Published in final edited form as:
Ear Hear. 2003 February ; 24(1 Suppl): 106S–120S. doi:10.1097/01.AUD.0000051692.05140.8E.

Measures of Working Memory Span and Verbal Rehearsal Speed in Deaf Children after Cochlear Implantation

David B. Pisoni and **Miranda Cleary**
Indiana University School of Medicine (D.B.P.), Department of Otolaryngology-Head and Neck Surgery, DeVault Otologic Research Laboratory, Indianapolis, Indiana; and Indiana University-Bloomington (M.C.), Department of Psychology, Speech Research Laboratory, Bloomington, Indiana

Abstract

Large individual differences in spoken word recognition performance have been found in deaf children after cochlear implantation. Recently, Pisoni and Geers (2000) reported that simple forward digit span measures of verbal working memory were significantly correlated with spoken word recognition scores even after potentially confounding variables were statistically controlled for. The present study replicates and extends these initial findings to the full set of 176 participants in the CID cochlear implant study. The pooled data indicate that despite statistical "partialling-out" of differences in chronological age, communication mode, duration of deafness, duration of device use, age at onset of deafness, number of active electrodes, and speech feature discrimination, significant correlations still remain between digit span and several measures of spoken word recognition. Strong correlations were also observed between speaking rate and both forward and backward digit span, a result that is similar to previously reported findings in normalhearing adults and children. The results suggest that perhaps as much as 20% of the currently unexplained variance in spoken word recognition scores may be independently accounted for by individual differences in cognitive factors related to the speed and efficiency with which phonological and lexical representations of spoken words are maintained in and retrieved from working memory. A smaller percentage, perhaps about 7% of the currently unexplained variance in spoken word recognition scores, may be accounted for in terms of working memory capacity. We discuss how these relationships may arise and their contribution to subsequent speech and language development in prelingually deaf children who use cochlear implants.

Individual Differences and Variation in Outcome

Despite the success of cochlear implants in many prelingually deafened, early-implanted children, enormous individual differences have been reported on a wide range of speech and language outcome measures. Some children do extremely well with their cochlear implant, whereas others derive only minimal benefits. Although large individual differences in outcome after implantation have been well documented for many years in the clinical literature, the factors responsible for variation in performance are still not well understood (Blamey et al., 2001; Hodges, Dolan-Ash, Balkany, Scholffman, & Butts, 1999; Kirk, 2000; Pisoni, 2000; Sarant, Blamey, Dowell, Clark, & Gibson, 2001). Identifying the reasons for the wide variability in outcome measures after cochlear implantation is a challenging

---

Address for correspondence: David B. Pisoni, Indiana University School of Medicine, Department of Otolaryngology-Head and Neck Surgery, DeVault Otologic Research Laboratory, Riley Research Wing 044, 699 West Drive, Indianapolis, IN 46202. pisoni@indiana.edu.

research problem because a large number of complex sensory, perceptual, cognitive and linguistic processes affect speech and language performance in any particular behavioral task. It may be fruitful to investigate these complex interactions directly using measures that assess individual component processes of speech and language behavior if we want to explain why some pediatric cochlear implant users do so well while others struggle and achieve only small benefits after receiving a cochlear implant.

The observed individual differences can be extremely striking. In some of our earlier research we have looked in detail at several of the factors distinguishing children who display exceptionally good performance with their cochlear implants, from those who derive only minimal benefit (Pisoni, Cleary, Geers, & Tobey, 2000). The children who show exceptional progress appear to acquire spoken language quickly and easily and seem to be on a developmental trajectory that parallels children with normal hearing (Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). The exceptionally good performance of these so-called "Stars" is not merely an anomaly, but rather can be viewed as an "existence proof" for the best-case scenario offered by cochlear implantation of prelingually deafened children: cochlear implants work very well for some pediatric cochlear implant users, greatly facilitating the processes of speech perception and language development. The problem is that cochlear implants do not work well with all deaf children. Why does this occur? What factors are responsible for the enormous variation in outcome? These are two of the primary questions we have pursued in our research program on individual differences.

Among implanted children in general, approximately 40 to 65% of the existing variance in outcome measures can be accounted for in terms of a small number of traditional demographic variables such as duration of deafness, length of device use, age at implantation, and residual hearing before implantation (Blamey et al., 2001; Dowell, Blamey, & Clark, 1995; Miyamoto et al., 1994; Sarant et al., 2001; Snik, Vermeulen, Geelen, Brokx, & van den Broek, 1997; Zwolan, Zimmerman-Phillips, Asbaugh, Hieber, Kileny, & Telian, 1997). Although the role played by these familiar demographic variables has been extensively studied over the past few years, it has become clear from the substantial amount of remaining unexplained variability, that further research using a new theoretical framework is needed to understand the large individual differences in performance outcome. Our earlier work has shown that the performance of the "Stars" cannot be explained merely by appeal to demographics alone: children with similar demographic backgrounds and medical histories often show widely differing degrees of success with an implant (Balkany, Hodges, Miyamoto, Gibbin, & Odabasi, 2001; Geers et al., 1999; Kirk, 2000; Pisoni, 2000; Pisoni, Svirsky, Kirk, & Miyamoto, 1997). New techniques and methodologies are needed at this time to reveal the source of these individual differences in speech and language outcomes.

One path of investigation has offered some promising new insights into the nature of the observed individual differences. The examination of "higher-level" perceptual, cognitive and linguistic factors has typically not received much attention in the field of cochlear implants until recently (Pisoni, 2000). One reason for the lack of knowledge about central auditory factors and cognitive processes in this clinical population is that most of the research on cochlear implants has been carried out by medical professionals who have been concerned primarily with questions of device "efficacy" and assessment of outcome and benefit after implantation. Research on device efficacy requires well-defined assessment measures of outcome performance that are familiar to surgeons and clinicians who work with deaf patients. However, to specify how various central factors may combine to determine the degree of benefit observed in individual patients after cochlear implantation, it is necessary to go beyond basic clinical assessment using only traditional audiological tools.

Over the past few years, we have begun to focus on questions surrounding variability in outcome using several new methodologies that go beyond the standard end-point assessment-based clinical measures usually administered after cochlear implantation. The results of our research suggest that additional sources of variance may indeed come from more central cognitive factors (Pisoni et al., 1997, 2000). An enormous amount of information processing takes place beyond the auditory periphery for spoken language understanding to occur, and we suggest that the time is ripe to focus on the process of how deaf children with cochlear implants are able to use the initial sensory input conveyed by their devices. That is, research efforts should examine not only what the children “hear” but what they are able to do with the sensory information provided by their cochlear implants.

For spoken language processing to proceed rapidly and efficiently, it is not only essential that auditory information be made available to the central auditory system, but also that once encoded, this information can then be reliably maintained, retrieved, and transformed into phonological and lexical representations for use in a range of different speech and language processing tasks. These cognitive processing abilities are not sprung fully formed in the human infant, but rather, even in normalhearing children, develop over time as a result of experience-dependent learning (see Jusczyk & Luce, 2002; Locke, 1993). To understand the development of these speech and language processes in deaf children with cochlear implants, it is important to understand how the language-learning environment modulates, shapes, and facilitates the developmental process. It is probably reasonable to suppose that some of the most radical neural changes that take place after cochlear implantation to make speech perception possible, occur at quite high levels of central auditory processing—not at the level of auditory periphery. Thus, our research on cochlear implants in deaf children has focused on the underlying basic cognitive information processing skills that are used to support the perception and production of spoken language (see Pisoni, 2000).

The Information Processing Approach to Cognition

To gain a better understanding of what deaf children are learning after they receive a cochlear implant and how they use auditory sensory input, we have adopted an information processing approach that looks closely at the content and flow of information within the nervous system and how it changes over time (Pisoni, 2000). The foundational assumption of this approach is to view the human nervous system as an information processor. An information processor is a system that encodes, stores and manipulates various types of symbolic representations (Haber, 1969; Lachman, Lachman, & Butterfield, 1979). Information exists in several different forms at a number of levels of representation in the nervous system ranging from early registration and encoding of the sensory input to permanent storage of linguistic representations in long-term memory.

By viewing the mechanisms of sensation, perception, attention, memory and learning within this larger integrated framework of information processing, cognitive scientists have gained many new insights into the structure and function of the central nervous system (Neisser, 1967; Reitman, 1965). The information processing framework has also stimulated the development of new tools and experimental methodologies to study the processes that underlie these behaviors and has led to new theoretical conceptualizations that can be used to explain and predict variation and variability in more complex higher-level behaviors such as speech and language in different populations. This approach to human cognition has also provided researchers with the theoretical framework for reformulating some longstanding problems as well as identifying new research questions. The results of these efforts have provided fundamental new knowledge about perceptual and cognitive development and the neural processing mechanisms that underlie behavior (Gazzaniga, 2000; Posner, 1989).

One of the most important and influential proposals that has emerged from the information processing framework is the construct of working memory. Working memory is usually defined as a temporary storage mechanism for holding in conscious awareness, information obtained from perception or retrieved from long-term memory (Baddeley, 1992; Baddeley & Hitch, 1974). Although this system is markedly limited in its capacity and can be subject to rapid forgetting and loss, it serves a vital role in temporarily maintaining information for further processing.

One traditional method of assessing individual differences in working memory capacity is to find the number of familiar items that can be recalled in correct serial order. Digit span is the most widely used measure of verbal working memory capacity, and is often administered using two different variants: "forward" digit span, requiring simple verbatim recall of the list of digits to be remembered, and "backward" digit span, requiring the subject to reproduce a given target list with the items in reverse order (Wechsler, 1991).*

Although the temporary nature of the working memory system and its limited capacity render these initial representations quite fragile, there are ways of circumventing these limitations. Rehearsal is a generic term used in cognitive psychology to refer to methods for maintaining information in working memory via "refreshing" or re-encoding of the material to be remembered (Atkinson & Shiffrin, 1968). One ubiquitous rehearsal method for normalhearing adults is verbal rehearsal—simple vocal or subvocal (internal/silent) repetition of the verbal materials to be remembered. Interestingly, it has been found that although normally functioning adults typically rehearse "silently" or subvocally "to themselves," measures of actual articulation speed tend to correlate well with the rates at which this internal verbal rehearsal is carried out (Landauer, 1962; Standing & Curtis, 1989). Verbal rehearsal and its relationship to overt articulation appears gradually in normal development, and begins to be employed by normal-hearing children between the ages of 5 and 7 yr (Flavell, Beach, & Chinsky, 1966; McGilly & Siegler, 1989).

A number of recent findings related to verbal rehearsal (see Baddeley, Gathercole, & Papagno 1998; Carpenter, Miyake, & Just, 1994; Gupta & MacWhinney, 1997) have suggested that investigating the properties of working memory may provide new insights into the nature and locus of the individual differences observed among children with cochlear implants. In this report, we extend and expand on some of the preliminary findings on working memory reported in Pisoni and Geers (2000) and Cleary, Pisoni, Kirk, Geers, and Tobey (Reference Note 1).

Pisoni and Geers (2000) found that among a group of 43 pediatric cochlear implant users with a relatively homogeneous demographic background, working memory measures of verbal digit span showed strong positive correlations with measures of speech perception, speech production, language development, and reading skills. In follow-up analyses, Pisoni et al. (2000) reported that individual differences in verbal digit span were strongly correlated with a measure of articulation time obtained from a separate speech production task. (The children reported on in these previous articles are a subset of the current group of children.)

---

[*] Although we are here using the terms "working memory," "short-term memory," and "immediate memory" interchangeably, the term "working memory" is sometimes reserved for tasks that require the maintenance of information while additional new information is presented for processing. By this latter view, verbal forward digit span is better described as a simple verbal short-term or immediate memory task and verbal backward digit span as a true working memory task.

Reference Note

1 Cleary, M., Pisoni, D. B., Kirk, K. I., Geers, A., & Tobey, E. (2000). Working memory and language development in children with cochlear implants. Poster presented at CI2000: The 6th International Cochlear Implant Conference. Miami, Florida, February, 2000.

The results of these two earlier studies suggested that it might be informative to examine how processing capacity and verbal rehearsal speed each contribute to the relationship found between verbal digit span and several of the outcome measures of interest. For the purposes of the present article, we focus primarily on the relationship between digit span and spoken word recognition. Our focus on spoken word recognition (as opposed to phoneme discrimination or auditory sentence comprehension) is motivated by the tendency for performance on this task to effectively separate out children who are receiving minimal benefit from their implant from those who are successfully acquiring spoken language (Pisoni et al., 1997).

Methods and Procedures

To obtain measures of working memory capacity from a large number of deaf children after cochlear implantation, we were fortunate to be able to collaborate with Ann Geers and her colleagues at Central Institute for the Deaf (CID) in St. Louis who already had an on-going large-scale research project underway. The CID project was designed to obtain a wide range of outcome measures of speech, language and reading skills from 8- and 9-yr-old children who had all used their cochlear implants for at least 3½ yr. Thus, chronological age and length of implant use were relatively controlled within the sample of children studied.

Using the test lists and procedures from the WISC III (Wechsler, 1991), forward and backward auditory digit spans were obtained from four groups of 8- and 9-yr-old children with cochlear implants. A total of 176 pediatric cochlear implant users were individually tested in separate groups at CID in St. Louis during the summers of 1997, 1998, 1999, and 2000. Forward and backward digit spans were also collected from an additional group of 45 age- and gender-matched normal-hearing 8- and 9-yr-old children who were tested in Bloomington, Indiana and served as a comparison group.

The WISC-III digit span memory task requires the child to repeat back a list of digits that are spoken live-voice by an experimenter at a rate of approximately one digit per second (WISC-III Manual, Wechsler, 1991). In this study, the digit span task was administered with the face of the clinician visible to the child. For the “digits-forward” section of the task, the child was required to simply repeat back the list as heard. For the “digits-backward” section of the task, the child was told to “say the list backward.” In both parts of the procedure, the lists began with two items, and were increased in length on successful repetition until a child got two lists incorrect at a given length, at which point the testing stopped. Points were awarded for each list correctly repeated with no partial credit. Each child’s digit span in points was calculated by summing the number of lists correctly recalled at each list length. The total points score for forward digit span could vary between zero and 16; the total points score for backward digit span could vary between zero and 14.

Results

Figure 1 shows the frequency distributions for the forward and backward spans for all 176 pediatric cochlear implant users. The top panel shows the forward spans; the bottom panel shows the backward spans. The distributions shown in Figure 1 closely approximate normal distributions and provide reassurance that the difficulty of the task was appropriate for the children tested.

A summary of the mean digit span results for all five groups of children is shown in Figure 2. Forward and backward digit spans are shown separately for each group. The children with cochlear implants are shown in the four panels on the left by year of testing; the mean scores for the group of normalhearing children are shown on the right.

Inspection of the data shown in Figure 2 reveals an orderly and systematic pattern of the forward and backward digit spans for the deaf children with cochlear implants. All four groups are quite similar to each other. Within each group, the mean forward digit span is clearly longer than the mean backward digit span. The pattern is quite stable over the 4 yr of testing despite the fact that these scores are based on independent groups of subjects. The difference in span length between forward and backward report was highly significant for the entire group of 176 deaf children and for each group taken separately ($p < 0.001$).

The mean forward and backward digit spans obtained from the group of 44 age-matched normal-hearing children are shown in the right-hand panel of Figure 2. Examination of these data show that the digit spans for the normal-hearing children differ in several ways from the digit spans obtained from the children with cochlear implants. Firstly, although the mean digit spans for the normal-hearing children shown in Figure 2 are age-appropriate based on the published norms for the WISC III (Wechsler, 1991), the mean spans for the cochlear implant group are noticeably lower than would be expected from the published norms. For both forward and backward digit span, the normal-hearing children display longer spans than those obtained from the deaf children with cochlear implants. The difference is especially marked in the case of forward digit spans. The average difference between the forward and backward digit span scores was significantly larger in the normal-hearing group compared with any of the cochlear implant groups, indicating that the hearing-impaired children may have been unable to utilize strategies already mastered by normal-hearing children to improve immediate recall under simple forward recall conditions. These findings suggest atypical development of short-term memory capacity in the children with cochlear implants and indicate possible differences between the two groups in the underlying processing mechanisms that are used to encode and maintain sequences of spoken digits in immediate memory.

Digit Span and Communication Mode

To account for the observed differences in auditory digit span among the children with cochlear implants, we examined the correlations between digit span and several of the traditional demographic variables such as age at onset of deafness, duration of deafness, age at implantation, duration of implant use, communication mode, age, gender, and number of active electrodes. Of the various demographic measures available, the only one that correlated notably with digit span was communication mode. Communication mode refers to the nature of the child’s early sensory and linguistic experience after receiving a cochlear implant and is here indexed by the degree of emphasis on oral versus manual language skills by parents, teachers and therapists in the home and in the child’s educational environment (Geers et al. 1999; Geers & Brenner, 2003).

To determine communication mode, each child’s degree of exposure to Oral-only communication methods was quantified by determining the type of communication environment experienced by the child in the year just before implantation, each year over the first 3 yr of cochlear implant use, and then in the year just before the current testing. A score was then assigned to each year, with a “1” corresponding to the use of “total communication” with a sign emphasis (that is, extensive use of manual signs in addition to spoken language), and a “6” indicating an auditory-verbal environment with a strong emphasis on auditory communication without the aid of lipreading (see Geers et al. 1999; Geers & Brenner, 2003, for details). Communication methods intermediate between these two extremes were assigned intermediate scores ranging from 2 to 5. These scores were then averaged over the five points in time. The mean communication mode score for the group over the five intervals was approximately 3.9 on this 6-point scale. A wide range of communication mode backgrounds was, however, present within the sample (range of average communication mode scores = 1.0 to 6.0).

We found that forward digit span was positively correlated with Communication Mode ($r = +0.34$, $p < 0.001$). Children who were in language learning environments that primarily emphasized oral skills tended to display longer forward digit spans than children who were in total communication (TC) environments. However, the correlation between digit span and communication mode was selective in nature because its statistical significance was restricted only to the forward digit span scores; the backward digit spans were not significantly correlated with communication mode ($r = +0.14$, $p = 0.06$) or with any other demographic variable, except for chronological age at time of testing ($r = +0.22$, $p < 0.01$).

To further examine the effects of early experience on working memory spans, a median split was carried out on the communication mode scores to create two subgroups, Oral children and TC children. Figure 3 shows the digit spans plotted separately for the Oral and TC children for each of the 4 yr of testing at CID. Examination of the forward and backward digit spans for these two groups of children indicates that the Oral groups consistently displayed longer average forward digit spans than the TC groups. Although the differences in mean forward digit span between Oral and TC groups were highly significant ($p < 0.001$), the differences in backward digit span were not ($p = 0.22$, NS).

The difference in forward digit span between Oral and TC children is present at each year of testing and suggests that forward digit spans are sensitive to the nature of the early sensory and linguistic experience that the child receives immediately after cochlear implantation. The differences observed in the forward digit spans could be due to several factors, such as better encoding of the initial stimulus patterns into more stable and robust phonological and lexical representations in working memory, greater speed and efficiency of the verbal rehearsal processes that are used to maintain information in working memory, or possibly even faster rates of retrieval of information from working memory during recall. All three factors could influence measures of information processing capacity and any one of these could affect the number of digits correctly recalled from immediate memory in this task.

Regardless of which factor or factors are responsible for the differences, the present results demonstrate that forward digit span is sensitive to the effects of early experience and suggest that several specific mechanisms in the information processing system may be affected by the nature of the early experience the child receives after implantation. Although these results indicate that early experience in an environment that emphasizes oral language skills is associated with increased information processing capacity in verbal working memory, additional converging measures of performance would be helpful to specify precisely what elementary processes and information processing mechanisms are responsible for the longer forward digit spans observed in these children.

Digit Span and Spoken Word Recognition

Although traditional demographic factors such as duration of deafness, length of device use, and age at implantation have been shown to be related to individual differences in spoken word recognition, we suggest that a portion of the remaining unexplained variance can be accounted for in terms of individual differences in information processing capacity as measured by verbal digit span. Numerous studies of normal-hearing children over the past few years have demonstrated close “links” between verbal short-term/working memory and learning to recognize and understand new words (Gupta & MacWhinney 1997; Gathercole, Hitch, Service, & Martin, 1997). More specifically, it has been demonstrated that individual differences in the ability to imitate sound forms of novel pseudo-words are positively correlated with individual differences in vocabulary and novel word learning (Baddeley et al., 1998; Gathercole et al., 1997). Other research (e.g., Adams & Gathercole, 2000) has suggested that important milestones in speech and language acquisition are associated with developmental changes in verbal working memory.

To determine whether measures of working memory capacity are related to spoken word recognition in deaf children after cochlear implantation, we correlated the WISC forward and backward digit span scores with three different measures of spoken word recognition performance that were obtained from the children tested at CID. A summary of the correlations between digit span and word recognition scores based on these 176 children is shown in Table 1 for the WIPI, LNT, and BKB word recognition tests.

The WIPI (Word Intelligibility by Picture Identification Test) is a closed-set test of auditory word recognition in which the child selects a word from among six alternative pictures (Ross & Lerman, 1979). The LNT is an open-set test of word recognition and lexical discrimination that requires the child to imitate and reproduce an isolated word (Kirk, Pisoni, & Osberger, 1995). This test is similar to the well-known PBK test, although the vocabulary on the LNT was designed to control for familiarity while lexical competition among the items was manipulated systematically to measure discrimination among phonetically similar words in the child's lexicon. Finally, the BKB is an open-set word recognition test in which key words are presented in sentence contexts (Bench, Kowal, & Bamford, 1979). For the CID study, all of the word recognition test materials were pre-recorded and presented in the auditory-only modality.

Table 1 displays two sets of correlations. The left-hand portion of the table shows the simple bivariate correlations of the forward and backward digit spans with the three measures of spoken word recognition. Examination of the correlations for both the forward and backward spans reveals that children who have longer WISC digit spans also display higher scores on all three word recognition tests. The correlations are all positive and reach statistical significance although the correlations of forward digit span with the three word recognition scores are somewhat larger than the correlations found for backward span.

The right-hand portion of the table shows a summary of the partial correlations among these same measures after statistically controlling for differences due to: chronological age, communication mode, duration of deafness, duration of device use, age at onset of deafness, number of active electrodes, and speech feature discrimination. As expected, when these seven "contributing variables" are statistically removed from the correlational analyses, the partial correlations between digit span and word recognition scores become smaller in magnitude overall. However, the correlations of the forward digit span with the three word recognition scores are still positive and statistically significant, whereas the correlations with the backward digit spans are now much weaker and no longer reach significance. These results demonstrate that children who have longer forward WISC digit spans show higher word recognition scores and this relationship is observed for all three word recognition tests even after the other contributing sources of variance are removed.

In these results, forward digit span accounts uniquely for approximately 7% of the currently unexplained variance in the word recognition scores, whereas backward digit span accounts for very little of the total variance in these scores. The present findings suggest a common source of variance that is shared between forward digit span and measures of spoken word recognition that is independent of other obvious mediating factors that have been found to influence variation in these outcome measures. As will be discussed further below, these findings are not overly surprising given that all three spoken word recognition tests require the use of some kind of working memory to maintain each lexical representation for a short period of time just before and during the child's response.

Digit Span and Sentence Duration

Although the findings on variation in digit span scores suggest that children who acquire language while using a cochlear implant may differ both from normal-hearing children and amongst themselves in some basic information processing component, these data are not sufficient on their own to identify the basis for the observed differences. Additional converging measures of performance are needed to pinpoint the locus of these processing differences more precisely. Fortunately, another set of behavioral measures was obtained from these children for an entirely different purpose and these data were made available to us for several new analyses. These data consisted of a set of acoustic measurements of speech samples obtained from each child to assess speech intelligibility and to measure changes in articulation and phonological development after implantation (see Tobey et al. 2000). These speech samples provided a unique opportunity for us to use converging measures to further understand and explain the digit span results.

The speech samples consisted of utterances elicited using the stimulus materials and experimental procedures originally developed by McGarr (1983) to assess the speech intelligibility and articulation of deaf children. For the recordings made at CID, a clinician presented each child with meaningful English sentences using the child's preferred communication mode (either speech, or speech and sign), together with a printed version of the sentence on a large index card. All of the utterances produced by the children were recorded and stored digitally for playback to groups of naïve adult listeners who were asked to transcribe what they thought the children had said. From the duration measurements made by Dr. Tobey's research group of the 12 seven-syllable McGarr sentences, we were able to obtain measurements of the average time it took each child to produce a sentence of this length.

These sentence durations provided us with quantitative measures of each child's articulation speed. A child's articulation speed is known from a large body of earlier research in the working memory literature to be closely related to the speed of their subvocal rehearsal processes (Cowan, Wood, Wood, Keller, Nugent, & Keller, 1998). Numerous studies with both adults and children over the past 25 yr have demonstrated strong relations between speaking rate and working memory span for digits and words (see Baddeley, Thomson, & Buchanan, 1975; Hulme & Tordoff, 1989; Johnston, Johnson, & Gray, 1987; Kail, 1992; Standing & Curtis, 1989). The results of these studies have been replicated with several different populations and suggest that measures of an individual's sentence duration reflect articulation speed; this measure, in turn, can be used as an index of rate of covert verbal rehearsal for phonological and lexical information in working memory (Baddeley et al., 1975). Individuals who speak more quickly have been found to have longer memory spans than individuals who speak more slowly.

Several different explanations for the relationship between speaking rate and working memory span have been proposed in the literature. One account assumes that more forgetting occurs from immediate memory at slower speaking rates because fewer words can be articulated within a given interval of time (see discussion in Cowan & Kail, 1996). Another proposal assumes that the mechanism that controls speaking rate is the same one that regulates the speed of verbal rehearsal processes in short-term memory (Baddeley, 1992). Thus, more words can be maintained in working memory at faster rehearsal speeds. Regardless of which explanation is correct, the relation observed between measures of speaking rate and immediate memory span is a reliable and robust finding reported in the literature on working memory that has been found in several different populations of subjects.

The forward digit span scores for all of the 176 children tested at CID are shown in Figure 4 plotted against estimates of their speaking rates obtained from measurements of the seven-syllable McGarr sentences. The digit spans are plotted on the ordinate; the average sentence durations are shown on the abscissa. The top panel shows mean sentence durations; the bottom panel shows the log-transformed mean sentence durations. Log-transformed scores were computed to obtain a more normally distributed set of data. The pattern of results in both figures is very clear; children who produce sentences with longer durations speak more slowly and, in turn, have shorter forward digit spans. The simple bivariate correlations between forward digit span and both the raw and transformed measures of sentence duration were strongly negative and highly significant ($r = -0.55$ and $r = -0.59$; $p < 0.001$, respectively). For backward digit span, the observed correlations were somewhat smaller, but still statistically significant ($r = -0.42$ and $r = -0.42$; $p < 0.001$)

These findings demonstrate that verbal digit span and articulation rate are correlated in this clinical population, as they are in normal-hearing school-age children and adults. That is, children who speak more quickly were found to have longer digit spans. This result suggests the existence of a common information processing mechanism responsible for the individual differences observed within both tasks, namely, limitations on verbal rehearsal speed.

Spoken Word Recognition and Sentence Duration

To determine whether verbal rehearsal speed is also related to individual differences in word recognition performance, we next computed correlations between sentence duration and the three different measures of spoken word recognition described earlier. Table 2 shows the correlations between speaking rate and word recognition scores on the WIPI, LNT and BKB. Despite the fact that the sentence duration measure draws more heavily on speech production whereas the word recognition measures are designed to assess speech perception, the observed correlations are quite large. Table 2 also shows a summary of the partial correlations that were computed between the raw and log-transformed McGarr sentence durations and the three measures of spoken word recognition performance already described. As in the earlier analyses, differences due to possible mediating variables including traditional demographic factors, were once again statistically controlled for by using partial correlation techniques. In all cases, the negative correlations between sentence duration and word recognition remained remarkably strong and were highly significant.

The results of these correlational analyses demonstrate that slower speaking rates as measured by longer sentence durations are robustly associated with poorer scores on all three measures of word recognition, regardless of the response format of the test. Speaking rate accounted for approximately 25% of the currently unexplained residual variance in the word recognition scores even after the variability linked to other mediating variables was statistically controlled. These correlations are strong even for a word recognition test such as the WIPI, which makes no apparent demands on overt speech production (recall that the child is only required to point to a correctly matched picture).

Why should processing speed play a role in what appears on the surface to be a relatively simple closed-set word identification task? Because spoken words extend temporally in time, early information must be retained as the remainder of the utterance is listened to and processed. In addition, some representation of the sensory pattern must be stored and maintained long enough for the listener to select the correctly matched picture or, in the open set tasks, to initiate a spoken/signed repetition of the item. That is, even simple word recognition tasks such as the WIPI require some kind of memory representation to be maintained over a short period of time, and it is likely that covert verbal rehearsal is the processing mechanism used to maintain these representations as a response is arrived at and initiated.

Verbal rehearsal processes may be particularly important when spoken word recognition takes place under effortful or demanding conditions, such as those that exist for a child with a cochlear implant who is attempting to categorize a noisy and degraded auditory-only speech signal. If short-term memory is viewed as an "interface" to long-term memory, and noisy degraded signals induce listeners to attempt "top-down" contextual processing to recover the intended signal, the demands on rehearsal and maintenance may be considerable before a decision is finally arrived at. When identification is easy and the signal is well specified, identification is fast and individual differences in the ability to maintain a phonological representation may not figure as prominently (see Rabbitt [1968] and Pichora-Fuller, Schneider, & Daneman [1995], for related discussion).

Digit Span, Spoken Word Recognition, and Sentence Duration

The intercorrelations observed between digit span, articulation rate and spoken word recognition require further analyses to be fully interpretable. The high degree of intercorrelation among these three variables cannot be attributed to just a single source of variance (e.g., just working memory capacity or just verbal rehearsal speed) until we look at the correlations between each pair of variables with the other variable of interest statistically partialled out. More specifically, for each pair of variables (e.g., digit span and word recognition), it is necessary to determine whether their correlation may be due entirely to their mutual relationship with the remaining variable of interest (e.g., sentence duration). The resulting partial correlations among the three variables are illustrated graphically in Figure 5. The correlations between forward digit span, word recognition, and log-transformed sentence duration are shown in the top panel. The correlations between backward digit span, word recognition, and log-transformed sentence duration are shown in the bottom panel.

As shown on the left side of each triangle, when sentence duration was partialled out of the analysis, the correlations between digit span and each of the three measures of word recognition essentially approached zero. This indicates that the associations observed between digit span and word recognition can be entirely accounted for in terms of individual differences in sentence duration, here interpreted as a measure of verbal rehearsal/processing speed. This is an interesting and important new result because it provides additional insight into the origins of the relationship between digit span and spoken word recognition. This finding also suggests that individual differences in verbal rehearsal speed may be largely responsible for the observed relationship between digit span and auditory word recognition, rather than individual differences in memory capacity (see also, Fry & Hale, 1996).

Examination of the negative correlations shown at the base of each triangle indicates that the relationship between digit span and sentence duration remains fairly strong even when individual differences in spoken word recognition are statistically controlled for. These results are consistent with earlier studies suggesting that individual differences in verbal working memory as measured by an auditory digit span task can, in large part, be accounted for in terms of variation in speaking rate. Exactly why this is true is still a matter of current debate—perhaps limitations on speaking rate lead to forgetting during list output, or alternatively, perhaps a capacity limitation causes slowed and effortful production when capacity limits are stretched by the repeating-back of a many-syllabled sentence (see Cowan & Kail, 1996, for discussion). But the robustness of the relationship between digit span and sentence duration even when the spoken word recognition measures are partialled out also reassures us that the observed relationship is not likely a result of shared speech perception components in both tasks (perceiving the digits and sentences to be repeated). The relationship may be due to some other mediating factor.

Finally, the strong negative correlations shown on the right side of each triangle reveal that longer sentence durations are associated with poorer spoken word recognition performance even after individual differences in digit span are partialled out. From this asymmetric pattern of correlations in each triangle, we can conclude that a common feature of both digit span and sentence duration, probably best described as individual differences in immediate memory capacity, relates both tasks to word recognition, but that speaking rate incorporates an additional component that relates it to spoken auditory word recognition performance even after variability linked to differences in memory capacity is accounted for. Conceptualized in terms of a stepwise multiple regression analysis, this last statement is equivalent to saying that there is variability in the word recognition scores that is predicted only by the sentence duration measure and not by digit span scores.

Note also that essentially identical results were obtained for forward versus backward digit spans. The noticeable differences between forward versus backward digit span in terms of their relationship to spoken word recognition performance are no longer evident once variability in verbal rehearsal rate is accounted for. The pattern of results that emerges from these analyses suggests that variation in performance on the examined measures can be traced to a common elementary process related to the speed of verbal rehearsal used to maintain phonological and lexical information in short-term working memory.

Discussion

Our investigation of working memory and speaking rate has provided new insights into the basic elementary information processing skills of deaf children with cochlear implants and the underlying cognitive factors that affect their speech and language performance on a range of outcome measures. These new studies were specifically designed to obtain process measures of performance that assessed the operation of verbal working memory to understand the nature of the capacity limitations in encoding and processing sensory information.

Several important findings have emerged from our analysis of the digit span and speaking rate data. The results obtained with these two process measures of performance suggest that working memory capacity and verbal rehearsal speed may contribute an additional unique source of variance to the outcome measures obtained with deaf children after cochlear implantation.

Although we found some overlap in the distributions of the digit span scores, the means of the forward and backward digit spans were shorter in length for the deaf children with cochlear implants than for a comparison group of age-matched normalhearing children. This pattern demonstrates clearly the presence of atypical development of short-term working memory capacity in these deaf children and supports our hypothesis that cognitive processing variables may contribute to explaining the variation and individual difference in a range of outcome measures used to assess speech and language performance in these children.

The presence of fundamental limitations in the capacity to process information in immediate memory— that is, to encode, maintain and retrieve verbal information in short-term working memory—may have several important implications for other speech and language tasks as well. It is very likely that differences in information processing capacity and verbal rehearsal speed in immediate memory will propagate throughout the system and may cascade to higher levels of processing to influence performance on the behavioral tasks typically used to measure speech and language outcomes after implantation such as word recognition, vocabulary development, comprehension and even speech production.

The only demographic variable that was correlated with digit span and processing capacity was the child’s communication mode. The deaf children who were immersed in oral-only environments displayed longer forward digit spans than the children who were in total communication environments. The presence of an effect of early sensory experience on forward digit span scores suggests that the stimulus environment and the specific kinds of interactions children have with their parents and caretakers in the language learning environment operate in a highly selective manner on a specific information processing mechanism and subcomponent of the human memory system that is used for initially encoding and maintaining phonological information in short-term memory. We suspect there may be something unique/different about the oral environment and the specific information processing activities that the child engages in on a regular basis that produces selective effects on the verbal rehearsal mechanism and the phonological coding of sounds.

Because children from TC environments may simply have less exposure to speech and spoken language in their early linguistic environment after implantation, they may display problems in both processing and rehearsing auditory information in short-term memory. In terms of initial encoding and recognition, the reduced exposure to speech and spoken language may affect the development of automatic attention and specifically the speed with which speech signals can be rapidly identified and coded into phonological representations in shortterm memory. Thus, TC children may have problems in scanning and retrieving information from short-term memory. In terms of verbal rehearsal processes, TC children may have slower and less efficient verbal rehearsal processes once information finally gets into short-term memory simply because they have had less experience in producing speech and actively generating phonological patterns on output.

Passive exposure to speech without explicit analysis and conscious manipulation of phonological representations may not be sufficient to develop robust lexical representations of spoken words and fluency in control of speech production. Deaf children who receive cochlear implants may need to be actively engaged in processing spoken language to develop automaticity and automatic attention strategies that can be carried out rapidly without conscious effort or processing resources. This may be one important direct benefit of oral-only education programs. The excellent spoken language skills acquired by some children in oral-only programs may reflect the development of highly automatized phonological analysis skills that permit the child to engage in active processing strategies in perception that first involve decomposition of a speech pattern into a sequence of discrete phonological units and then the reassembly of those individual units into a sequence of gestures for use in speech production and articulation.

The development of phonological coding skills of this kind may result in increases in the speed and efficiency of constructing phonological and lexical representations of spoken words in short-term memory. Recovering the internal structure of an input pattern as a result of perceptual analysis and then reconstructing the same pattern in speech production may establish permanent links between speech perception and production and may lead to further development of highly efficient sensory-motor articulatory programs for verbal rehearsal and coding in working memory. Thus, the development of phonological processing skills may simply be a byproduct of the primary emphasis on speech and oral language skills in oral-only educational environments and may account for why oral children consistently display better scores on a wide range of outcome measures of speech and language, particularly oral language tests.

These new findings permit us to identify a specific information processing mechanism, the verbal rehearsal process in working memory, responsible for the limitations on processing capacity. Processing limitations are present in a range of behavioral tasks that make use of verbal rehearsal and phonological processing skills to encode, store, maintain and retrieve spoken words from working memory. We suggest that these fundamental information processing operations are common components of almost all of the current outcome measures routinely used to assess both receptive and expressive language functions. The present findings suggest that the variability in performance on the traditional clinical outcome measures used to assess speech and language processing skills in deaf children after cochlear implantation may actually reflect fundamental differences in the speed of information processing operations such as verbal rehearsal and the rate of encoding phonological and lexical information in working memory.

The present set of findings are theoretically significant because they provide converging evidence from several different behavioral measures obtained on a large group of deaf children for the existence and operation of a common information processing mechanism used for storage and maintenance of phonological and lexical information in working memory and they suggest a motivated explanation for the variability and individual differences observed in a wide range of speech and language processing tasks that make use of the same verbal rehearsal processes. Verbal rehearsal is a fundamental processing component that is present in every one of the outcome measures typically used to assess speech perception, spoken word recognition, vocabulary, comprehension and speech intelligibility in this clinical population. As in normal-hearing children, differences in verbal rehearsal strategies may be the key to explaining the large individual differences in speech and language development observed in deaf children after cochlear implantation.

Acknowledgments

This work was supported by NIH-NIDCD Training Grant T32DC00012 and NIH-NIDCD Research Grants R01DC00111, NIH NIDCD R01DC00064 to Indiana University and NIH Research Grant R01DC03100 to Central Institute for the Deaf. We would like to thank Ann Geers, Chris Brenner, and Mike Strube of CID for their help and assistance. We also thank Tonya Bergeson, Steven Chin, and Karen I. Kirk for comments on an earlier version of this paper. Several portions of this report are based on a longer chapter describing related research to be published in Springer Handbook of Auditory Research: Auditory Prostheses, SHAR Volume X. F.G. Zeng, A.N. Popper, & R.R. Fay (Eds.).

References

Adams AM, Gathercole SE. Limitations in working memory: Implications for language development. International Journal of Language & Communication Disorders. 2000; 35:95–116. [PubMed: 10824227]

Atkinson RC, Shiffrin RM. The control of short-term memory. Scientific American. 1968; 225:82–90. [PubMed: 5089457]

Baddeley AD. Working memory. Science. 1992; 255:556–559. [PubMed: 1736359]

Baddeley AD, Gathercole SE, Papagno C. The phonological loop as a language learning device. Psychological Review. 1998; 105:158–173. [PubMed: 9450375]

Baddeley, AD.; Hitch, G. Working memory. In: Bower, GH., editor. The Psychology of Learning and Motivation. Vol. Volume 8. New York: Academic Press; 1974.

Baddeley AD, Thomson N, Buchanan M. Word length and the structure of short-term memory. Journal of Verbal Learning and Verbal Behavior. 1975; 14:575–589.

Balkany TJ, Hodges A, Miyamoto RT, Gibbin K, Odabasi O. Cochlear implants in children. Otolaryngologic Clinics of North America: Implantable Electronic Otologic Devices, State of the Art. 2001; 34:455–467.

Bench J, Kowal A, Bamford J. The BKB (Bamford-Kowal-Bench) sentence lists for partially-hearing children. British Journal of Audiology. 1979; 13:108–112. [PubMed: 486816]

Blamey PJ, Sarant JZ, Paatsch LE, Barry JG, Bow CP, Wales RJ, Wright M, Psarros C, Rattigan K, Tooher R. Relationships among speech perception, production, language, hearing loss, and age in children with impaired hearing. Journal of Speech Language & Hearing Research. 2001; 44:264–285.

Carpenter, PA.; Miyake, A.; Just, MA. Working memory constraints in comprehension: Evidence from individual differences, aphasia, and aging. In: Gernsbacher, MA., editor. Handbook of Psycholinguistics. San Diego: Academic Press; 1994. p. 1075-1122.

Cowan, N.; Kail, R. Covert processes and their development in short-term memory. In: Gathercole, SE., editor. Models of Short-Term Memory. London: Psychology Press, Erlbaum Taylor & Francis; 1996. p. 29-50.

Cowan N, Wood NL, Wood PK, Keller TA, Nugent LD, Keller CV. Two separate verbal processing rates contributing to short-term memory span. Journal of Experimental Psychology: General. 1998; 127:141–160. [PubMed: 9622911]

Dowell RC, Blamey PJ, Clark GM. Potential and limitations of cochlear implants in children. Annals of Otology, Rhinology and Laryngology Supplement. 1995; 166:324–327.

Flavell JH, Beach DH, Chinsky JM. Spontaneous verbal rehearsal in a memory task as a function of age. Child Development. 1966; 37:283–299. [PubMed: 5941895]

Fry AF, Hale S. Processing speed, working memory, and fluid intelligence: Evidence for a developmental cascade. Psychological Science. 1996; 7:237–241.

Gathercole SE, Hitch GJ, Service E, Martin AJ. Phonological short-term memory and new word learning in children. Developmental Psychology. 1997; 33:966–979. [PubMed: 9383619]

Gazzaniga, MS. The New Cognitive Neurosciences. 2nd Edition. Cambridge, MA: MIT Press; 2000.

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

Geers, AE.; Nicholas, J.; Tye-Murray, N.; Uchanski, R.; Brenner, C.; Crosson, J.; Davidson, LS.; Spehar, B.; Torretta, G.; Tobey, EA.; Sedey, A.; Strube, M. Central Institute for the Deaf Research Periodic Progress Report No. 35. St. Louis: Central Institute for the Deaf; 1999. Center for Childhood Deafness and Adult Aural Rehabilitation, Current research projects: Cochlear implants and education of the deaf child, second-year results; p. 5-20.

Gupta P, MacWhinney B. Vocabulary acquisition and verbal short-term memory: Computational and neural bases. Brain & Language. 1997; 59:267–333. [PubMed: 9299067]

Haber, RN. Information-Processing Approaches to Visual Perception. New York: Holt, Rinehart and Winston; 1969.

Hodges AV, Dolan-Ash M, Balkany TJ, Schloffman JJ, Butts SL. Speech perception results in children with cochlear implants: Contributing factors. Otolaryngology-Head & Neck Surgery. 1999; 12:31–34. [PubMed: 10388873]

Hulme C, Tordoff V. Working memory development: The effects of speech rate, word length, and acoustic similarity on serial recall. Journal of Experimental Child Psychology. 1989; 47:72–87.

Johnston RS, Johnson C, Gray C. The emergence of the word length effect in young children: The effects of overt and covert rehearsal. British Journal of Developmental Psychology. 1987; 5:243–248.

Jusczyk PW, Luce PA. Speech perception and spoken word recognition: Past and present. Ear and Hearing. 2002; 23:2–40. [PubMed: 11881915]

Kail R. Processing speed, speech rate, and memory. Developmental Psychology. 1992; 28:899–904.

Kail R, Hall LK. Distinguishing short-term memory from working memory. Memory & Cognition. Special Issue. 2001; 29:1–9.

Kirk, KI. Challenges in the clinical investigation of cochlear implants. In: Niparko, JK.; Kirk, KI.; Mellon, NK.; Robbins, AM.; Tucci, DL.; Wilson, BS., editors. Cochlear Implants: Principles and Practices. Philadelphia: Lippincott Williams & Wilkins; 2000. p. 225-259.

Kirk KI, Pisoni DB, Osberger MJ. Lexical effects on spoken word recognition by pediatric cochlear implant users. Ear and Hearing. 1995; 16:470–481. [PubMed: 8654902]

Lachman, R.; Lachman, JL.; Butterfield, EC. Cognitive Psychology and Information Processing: An Introduction. Hillsdale, N.J: Lawrence Erlbaum Associates; 1979.

Landauer TK. Rate of implicit speech. Perceptual & Motor Skills. 1962; 15:646. [PubMed: 13928442]

Locke, JL. The Child's Path to Spoken Language. Cambridge, MA: Harvard University Press; 1993.

McGarr NS. The intelligibility of deaf speech to experienced and inexperienced listeners. Journal of Speech and Hearing Research. 1983; 26:451–458. [PubMed: 6645470]

McGilly K, Siegler RS. How children choose among serial recall strategies. Child Development. 1989; 60:172–182. [PubMed: 2702867]

Miyamoto RT, Osberger MJ, Todd SL, Robbins AM, Stroer BS, Zimmerman-Phillips S, Carney AE. Variables affecting implant performance in children. Laryngoscope. 1994; 104:1120–1124. [PubMed: 8072359]

Neisser, U. Cognitive Psychology. New York: Appleton-Century-Crofts; 1967.

Pichora-Fuller MK, Schneider BA, Daneman M. How young and old adults listen to and remember speech in noise. Journal of the Acoustical Society of America. 1995; 97:593–608. [PubMed: 7860836]

Pisoni DB. Cognitive factors and cochlear implants: Some thoughts on perception, learning, and memory in speech perception. Ear and Hearing. 2000; 21:70–78. [PubMed: 10708075]

Pisoni DB, Cleary M, Geers AE, Tobey EA. Individual differences in effectiveness of cochlear implants in children who are prelingually deaf: New process measures of performance. Volta Review. 2000; 101:111–164. [PubMed: 21666760]

Pisoni DB, Geers A. Working memory in deaf children with cochlear implants: Correlations between digit span and measures of spoken language processing. Annals of Otology, Rhinology & Laryngology. 2000; 109:92–93.

Pisoni, DB.; Svirsky, MA.; Kirk, KI.; Miyamoto, RT. Research on Spoken Language Processing Progress Report No. 21 (1996–1997). Bloomington, IN: Speech Research Laboratory; 1997. Looking at the "Stars": A first report on the intercorrelations among measures of speech perception, intelligibility, and language development in pediatric cochlear implant users; p. 51-91.

Posner, MI. Foundations of Cognitive Science. Cambridge, MA: MIT Press; 1989.

Rabbitt PMA. Channel-capacity, intelligibility, and immediate memory. Quarterly Journal of Experimental Psychology. 1968; 20:241–248. [PubMed: 5683763]

Reitman, WR. Cognition and Thought: An Information-Processing Approach. New York: Wiley; 1965.

Ross M, Lerman J. A picture identification test for hearing-impaired children. Journal of Speech and Hearing Research. 1979; 13:44–53. [PubMed: 4192711]

Sarant JZ, Blamey PJ, Dowell RC, Clark GM, Gibson WPR. Variation in speech perception scores among children with cochlear implants. Ear and Hearing. 2001; 22:18–28. [PubMed: 11271973]

Snik AF, Vermeulen AM, Geelen CP, Brokx JP, van den Broek P. Speech perception performance of children with a cochlear implant compared to that of children with conventional hearing aids. II. Results of prelingually deaf children. Acta Oto-Laryngologica (Stockholm). 1997; 117:755–759.

Standing L, Curtis L. Subvocalization rate versus other predictors of the memory span. Psychological Reports. 1989; 65:487–495. [PubMed: 2798667]

Svirsky MA, Robbins AM, Kirk KI, Pisoni DB, Miyamoto RT. Language development in profoundly deaf children with cochlear implants. Psychological Science. 2000; 11:153–158. [PubMed: 11273423]

Tobey EA, Geers AE, Morchower B, Perrin J, Skellett R, Brenner C, Torretta G. Factors associated with speech intelligibility in children with cochlear implants. Annals of Otology, Rhinology and Laryngology Supplement. 2000; 185:28–30.

Wechsler, D. Wechsler Intelligence Scale for Children, Third Edition (WISC-III). San Antonio, TX: The Psychological Corporation; 1991.

Zwolan TA, Zimmerman-Phillips S, Asbaugh CJ, Hieber SJ, Kileny PR, Telian SA. Cochlear implantation of children with minimal open-set speech recognition skills. Ear and Hearing. 1997; 18:240–251. [PubMed: 9201459]

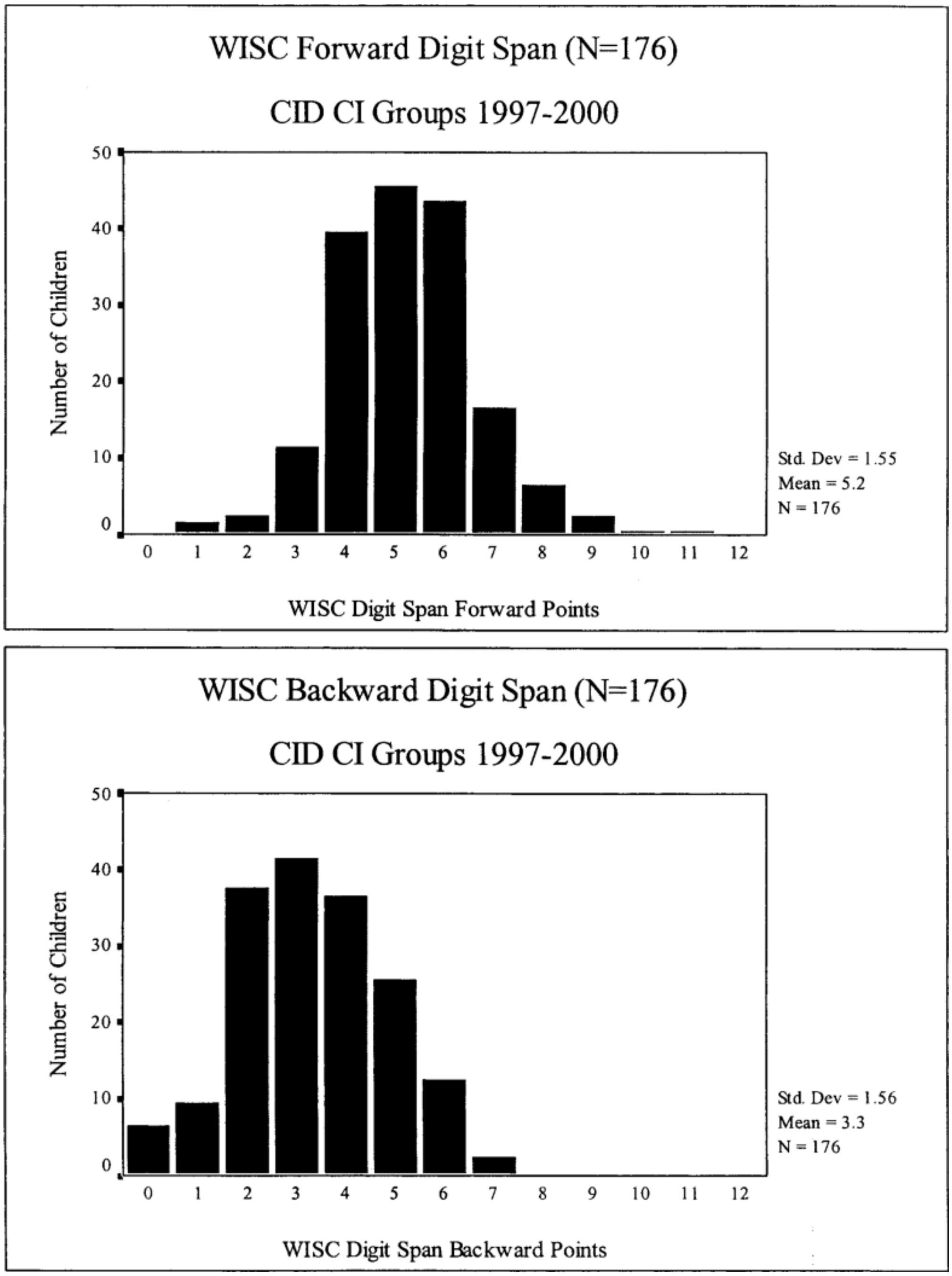

Figure 1.

Frequency histograms of WISC digit span scored by points for the 176 8- and 9-yr-old children with cochlear implants. Forward digit spans are in the top panel, backward digit spans in the bottom panel.

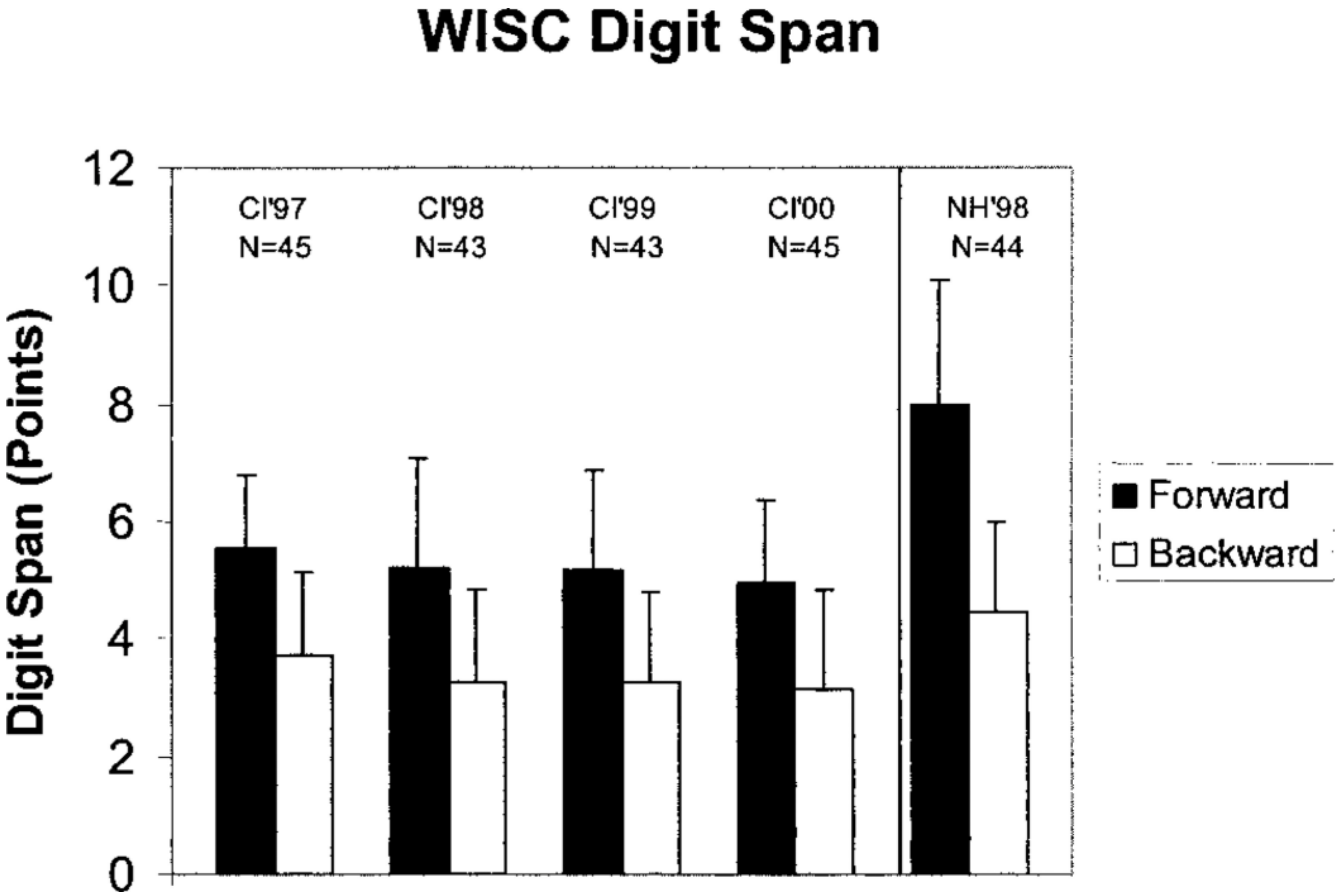

Figure 2.
Mean WISC digit spans scored by points for the four groups of 8- and 9-yr-old children with cochlear implants and for a comparison group of 8- and 9-yr-old normal-hearing children. Forward digit spans are shown by the shaded bars, backward digit spans by the open bars. Error bars indicate one standard deviation from the mean.

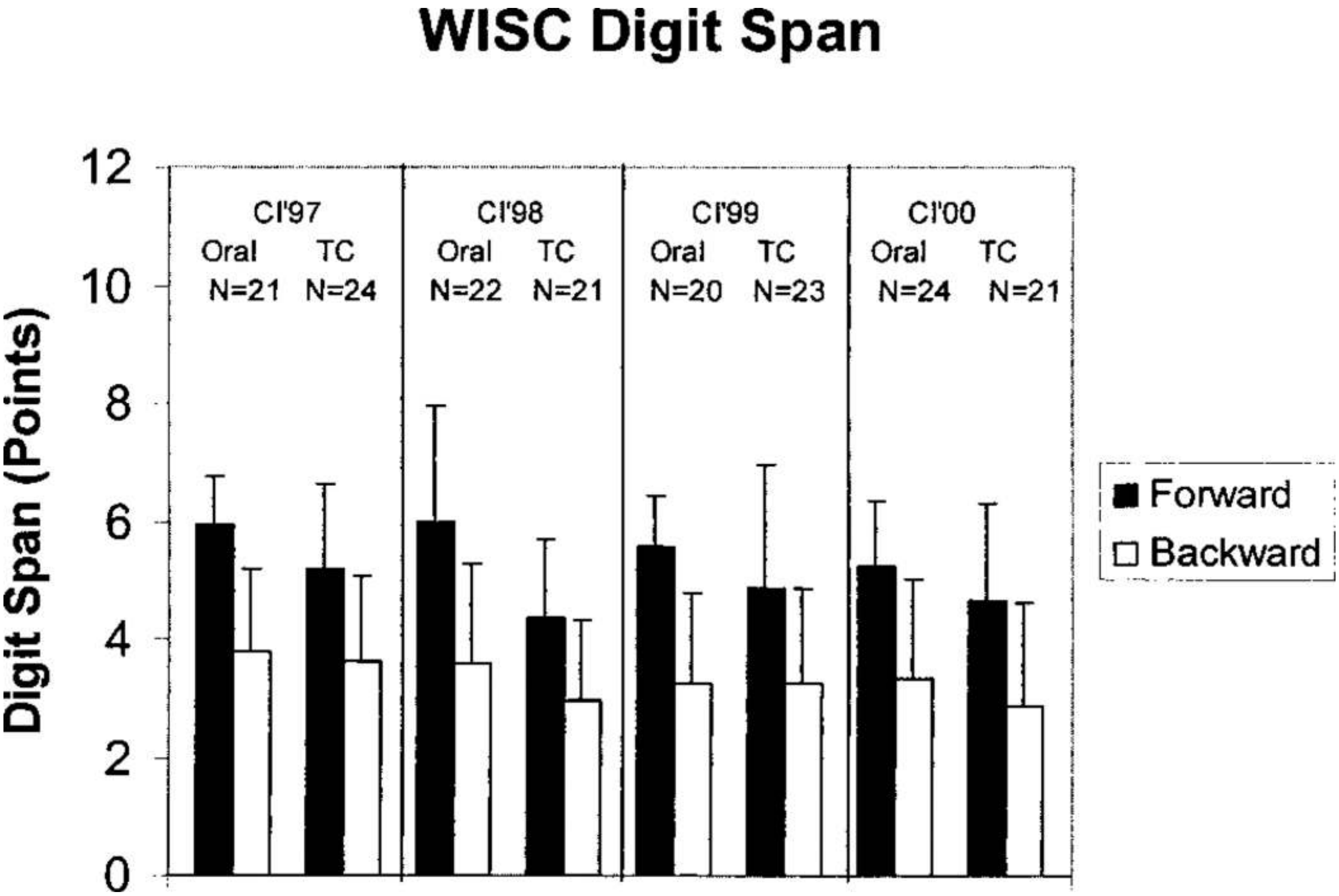

Figure 3.
Mean WISC digit spans scored by points for the four groups of 8- and 9-yr-old children with cochlear implants, separated by communication mode. For each year, scores for the oral group are shown to the left of those for the total communication group. Forward digit spans are shown by the shaded bars, backward digit spans by the open bars. Error bars indicate one standard deviation from the mean.

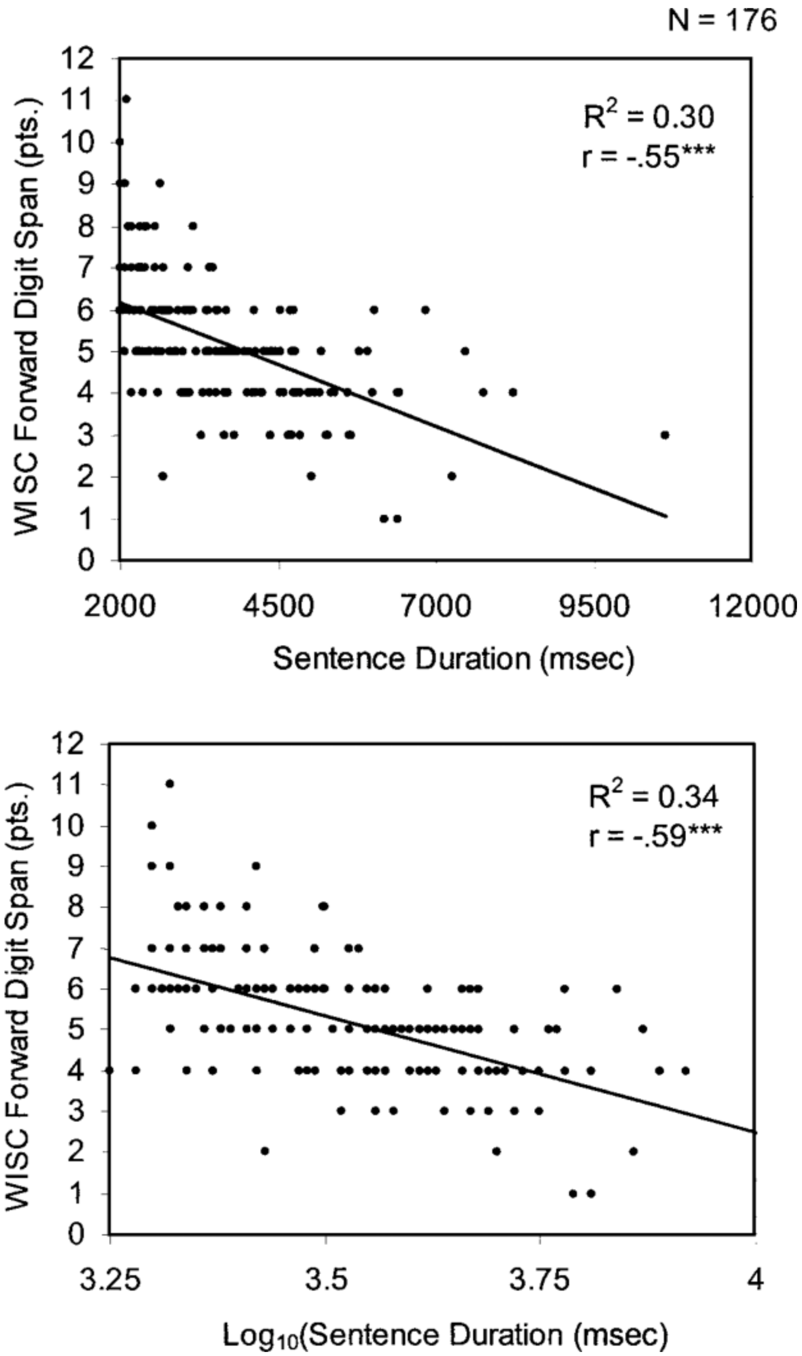

Figure 4.

Scatterplots illustrating the relationship between average sentence duration for the seven-syllable McGarr Sentences (abscissa) and WISC forward digit span scored by points (ordinate). Each data point represents an individual child. Nontransformed duration scores are shown in the top panel, log-transformed duration scores in the bottom panel. R-squared values indicate percent of variance accounted for by the linear relation.

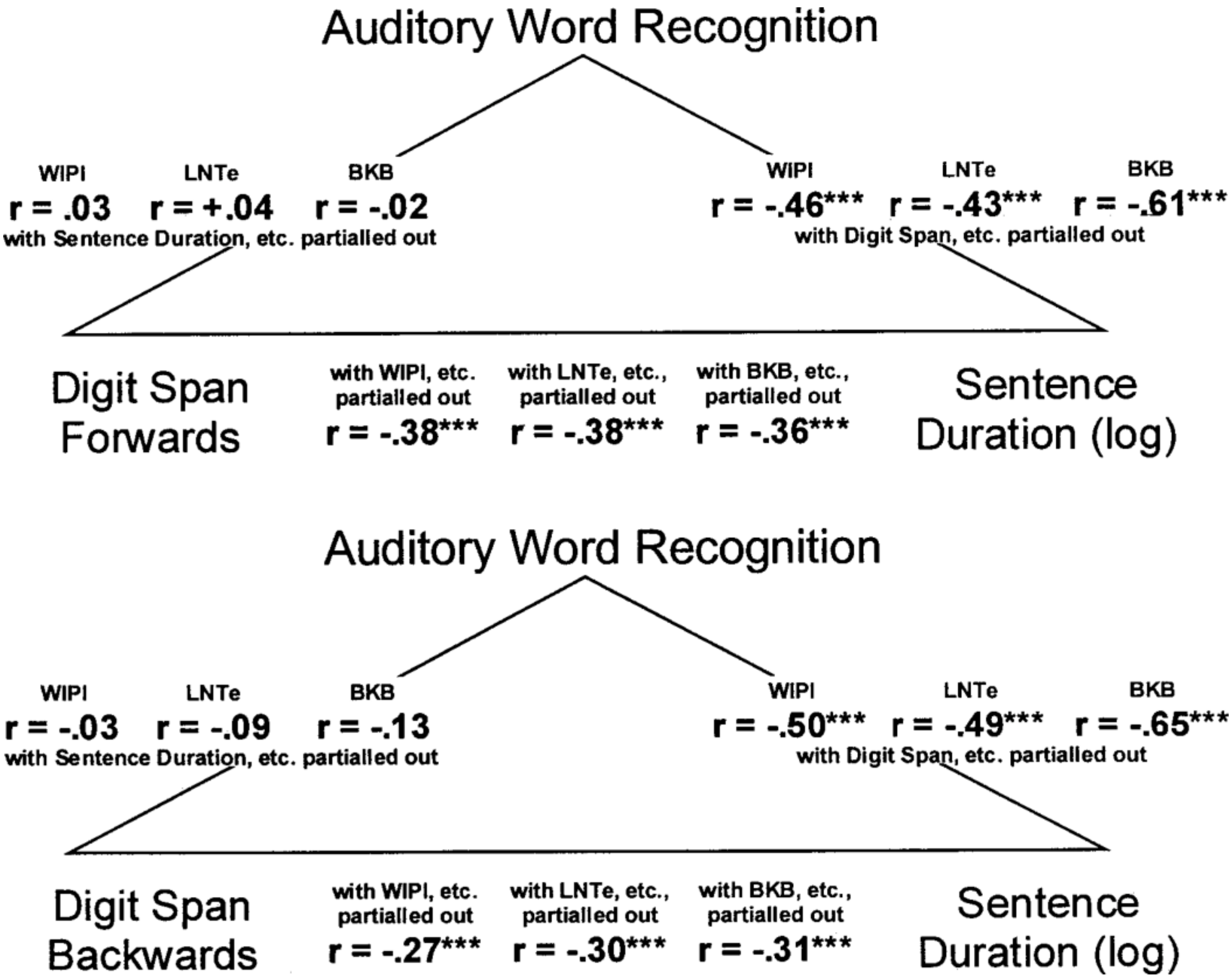

Figure 5.

Illustrates the 3-way relationship between auditory word recognition (WIPI, LNT-E, BKB), digit span, and sentence duration. The top panel shows the relations for forward digit span, the bottom panel shows the relations for backward digit span. Communication mode, age at onset of deafness, duration of deafness, duration of implant use, number of active electrodes, chronological age at test, and VIDSPAC total segments correct (a speech feature perception measure), have all been partialled out of each correlation, along with the influence due to the variable listed at the opposite vertex.

TABLE 1

Correlations between digit span and word recognition scores

	Simple Bivariate Correlations		Partial Correlations[a]	
	WISC Forward Digit Span	WISC Backward Digit Span	WISC Forward Digit Span	WISC Backward Digit Span
Closed set word recognition (WIPI)	0.42[***]	0.28[***]	0.25[**]	0.12
Open set word recognition (LNT-E)	0.41[***]	0.20[**]	0.24[**]	0.07
Open set word recognition in sentences (BKB)	0.44[***]	0.24[**]	0.27[***]	0.09

[***] $p < 0.001$;

[**] $p < 0.01$.

[a] Statistically controlling for: communication mode score, age at onset of deafness, duration of deafness, duration of cochlear implant use, number of active electrodes, VIDSPAC total segments correct (speech feature perception measure), age.

TABLE 2

Correlations between speaking rate and word recognition scores on the WIPI, LNT, and BKB

	Simple Bivariate Correlations		**Partial Correlations**[a]	
	Sentence Duration	**Log (Sentence Duration)**	**Sentence Duration**	**Log (Sentence Duration)**
Closed set word recognition (WIPI)	−0.65***	−0.68***	−0.47***	−0.51***
Open set word recognition (LNT-E)	−0.60***	−0.65***	−0.45***	−0.48***
Open set word recognition in sentences (BKB)	−0.71***	−0.76***	−0.59***	−0.64***

*** $p < 0.001$;

** $p < 0.01$.

[a] Statistically controlling for: communication mode score, age at onset of deafness, duration of deafness, duration of cochlear implant use, number of active electrodes, VIDSPAC total segments correct (speech feature perception measure), age.