families signed consent and assent forms approved by the Institutional Review Board of the University of Texas at Dallas. Geers et al (2010) describe this population in depth, comparing the characteristics of the 112 children returning to participate with those 72 children who did not participate in the follow-up study. The adolescents who returned for follow-up testing had significantly higher speech perception, speech intelligibility and reading scores when they were in elementary grades than the 72 students who did not return.

The first data collection phase of the CID project was designed to obtain a broad array of outcome measures of speech, language and reading skills from 8- and 9-year old children in elementary grades who had used their cochlear implants for at least three and one-half years (CI-E). Thus, the range of chronological age and length of implant use within the sample were relatively narrow. The second data collection phase took place at about age 16 years (CI-HS). Key measures of speech perception, speech production, language and reading processes which were used for this paper as outcome variables were the LNT Word Recognition Test (Kirk, Pisoni, & Osberger, 1995), BKB Sentence Test (Bamford & Wilson, 1979), VidSpac Speech Feature test (Geers, Brenner, & Davidson, 2003), Speech Intelligibility (McGarr, 1983), PPVT (Dunn & Dunn, 1981), CELF-4 (Semel-Mintz, Wiig, & Secord, 2003), PIAT (Dunn & Markwardt, 1989) and the Children's Nonword Repetition test (Gathercole & Baddeley, 1996). Measures and procedures unique to the results reported in this paper are described below.

Information Processing Measures

Digit Span Subtest—Using the Digit Span subtest procedures from the Wechsler Intelligence Scale for Children, Third Edition (WISC-III; Wechsler 1991), forward and backward auditory digit spans were obtained from children with cochlear implants at both periods of data collection (N=108 for CI-E; N=112 for CI-HS).

The WISC-III Digit Span subtest requires the child to repeat a list of digits that are spoken live-voice by an experimenter at a rate of approximately one digit per second. The Digit Span testing was conducted by two female school psychometrists who were trained and experienced in administering the Wechsler Intelligence scales. Administration was conducted with both auditory and visual cues at a close (approximately 3 feet) range. Although reception of the digits may have been influenced by auditory-visual speech perception abilities, conditions were similar across all subjects and test sessions. For the “digits-forward” recall condition (DSF), the child was required to repeat the list of digits in the order that it was originally presented. For the “digits-backward” condition (DSB), the child repeated the list of digits in backward order from the original presentation. In both parts of the procedure, test items consisted of two lists of spoken digits administered at each list length, beginning with a length of two digits, and increasing in length by one digit

following successful repetition of at least one list of digits at a given length. Testing of DSF or DSB was discontinued when a child repeated two lists incorrectly at the same length.

Digit Span scores may be calculated using the total number of items (digit lists) correctly repeated ("Raw Scores"; see Pisoni & Cleary, 2003) or the longest list length correctly recalled ("Longest Span Scores"). The total Digit Span raw score, which is based on the sum of the Digits Forward and Digits Backward raw scores (i.e., total number of items/lists correctly repeated) can be converted to a scaled score, which is an age-based, norm-referenced score for each subject, based on a mean of 10 and SD of 3 in the large, nationally representative WISC-III norm sample of NH children (Wechsler, 1991). Additionally, we used longest length span scores (longest digit list length correctly recalled) when reporting separate results for the forward (Longest Digit Span Forward, LDSF) and backward (Longest Digit Span Backward, LDSB) recall conditions of the Digit Span subtest. Longest span length measure was used when reporting separate results for DSF and DSB because it provides a meaningful index of actual span length (i.e., the maximum number of items that a child was able to correctly recall) and because WISC-III norms are available for LDSF and LDSB scores but not for DSF and DSB raw scores. Thus, in this study, the overall Digit Span raw scores and scaled scores were used as measures of overall total performance on Digit Span (sum of the DSF and DSB tasks). Additionally, LDSF and LDSB scores were used as separate measures of forward and backward digit spans, respectively. Results of analyses conducted using Digit Span raw scores for the DSF and DSB conditions were very similar to those carried out using LDSF and LDSB scores; the analyses of these raw digit span scores generally yielded stronger correlations and many more of the correlations reached statistical significance.

McGarr 7-Syllable Sentence Durations—The duration of each child's repetition of the 7-syllable McGarr sentences in milliseconds (McGarr-7 Duration) was measured using the procedures described by Tobey et al., (2003; this volume) as part of the assessment of speech intelligibility. Duration measures were obtained for all sentence repetitions, whether or not they were repeated correctly. When a child gave no response or a partial response, the examiner repeated the sentence and tried to elicit a more complete version of the sentence. Duration was measured for the last attempt elicited by the examiner. We used this speech timing measure as a proxy for verbal rehearsal speed (see Pisoni & Cleary, 2003; Cowan et al., 1994, 1998).

Results

Immediate Verbal Memory Capacity (Digit Spans)

Digit Span Total Scores – Comparison to Norms and Change Over Time—

Figure 1 shows a summary of total Digit Span scaled scores for the entire sample, rank ordered from lowest to highest scores at both CI-E and CI-HS test sessions. For each subject, the scaled score indicates performance on the Digit Span test relative to age-based norms (normative mean=10, SD=3). Hence, the CI-E and CI-HS groups were compared to norm-samples based on their age in order to obtain Digit Span scaled scores, and as a result the differences in scaled scores shown in Figure 1 from CI-E to CI-HS are differences relative to a normative pattern of growth. The group demonstrated a wide range of variability in total Digit Span scaled scores with a range of 1 to 13. The mean scaled score of 6.4 at both CI-E and CI-HS test sessions (Table 1) is well below average for NH children and indicates that the deficit in immediate verbal memory capacity relative to typically-developing peers on the Digit Span subtest remained approximately constant even after 8 years of CI use. Only 9 of the 112 children showed Digit Span scaled scores at CI-HS that were at or above the normative scaled score mean of 10. These scores suggest that the

immediate verbal memory skills of this group of children are significantly delayed relative to their NH peers. Moreover, the difference in Digit Span scaled scores compared to normative performance at CI-E still remains the same at CI-HS.

Forward & Backward Digit Spans at CI-E and CI-HS—Figure 2 shows a summary of the frequency distributions for the forward (LDSF) and backward (LDSB) digit spans obtained at CI-E and CI-HS. Mean LDSF for the group increased over time, and the difference in span length between the mean LDSF for the CI group and the norm group remained the same at both ages. Unlike the forward digit spans, however, LDSB showed little increase from CI-E to CI-HS but the difference between the CI and normative mean scores increased by a factor of four, from 0.22 at CI-E to 0.84 at CI-HS (see Table 1).

Figure 3 shows LDSF and LDSB scores for individual subjects arranged in rank order from lowest to highest. For LDSF, at CI-E, 75 percent of the CI sample fell one standard deviation or more below the normative mean (shown by the solid horizontal line), whereas only 58 percent of the sample fell below the mean at 16 years of age. However, for backward span, the opposite pattern of change was observed. Only 23 percent of the children fell one standard deviation or more below the normative mean at CI-E, but this value rose to 38 percent of the children by CI-HS. At both test sessions, LDSF and LDSB scores were modestly, albeit significantly correlated ($r^s=0.26$ and 0.25 , respectively, $p<0.05$). LDSF at CI-E was significantly correlated with LDSF at CI-HS ($r=0.51$, $p<0.001$), whereas LDSB scores at CI-E and CI-HS were unrelated ($r=0.12$, NS).

Correlations with Core Speech and Language Outcome Measures—

Correlational analyses were conducted with the LDSF and LDSB scores (at CI-E and CI-HS) as well as LDSF and LDSB change scores (span at CI-HS minus span at CI-E, reflecting improvement in immediate verbal memory capacity) and eight of the core speech and language outcome measures. As shown in Table 2, forward digit span at CI-E and CI-HS was significantly correlated with all eight speech-language outcome measures, whereas backward digit span was related to a smaller subset of speech-language outcomes.

Inspection of these “time-lagged” correlations shows that early performance on LDSF tended to be more strongly correlated with later speech and language outcome measures that placed greater processing demands on auditory attention and cognitive control processes such as speech perception in noise (as compared to quiet; e.g., LNT-70 vs. LNT-50 and BKB in Noise vs. BKB in quiet, see Davidson et al., this volume) and language processing tasks that require greater phonological processing resources such as the CELF (Semel-Mintz et al., 2003) and PPVT (Dunn & Dunn, 1981). LDSB at CI-E, on the other hand, was a much stronger predictor of later more complex language processing measures, such as the PPVT, CELF, and PIAT reading (Dunn & Markwardt, 1989) than with later performance on basic speech perception and production tests such as LNT, BKB (Bamford & Wilson, 1979) and nonword repetition (Gathercole & Baddeley, 1996). Improvement in Digits Forward performance over the 8-year period was significantly related to most of the speech and language outcome measures at CI-HS, indicating that long-term speech-language outcomes are strongly dependent on the growth and development of immediate verbal memory capacity.

Additional analyses were carried out using partial correlation techniques in which age of onset of deafness, age of implantation, duration of deafness, and duration of CI use were controlled to evaluate the degree to which the observed relations between digit span scores and these eight outcome measures could be explained by demographic and background characteristics. Partial correlations were also calculated controlling for Performance IQ

scores. The results of the partial correlations were essentially the same as the zero-order correlations described above.

Digit Span Subgroups—In order to further understand the process of development of immediate verbal memory capacity and its relationship with speech and language outcomes, we divided the sample into 4 subgroups, based on change in the profiles of the LDSF and LDSB scores from CI-E to CI-HS. Subjects were considered to demonstrate positive development and growth over time (+) if their score at CI-HS exceeded their score at CI-E (which is developmentally normal); subjects were considered to show no development if their score at CI-HS was less than or equal to their score at CI-E (−). For example, a subject with LDSF score of 3 at CI-E and 5 at CI-HS would be considered to show positive development (LDSF+), whereas a subject with LDSB score of 3 at CI-E and 3 at CI-HS would be considered to show no development (LDSB−). Using this classification process, we obtained four DS subgroups based on the presence or absence of development in their LDSF and LDSB scores over time. Nearly half of the sample (N=47; 43.5%) showed positive development in *both* LDSF and LDSB (LDSF+/LDSB+; Group I), and another one-third showed positive development in LDSF but no change in LDSB (N=37; 34.2%; LDSF+/LDSB−; Group II). Approximately 10% fell in each of the other two groups (LDSF−/LDSB−, Group III, N=11; LDSF−/LDSB+, Group IV, N=13).

Analyses of the speech-language outcome scores in the four groups shown in Table 3 revealed some expected and some unexpected results. In general, the two LDSF+ groups (Groups I and II) showed much stronger performance on speech-language tests than the LDSF− groups (Groups III and IV), consistent with the earlier correlational analyses showing strong associations between LDSF and speech-language outcomes. However, results for the two LDSF− groups indicated that the subgroup that showed no development in LDSB (LDSF−/LDSB−; Group III) performed more strongly on several speech perception and speech-language measures than the subgroup that displayed positive development in LDSB (LDSF−/LDSB+; Group IV).

In order to better understand this latter unexpected finding, additional analyses were conducted on the LDSF/LDSB subgroups. Results of these analyses revealed that 69% (9/13) of children in Group IV used simultaneous communication (SC) strategies in school at CI-E (as opposed to oral communication [OC] programs; see Geers et al., this volume, for a description of the classroom mode rating scale), compared to 46% (21/47), 49% (18/37), and 45% (5/11) in Groups I, II, and III, respectively (Fisher's exact test comparing SC children in Group IV to the other three groups, $p < 0.15$). Additionally, the four subgroups differed significantly in WISC-III Verbal IQ (VIQ; $F(3,104) = 3.60$, $p < 0.02$). Groups I and II showed higher VIQ scores (mean scores = 92.9 and 94.0, respectively; SDs = 14.6 and 13.4, respectively) than Groups III and IV (mean scores = 82.4 and 82.4, respectively; SDs = 16.5 and 14.5, respectively; $p < 0.05$ for all comparisons of Groups I and II vs. Groups III and IV). However, a different pattern was observed for the WISC-III Performance IQ (PIQ); in this case, the subgroups did not differ significantly ($F(3,104) = 0.65$, $p > 0.50$). PIQ scores were as follows (mean, SD): Group I (101.3, 16.7), Group II (104.3, 14.2), Group III (106.6, 14.1), and Group IV (99.4, 20.3). Hence, no statistically significant differences between Groups III and IV were found for Verbal or Performance IQ. A comparison of school communication strategies (SC vs. OC) between the LDSF/LDSB groups, while indicating a higher rate of SC use in Group IV, did not reach statistical significance.

Verbal Rehearsal Speed (McGarr-7 Duration)

McGarr-7 Syllable Sentence Durations at CI-E and CI-HS—Figure 4 shows the mean McGarr-7 sentence durations for the sample at CI-E (top) and CI-HS (middle) along

with McGarr-7 sentence durations obtained from a control group (bottom) of 46 NH 16 year old students (NHC-HS) described in Geers et al., this volume. The mean McGarr-7 Durations in the CI sample decreased from 3.275 seconds at CI-E to 2.024 seconds at CI-HS, and the variability (reflected by standard deviation) also was substantially smaller by age 16 years ($SD=1.166$ sec at CI-E compared to $SD=0.461$ sec at CI-HS; Table 1). Of the 109 children with CIs who provided McGarr-7 Duration scores at both ages, only 3 children failed to show a decrease in their sentence durations over time after 8 years of CI use. For normal hearing children at age 16, not only was the McGarr-7 Duration mean lower than the mean duration for the CI group (1.777 seconds), but the standard deviation was much smaller ($SD=0.162$ seconds) as well, suggesting that normal hearing adolescents have both faster and more consistent verbal rehearsal speeds than the group of CI adolescents. McGarr-7 Durations at CI-E and CI-HS were also strongly correlated ($r=0.72$), suggesting that improvement in verbal rehearsal speed is highly consistent across individual subjects over this 8 year period.

Relations Between McGarr-7 Duration and Digit Span Measures—Bivariate correlations were initially carried out to assess the associations between the McGarr-7 Duration measures of verbal rehearsal speed and Digit Span measures of immediate memory capacity. As shown in Table 4, the McGarr-7 Durations and LDSF scores were moderately and significantly correlated at all ages, whereas correlations between McGarr-7 Durations and LDSB were much smaller or nonsignificant. It is especially notable that McGarr-7 Durations at CI-E were strongly correlated ($r=-0.50$) with Digits Forward performance at CI-HS. In addition, faster verbal rehearsal speed at CI-E predicted greater improvement in Digits Forward scores between CI-E and CI-HS ($r=-0.20$). These findings indicate a strong predictive relationship between early verbal rehearsal speed and later verbal-phonological sequential memory as indexed by digit span scores which provide a process-based measure of immediate memory capacity.

Correlations with Core Speech and Language Outcome Measures (CI-E and CI-HS)—As shown in Table 5, verbal rehearsal speed, as measured by the McGarr-7 Durations, was consistently associated with all measures of speech and language outcome. Relations between McGarr-7 Duration scores at CI-E and speech-language scores at CI-HS frequently exceeded 0.60, showing very strong time-lagged predictive relations with all of the conventional outcome measures. In fact, several of the correlations between the CI-E McGarr-7 Durations and the speech-language outcomes at CI-HS were stronger than those obtained for the McGarr-7 Duration scores at CI-HS. As with the digit span scores, the relations between McGarr-7 Durations and the eight outcome measures were essentially unchanged after partial correlations were carried out to control for age of onset of deafness, age of implantation, duration of deafness, duration of CI use, and Performance IQ.

Discussion

The most important problem in the field of cochlear implant research today is understanding and explaining the enormous variability and individual differences in speech and language outcomes in prelingually deaf children. As noted in the introduction, one of the primary reasons for our lack of substantial progress in understanding variability in outcomes is that the conventional methods of assessing outcomes and benefit in use today have relied on a small battery of endpoint or product-based clinical measures of audiological and speech-language performance, with insufficient attention to more basic underlying core neurocognitive processes that are also impacted by hearing impairment and that can influence speech and language outcomes (Pisoni, 2000).

In this paper, we reported several new findings on the development of immediate memory capacity and verbal rehearsal speed in the group of 112 prelingually deaf children tested in the St. Louis project after 8 years of CI use. Participants volunteered for this study and although all who qualified were included, their use of a CI and their decision to apply for the study was not random. Therefore, we must consider the impact of sample selection bias on these results. The sample included in this study was drawn from implant programs and educational settings across North America and exhibited a mean and standard deviation of nonverbal intelligence quotient (103 and 16, respectively) close to the values established for the normative sample of hearing age-mates (i.e., 100 and 15). However, in some respects, these children were different from the general population. Their families spoke only English at home, and children with additional diagnosed disabilities were not included in the sample. Furthermore, the mean parental education and income level was higher than the average for the general American population. Further selection took place due to attrition, since 72 of the original sample did not return for follow-up testing. Families who felt their children were performing reasonably well might have been more likely to return for follow-up testing. Although the 112 follow-up participants did not differ in PIQ, age at CI, or family socio-economic status from the 72 students who did not return, returning students had significantly higher speech perception, speech intelligibility, and language scores at CI-E (see Geers et al., 2010 in this volume). Some of the families who declined to participate in the follow up study may have done so because their child was either no longer using his/her cochlear implant or because they did not achieve the level of outcomes with the device that the family had hoped. These sample selection factors may have resulted in an overestimation of the digit span scores and underestimation of the average sentence duration for adolescents with long-term use of CIs. The relative selectivity of the sample may also have resulted in our underestimating relationships between speed of verbal rehearsal and language outcomes. These results could be even stronger in a more representative sample of profoundly deaf children with CIs.

Based on the earlier analyses of immediate memory capacity and verbal rehearsal speed in the CI-E sample carried out by Pisoni and Cleary (2003), we assumed that these two elementary core neurocognitive measures of information processing, immediate memory capacity and verbal rehearsal speed, are components of all conventional speech and language outcome measures. Our analyses of the changes in forward and backward digit spans and speaking rates over time after 8 years of additional implant use and experience, combined with a series of correlational analyses using a subset of the core speech and language outcome measures, have provided a number of new insights about the underlying neurocognitive information processing factors that are associated with variability in outcomes following implantation in this group of deaf children.

Analyses of Digit Span subtest results demonstrated a complex developmental pattern with the core speech and language outcome measures. The CI group demonstrated nearly identical delays in total Digit Span scores at CI-E and CI-HS, with an average total Digit Span score greater than 1 SD below the normative mean, reflecting a consistent delay and developmental lag relative to normal hearing peers despite the benefit of CI use. The total combined digit span score, however, masks important differences in development of more basic information processing skills underlying the Digits Forward and Digits Backward subsections of the test (Rudel & Denckla, 1974, St Clair-Thompson, 2010). Additionally, there is considerable evidence that Digits Forward and Digits Backward, while related, also have significant components of unique variance (Alloway, 2007; Gathercole & Alloway, 2008). Hence, results based on the total Digit Span score should be interpreted with caution and in the context of the separate scores for Digits Forward and Digits Backward.

On Digits Forward (LDSF), about 75 percent of the sample scored well below average at CI-E, but almost half fell in the average range (scoring 1 SD below the mean or higher) by CI-HS. This suggests improvement in rapid phonological coding and short-term memory skills (rote sequential serial item and order memory for verbal information, with no demands for mental transformation or concurrent management of other cognitive processing operations), relative to norms, during the 8 year period. However, despite this improvement in a significant subset of the sample, a large percentage of children either showed no improvement in LDSF and/or continued to lag significantly behind their NH peers. This variability in immediate verbal memory capacity will be important to explain and address in future research.

On the other hand, only 23% of the sample scored 1 SD or more below the normative mean on the Digits Backward (LDSB) subtest at CI-E, but this number *increased* over the 8 year period, indicating that a larger number of children showed highly specific weaknesses and delays in their verbal working memory skills (verbal memory capacity when concurrent mental processing is required). Further evidence of a dissociation in development of phonological short-term verbal memory and declines in verbal working memory was provided by the Digit Span subgroup profile analyses which revealed that over 75% of the sample demonstrated improvement in LDSF over the 8 year period, compared to only about 45% of the sample who demonstrated improvement in LDSB. By comparison, in the WISC-III normative sample, LDSF and LDSB increased about the same amount (about 1.5 digits) between age 8 years (LDSF=5.3, LDSB=3.3) and 16 years (LDSF=6.7, LDSB=4.7), reflecting about a 1 SD improvement over that age span (Wechsler, 1991).

The greater tendency to see improvement in LDSF as opposed to LDSB may be a result of several factors related to learning, memory and attention. Because input provided by the CI is sequential and temporal in nature, more closely matching the task demands involved in LDSF, it is very likely that improved LDSF scores reflect the direct benefit of novel auditory experience and activities related to having exposure and access to sound and time-varying temporal patterns. Recently, Conway et al. (2009) have suggested that experience and activities with auditory input develops a broad set of domain-general sequential processing capacities, which would include rote phonological memory strategies. Alternatively, some of the improvement in LDSF may be a result of regression to the mean, as scores well below the mean are more likely to show improvement at retesting (based on chance alone) than they are to show no change or decline. However, regression to the mean alone is unlikely to fully explain the improvement in LDSF, because the degree of improvement in LDSF was also found to be related to speech and language outcomes (Table 2), suggesting some meaningful (i.e., nonrandom) component to the change in LDSF scores.

Digit Span Backward, on the other hand, is widely considered to be a measure of executive control and processing, focus and planning involving the active manipulation of verbal information in immediate memory under some cognitive load (Pickering & Gathercole, 2001). Research suggests that the Digits Backward task also accesses visual-spatial memory strategies and executive functioning skills, which may be less directly enhanced by experience and activities with a CI (see Wilson & Emory, 1997).

The present set of results also showed that scores on the Digits Forward task were also strongly associated with speech and language outcomes at CI-HS, whereas scores on the Digits Backward task were related only to higher-order language processing outcomes at CI-HS. This dissociation in the pattern of correlations over time may indicate that rapid phonological coding and verbal-sequential short-term phonological memory, as measured by the Digits Forward task, is an obligatory foundational building block for the development of robust speech perception and speech-language skills. Verbal-sequential phonological

memory is used extensively in all language processing tasks, requiring the child to encode, store and maintain representations of speech sounds, spoken words, and sentence meanings in conscious working memory as long sequences of additional spoken words and sentences are perceived and encoded rapidly in real-time. Over years of development, the ability to rapidly encode, store and maintain large amounts of verbal information in short-term phonological memory provides a significant advantage in learning to use verbal mediation processes in a wide range of language-dependent processing domains such as reading, writing and mathematical cognition. Results demonstrating significant time-lagged associations across an 8 year period between Digits Forward scores (both at CI-E and Digits Forward change from CI-E to CI-HS) and speech and language outcomes demonstrates a strong predictive relationship across a long period of time during which many aspects of brain, behavior and language processing skills are developing rapidly.

Digits Backward scores, on the other hand, correlated significantly only with higher-order language measures such as vocabulary knowledge, spoken language comprehension, and reading skills. This finding which is consistent with a large body of previous research suggests that verbal working memory during simultaneous mental operations, as measured by Digits Backward Span, is more critical for comprehension, information integration and organizational skills than for more basic speech perception and phonological coding. Earlier research has shown that Digits Backward is also strongly associated with complex executive functioning skills (Baddeley's "Central Executive") involving active mental control, planning and reasoning, as well as with visual-spatial processing (Engle et al., 1999; Pickering & Gathercole, 2006). Visual-spatial processing, executive functioning, and reasoning skills are more likely to come into play in more complex learning situations involving real-time on-line language comprehension and production than in more basic lower-level phonological processing tasks that assess skills such as speech perception, spoken word recognition, speech production and speech intelligibility.

An alternative explanation for the delay in Digit Span scores and for the relationship between Digit Span and the speech and language outcome measures may be the effect of speech perception delays on both Digit Span and other language outcome scores. Speech perception may affect Digit Span scores in several key ways: (1) increasing the digit perception failure rate (i.e., failing to recognize the digit or recognizing the digit inaccurately); (2) increasing the cognitive load of the task (i.e., need to allocate more attentional resources to perception, thereby reducing the cognitive resources available for working memory); and (3) reducing the quality and specificity of the internal cognitive representation of phonological information in STM. The latter two effects (cognitive load and representational specificity) may provide explanations for the way in which degraded auditory input affects working memory skills. For example, short-term and working memory tasks all involve some effort of the central executive, which is assumed to manage and direct cognitive resources during memory tasks (Baddeley, 2007). Increased cognitive load (from the added effort of speech perception) would further tax the central executive and reduce the efficiency of working memory. Similarly, reduced representational specificity of phonological information in STM would make storage and retrieval more taxing and difficult (Oberauer et al., 2000; Conlin et al., 2005; Francis & Nusbaum, 2009). The first effect (item identification failure) may have had an impact for some digit lists. However, data from this study suggests that the items perception failure rate alone is probably not the key factor involved, because this factor would presumably affect Digits Forward and Digits Backward approximately equally (since both are presented identically, as sequential lists of digits read by the examiner at 1 second intervals). The pattern of results for Digits Forward and Digits Backward were different, in terms of comparison to norms, change over time, and relations with speech and language outcomes. Hence, speech perception differences are likely contributors to Digit Span results, in ways that relate directly to underlying working

memory processes (cognitive load and representational specificity) and in ways that are related more to perceptual than to working memory processes (perception failures). Future research in this area will be important for increasing our understanding of verbal working memory delays in children with CIs.

The finding that Digits Forward and Digits Backward measure distinct neurocognitive processes has been reported and discussed by other researchers and is not unique to this clinical sample (Gathercole & Alloway 2007; 2008). However, we identified additional relations between Digits Forward and Digits Backward that showed unexpected associations with speech and language outcomes. When the group was divided using digit span profiles based on the degree of improvement in Digits Forward and Digits Backward scores, nearly half of the sample showed improvement in both digit spans (LDSF+/LDSB+) and about another third showed improvement in LDSF but no improvement in LDSB (LDSF+/LDSB-). Both of these subgroups also demonstrated the best overall outcomes in speech perception and speech-language scores, and they did not differ from each other. However, for the two groups that failed to show any increase in Digits Forward (LDSF-), improvement in Digits Backward was related to *poorer* speech-language outcomes, with the LDSF-/LDSB+ group showing the lowest scores across all eight outcome measures. This finding was unexpected, since Digits Backward was related to better language functioning across the entire sample, and the skills measured by Digits Backward (verbal central executive control and working memory capacity) are typically considered to be critical prerequisites to language learning, comprehension and reading (Baddeley, Gathercole & Papagno, 1998; Gathercole & Alloway, 2007; 2008). This unexpected finding is difficult to explain because examination of other characteristics of the LDSF-/LDSB+ subgroup (such as use of SC vs. OC communication strategies at school, or differences in Verbal or Performance IQ) did not reveal significant differences between the LDSF-/LDSB- and LDSF-/LDSB+ groups. Specifically, both LDSF- groups scored lower than the LDSF+ groups on Verbal IQ, but did not differ from each other. Additionally, the LDSF-/LDSB+ group had a large (but not statistically significant, in comparison to the other groups) percentage of children using SC (69%) as opposed to OC communication mode at school. Future research will be needed to better understand the changes in memory span over time.

Unlike Digit Span, which improved in some children and failed to improve in others, verbal rehearsal speed consistently improved for almost every subject from CI-E to CI-HS. Furthermore, McGarr-7 Durations were strongly intercorrelated at CI-E and CI-HS. These findings demonstrate that increases in verbal rehearsal speed are universal in children with cochlear implants and that measures of early verbal rehearsal speed are robust predictors of later verbal rehearsal speed and immediate memory capacity.

McGarr-7 Durations at CI-E were also highly predictive of speech and language outcomes at CI-HS. In fact, the correlations of McGarr-7 Durations and all of the speech-language outcome measures exceeded -0.45 in all cases and were in excess of -0.60 for about half of the outcome variables. These values are extremely high for a single behavioral measure (McGarr-7 Duration) predicting outcome 8 years later. Moreover, in most cases, the time-lagged correlations between McGarr-7 Duration scores at CI-E with speech-language outcomes at CI-HS were stronger than those between McGarr-7 Durations at CI-HS with speech-language outcomes at CI-HS, despite the fact that the latter correlations compared scores at the same time point in development. These new findings suggest that measures of verbal rehearsal speed at baseline are stronger predictors of speech-language outcomes than measures of verbal rehearsal speed obtained after 8 years of CI use. Stated differently, the early influence of verbal rehearsal speed on speech-language outcome appears to be dependent more on where the child starts (e.g., at 8 years of age) than on where the child finishes (e.g., at 16 years of age) and strongly suggests that the nature of the early sensory,

neurocognitive and linguistic experiences and activities immediately following cochlear implantation may play even greater roles in development and long-term speech and language outcomes than previously acknowledged in the past.

The present set of findings also suggests that verbal rehearsal speed is a core elementary underlying process that develops concurrently with speech and language skills in children with cochlear implants. Efficiency, speed, and fluency of phonological coding and processing, reflected in McGarr-7 Durations, likely influences speech-language outcomes by enhancing the volume and “throughput” of phonological information that can be rapidly encoded, processed and stored in immediate memory, allowing the child to perceive, rehearse, and retrieve larger chunks of verbal information per unit of time (Neufeld et al., 2007). Over a long period of development, changes in capacity and flow of information would likely reflect the effects of greater experience and practice encoding, rehearsing and retrieving verbal information from long-term memory (Hart & Risley, 1995; 1999).

The results of this study show that immediate verbal short-term phonological memory (evaluated in this study with Digits Forward), immediate verbal working memory (evaluated in this study with Digits Backward), and verbal rehearsal speed (evaluated in this study with McGarr-7 sentence durations) are core elementary underlying neurocognitive factors that develop concurrently with auditory, speech, and language experience and that influence a wide spectrum of different speech and language outcomes in children with cochlear implants. In addition to correlating with eight different conventional speech and language outcome measures, these underlying core neurocognitive factors also correlate with each other, particularly the McGarr-7 Durations and Digits Forward span scores shown in Table 4. The shared neurocognitive components in these two tasks may be conceptualized as “representational efficiency,” or more generally “information processing capacity,” reflecting the degree to which the individual is able to rapidly and fluently (“efficiently”) encode, store, maintain and retrieve phonological and lexical representations from short-term working memory.

Representational efficiency is required for the verbal storage capacity demands of the digit span task as well as for the rapid encoding and immediate response demands of the McGarr sentence repetition task. Representational efficiency and information processing capacity are also core neurocognitive factors underlying the development of phonological processing skills in children who are learning and developing spoken language skills based on the highly degraded acoustic-phonetic input provided by their cochlear implant over the childhood age span. We suggest that the degree to which deaf children can rapidly and efficiently construct phonological and lexical representations and encode, store and manipulate these representations in conscious working memory is related to their long-term speech and language outcomes.

Understanding the relations between these core underlying neurocognitive processes such as representational efficiency, immediate memory capacity, and verbal rehearsal speed and speech-language outcomes in children with CIs may provide clinical researchers with new basic knowledge and theoretical insights that can be used to develop novel approaches to intervention and treatment of deaf children who may be performing poorly with their cochlear implants. Moreover, new knowledge and understanding about the underlying neurocognitive factors responsible for variability and individual differences in speech and language outcomes could be used to develop new methods to identify deaf children at an early age who are at high risk for poor speech and language outcomes following cochlear implantation. This is a critical time period in language and neurocognitive development when novel interventions can be initiated to ameliorate delays and deficits in selected information processing domains associated with specific problems in speech perception,

spoken word recognition, vocabulary knowledge, sentence production, speech intelligibility, spoken language comprehension and reading (Alloway & Gathercole, 2006). However, before any treatment protocol can be initiated, it is necessary to identify the underlying neurocognitive processing domains that should be targeted for intervention. These areas should be related to speech-language processing or other adaptive functioning outcomes and should be delayed relative to available norms for normal hearing children.

In the present study, for example, immediate verbal-phonological short-term memory, assessed with Digits Forward, was found to be strongly related to speech-language outcomes and was delayed relative to normal-hearing peers. Recently, our research team has completed a pilot feasibility study using the Cogmed Working Memory Training program to attempt to improve this core area of neurocognitive functioning in a small sample of deaf children with CIs. Cogmed Working Memory Training consisted of 25 sessions of computer-based memory exercises completed over a 5-week period, that was designed to enhance working memory and executive functioning (Klingberg et al., 2005). Results showed improvement not only in immediate verbal-phonological memory (as assessed by Digit Span), but also increases in sentence memory, attention, concentration and executive control (Kronenberger et al., 2009). Continued evaluation of novel interventions targeting core areas of neurocognitive functioning offers the potential to apply the findings obtained in this study to groups of children with CIs who have suboptimal speech and language outcomes.

In summary, the results reported in this paper clearly demonstrate the utility of substantially broadening the conventional battery of speech and language outcome measures used to assess the benefits of cochlear implants in deaf children. Our long term objective is to identify the core neurocognitive processes that underlie development of speech and language functioning in children with CIs and to develop novel efficacious scientifically-based interventions to improve the outcomes of children who demonstrate vulnerabilities in these areas of speech and language development.

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Glossary

Auditory Attention	Selecting and processing important stimuli and ignoring the unimportant stimuli; in this case, auditory signals.
Executive Control Processes	Higher level cognitive processes involved in planning, inhibition, and organization of behavior, in order to promote goal directed-behaviors.
Immediate Memory Capacity	The maximum ability of an individual to recall information recently presented, although this information may be forgotten rapidly without coding and rehearsal processes.

Neurocognitive Processes	Specific cognitive (thought) processes and abilities related to brain functions, such as perception, attention, memory, learning and decision making.
Phonological Decomposition	Linguistic processes involved in constructing a structural description for a sequence of speech sounds.
Phonological Loop	A component of working memory that maintains verbal information by active rehearsal over short intervals of time.
Phonological Reassembly	Linguistic processes involved in combining sequences of speech sounds into motor commands for phonetic implementation and speech output.
Phonological Storage	Storage of information about to speech sound sequences in spoken language processing tasks.
Process-based Outcome Measures	Measures that reflect the methods and abilities used to construct a cognitive product (e.g., answer or response), which may include abilities such as speed, efficiency and capacity to encode, store and retrieve information from memory.
Processing Load	The maximum amount of information an individual can successfully understand and manipulate at one time.
Retrieval Strategies	Processes involved in recovering information previously known and stored in memory.
Sensory Encoding	Processing of sensory inputs into memory.
Short-term Memory	Temporary memory system responsible for storage and retrieval of information over a short period of time, typically 30 seconds or less.
Speech Feature Discrimination	Measures of speech discrimination for minimal pairs of syllables or words that differ by one phoneme using closed-set forced-choice tasks.
Stimulus Encoding	Processing of stimulus input into memory codes used in short-term memory.
Time-lagged Correlations	Correlations of a measure at one point in time with a related measure at a different point in time.
Verbal Rehearsal	Repeating spoken words covertly so that they can be maintained in short-term or working memory.
Verbal Sequential Memory	Memory for the temporal sequence of sounds or spoken and written words.
Verbal Short-term Storage	Memory for speech sounds or linguistic information (usually syllables words) in immediate memory
Visuo-spatial Coding Strategies	Recoding strategies using visually-based internal representations.
Working Memory	Memory system involved in the storage, representation, and manipulation of verbal and visual-spatial information that is immediately available for processing and that is maintained during other concurrent cognitive activity.

Figure 1.

WISC III Digit Span Scaled Scores obtained at CI-E (age 8;0 to 9;11; N=108) and CI-HS (age 15;0 to 18;6; N=112) for the sample of children with cochlear implants rank ordered from lowest to highest score. Scaled Scores based on a normative sample of typically-developing normal-hearing age-mates, have a mean of 10 and SD of 3. The Scaled Scores at CI-E are shown by the filled diamonds; the Scaled Scores at CI-HS are shown by the filled squares. The dashed horizontal line at 10 shows the mean score from the WISC III norms for normal-hearing aged peers. The two solid horizontal lines with means of 6.4 show the mean scores at CI-E and CI-HS.

Forward Spans CI-E

Backward Spans CI-E

Forward Spans CI-HS

Backward Spans CI-HS

Figure 2.

Frequency distributions for the WISC III longest digit span forward and digit span backward scores at CI-E (age 8;0 to 9;11) and CI-HS (age 15;0 to 18;6). The ordinate shows the frequency (number of children) while the abscissa shows the longest digit span length correctly recalled. The top panels show the longest span scores at CI-E; the bottom panels show the longest span scores at CI-HS. Within each panel, the solid vertical lines represent the mean for the CI group; the dashed vertical lines represent the mean obtained from the norms for NH aged peers.

Individual Scores

Figure 3.

Individual longest digit span scores at CI-E (age 8;0 to 9;11) and CI-HS (age 15;0 to 18;6) rank ordered from lowest to highest. The top two panels show the scores at CI-E; the bottom panels show the scores at CI-HS. The panels on the left show the forward span scores; the panels on the right show the backwards span scores. The horizontal dashed lines within each panel show the mean obtained from the WISC III norms for typical-developing age-peers. The horizontal solid lines represent the scores that are 1 SD from the mean of the norm sample. The percentages shown in each panel represent the number of children who fell more than 1 SD from the mean of the norm sample.

Sentence Durations of CI Children (CI-E)

Sentence Durations of CI Children (CI-HS)

Figure 4.

Frequency distributions for the McGarr sentence durations in msec obtained from the CI study sample at CI-E (age 8;0 to 9;11) [top panel] and then after 8 years of additional implant use at CI-HS (age 15;0 to 18;6) [middle panel]. The bottom panel shows the McGarr sentence durations obtained from a control group of normal-hearing adolescents (N=46). Number of children (frequency) is shown on the ordinate and sentence duration in msec is shown on the abscissa in each panel.

Table 1

Sample Digit Span and Verbal Rehearsal Speed Scores

	CI-E		CI-HS	
	Mean	SD	Mean	SD
Digit Span Total Scaled Score	6.44	2.53	6.38	2.24
Longest Digit Span Forward	4.05	0.78	5.29	1.04
Longest Digit Span Backward	3.08	0.92	3.94	0.88
McGarr Durations (Sec.)	3.27	1.17	2.02	0.46

Note: McGarr Duration values are in seconds (N=109). N=108 for Digit Span at CI-E and 112 for Digit Span at CI-HS.

Table 2

Correlations between Digit Span and Speech-Language Outcomes

Outcome Measures:	Longest Digit Span (CI-E)		Longest Digit Span (CI-HS)		Difference Scores (HS-E)	
	LDSF	LDSB	LDSF	LDSB	LDSF-diff	LDSB-diff
1. Speech Perception:						
LNT-70	+233*	+113	+409***	-.019	+269***	-.099
LNT-50	+142	+082	+374***	-.034	+285***	-.062
2. Sentence Recognition:						
BKB-Q	+207*	+144	+375***	-.066	+258***	-.166
BKB-N	+267**	+176	+398***	-.022	+230*	-.143
3. Speech Feature Discrimination:						
Vid Spac-8	+248**	+287**	+265**	+001	+091	-.226*
4. Speech Intelligibility						
TOTKEY Words	+237*	+245*	+369***	-.038	+225*	-.227*
SpInt Q	+237*	+177	+309***	-.084	+159	-.211*
5. Vocabulary:						
PPVT-TC	+174	+325***	+359***	+247**	+311***	-.078
PPVT-OC	+218*	+360***	+418***	+155	+334***	-.185
6. Language:						
CELF-LC	+227*	+287**	+331***	+257**	+220*	-.044
7. Reading:						
PIAT rdg	+270**	+375***	+437***	+230*	+315**	-.130
REC	+274**	+375***	+485***	+209*	+370***	-.145
Comp	+237*	+340***	+373***	+229*	+264**	-.098
8. Non Word Repetition:						
NW Phon (PCC)	+291**	+155	+438***	-.025	+261**	-.140
NW Correct	+262**	+029	+321***	+074	+145	+043

Outcome Measures:	Longest Digit Span (CI-E)		Longest Digit Span (CI-HS)		Difference Scores (HS-E)	
	LDSF	LDSB	LDSF	LDSB	LDSF-diff	LDSB-diff
NW Supra	+331 ***	+164	+424 ***	-.046	+219	-.167

*
p < .05
**
p < .01

p < .001

Table 3

Speech-Language Differences by Digit Span Subgroup

Outcome Measures:	Group I (N=47) [+ +]	Group II (N=37) [+ -]	Group III (N=11) [- -]	Group IV (N=13) [- +]
1. Speech Perception:				
LNT-70	65.74 (21.6)	60.86 (20.9)	56.54 (23.8)	38.92 (31.1)
LNT-50	53.19 (22.5)	50.22 (22.1)	42.54 (25.5)	27.69 (30.9)
2. Sentence Recognition:				
BKB-Q	85.79 (25.6)	81.78 (19.9)	80.00 (25.4)	53.54 (39.6)
BKB-N	56.81 (25.7)	53.30 (22.2)	48.91 (31.6)	33.07 (34.8)
3. Speech Feature Discrimination:				
Vid Spac-8	66.09 (20.1)	71.89 (16.9)	65.82 (19.2)	59.23 (24.9)
4. Speech Intelligibility				
TOTKEY Words	68.37 (28.6)	76.45 (19.8)	67.54 (33.0)	51.89 (33.4)
Splnt Q	84.6 (20.3)	87.4 (12.4)	83.60 (19.2)	73.29 (19.6)
5. Vocabulary:				
PPVT-TC	95.79 (15.4)	95.6 (16.4)	87.18 (16.1)	78.92 (18.7)
PPVT-OC	91.79 (19.3)	95.2 (21.6)	80.18 (23.9)	70.10 (28.1)
6. Language:				
CELF-LC	94.2 (17.9)	94.03 (19.0)	87.45 (16.9)	81.15 (22.0)
7. Reading:				
PIAT rdg	84.41 (15.1)	85.79 (16.9)	79.00 (17.8)	71.85 (15.8)
REC	82.09 (14.2)	85.95 (17.2)	76.73 (15.9)	72.46 (17.6)
Comp	89.72 (17.1)	91.66 (21.7)	85.00 (19.6)	77.15 (15.8)
8. Non Word Repetition:				
NW Phon (PCC)	41.15 (16.1)	45.97 (19.2)	39.64 (22.3)	32.46 (21.0)
NW Correct	2.63 (5.9)	5.05 (10.4)	3.69 (6.2)	1.22 (4.4)
NW Supra	62.61 (18.5)	67.64 (15.6)	64.54 (19.9)	55.77 (21.3)

Table 4

Correlations between McGarr Sentence Durations and Digit Span Scores

	McGarr Durations (CI-E)		McGarr Durations (CI-HS)	
	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
Longest Digit Span (CI-E):				
LDSF-CI-E	-.433	.001	-.344	.001
LDSB-CI-E	-.400	.001	-.233	.016
Longest Digit Span (CI-HS):				
LDSF-CI-HS	-.501	.001	-.421	.001
LDSB-CI-HS	-.102	NS	-.135	NS
Difference Scores (CI-HS – CI-E):				
LDSF-diff	-.203	.035	-.201	.039
LDSB-diff	+.239	.013	+.086	NS

Table 5

Correlations between McGarr Sentence Durations and Speech-Language Outcomes

Outcome Measures:	McGarr Durations (CI-E)		McGarr Durations (CI-HS)	
	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
1. Speech Perception:				
LNT-70	-.474	.001	-.471	.001
LNT-50	-.457	.001	-.478	.001
2. Sentence Recognition:				
BKB-Q	-.485	.001	-.550	.001
BKB-N	-.539	.001	-.520	.001
3. Speech Feature Discrimination:				
Vid Spac-8	-.596	.001	-.555	.001
4. Speech Intelligibility				
TOTKEY Words	-.691	.001	-.693	.001
Splnt Q	-.549	.001	-.572	.001
5. Vocabulary:				
PPVT-TC	-.626	.001	-.491	.001
PPVT-OC	-.704	.001	-.588	.001
6. Language:				
CELF-LC	-.626	.001	-.490	.001
7. Reading:				
PIAT rdg	-.601	.001	-.554	.001
REC	-.604	.001	-.556	.001
Comp	-.462	.001	-.444	.001
8. Non Word Repetition:				
NW Phon (PCC)	-.641	.001	-.583	.001
NW Correct	-.375	.001	-.219	.001
NW Supra	-.646	.001	-.585	.001