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**Working Memory Capacity, Verbal Rehearsal Speed, and Scanning
in Deaf Children with Cochlear Implants¹**

Rose A. Burkholder and David B. Pisoni

*Speech Research Laboratory
Department of Psychology
Indiana University
Bloomington, Indiana 47405*

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Abstract. Cochlear implants have been an effective intervention for many profoundly deaf adults and children. Specifically, in prelingually deaf children, cochlear implants provide the first exposure to both environmental sounds and spoken language. After gaining access to sound and spoken language, many children using cochlear implants have been found to develop language with a developmental trajectory that is similar to normally-hearing children. However, several other cognitive skills of deaf children using cochlear implants appear to be atypical and do not develop fully even after several years of cochlear implant use. In this chapter, we review recent findings on cognitive processes in profoundly deaf children who use cochlear implants. Specifically, we discuss the shorter immediate memory spans of deaf children using cochlear implants and explain why measures of their speaking rate and speech timing provide important new clues to their verbal rehearsal and scanning processes. In addition, we also consider recent findings on the nonword repetition skills of deaf children who use cochlear implants. These results suggest that some deaf children with cochlear implants may have difficulties in rapidly encoding, rehearsing, and repeating novel phonological patterns. Our recent findings suggest that fundamental cognitive processes play an important role in the development of speech and language following cochlear implantation.

Introduction

The development of spoken language and other fundamental cognitive skills is strongly influenced by a variety of early social and sensory experiences. Although both vision and audition contribute to the early sensory experience of typical infants, audition may play a more important role in the earliest stages of perceptual and cognitive development. For instance, even before birth, in the third trimester, sounds and voices that penetrate the womb are easily detectable to most fetuses (Aslin, Jusczyk, & Pisoni, 1998). This auditory prenatal experience has been shown to have an impact on infants' subsequent abilities to recognize speech after birth (DeCasper & Spence, 1986). Thus, early vocal input is highly salient to infants and important for the development of communicative abilities. These findings also suggest that auditory information may provide the basis for some of the earliest memories in infants.

In addition, at birth, although inner ear structures are still developing, a normal infant's hearing is nearly as acute as an adult's (Aslin et al., 1998). However, visual acuity is extremely poor at birth and is typically not fully mature until several months later (Morrone & Burr, 1986). The precocious development of audition in infants suggests that hearing is likely to be the dominant sensory modality that contributes to early language and communication development and may also facilitate the development of cognitive abilities in other domains, including multimodal processing, attention, learning, and memory.

Based on these findings from normally-hearing, typically developing populations, it is important from both a theoretical and clinical perspective to begin investigating the cognitive development of infants who have been deprived of early sensory experience with sound. The lack of sufficient auditory input in humans has been found to have detrimental effects on the development of speech and language in a handful of well known cases of abused and abandoned children such as Genie (Curtis, 1977) and Victor the "Wild Boy of Aveyron" (Lane, 1979). Unfortunately in examinations of such feral children, any experimental outcomes and interpretations are confounded by the social and emotional isolation and abuse that these children may have experienced. However, unlike these rare cases, profoundly deaf

children are likely to be unscathed by such severe and tragic circumstances, making them a unique and potentially important clinical population in which to examine the impact of early spoken language deprivation on cognitive and linguistic development. In addition, in recent years, a smaller subset of profoundly deaf children has provided an unusual opportunity to answer what is perhaps an even more provocative question: What happens to the cognitive development of deaf children deprived of early auditory and linguistic experience who later gain exposure to sound and spoken language through a cochlear implant? In this chapter, some preliminary answers to this question are provided.

Due to prior inadequacies in diagnosing hearing problems in newborns and current FDA constraints on implanting deaf children very soon after birth, most profoundly deaf children who receive a cochlear implant have been deprived of auditory input for one or more years (Kirk, 2002). In addition, for many congenitally and prelingually deaf children, cochlear implants provide the first exposure to both environmental sounds and spoken language and, in some cases, may provide the first opportunity for these children to learn any language, spoken or signed. Because of this delayed onset of exposure to spoken language, deaf children using cochlear implants are a unique clinical population in which researchers can examine the ramifications of extended periods of auditory deprivation on the development of speech, language, and other cognitive abilities. In addition to the effects that early auditory deprivation can have on the eventual development of deaf children who have received cochlear implants, the children's behavioral and physiological responses to their new sensory input are important to study as well. Another paramount question to address in these deaf children is whether the sensory input from a cochlear implant can adequately facilitate normal spoken language development and other cognitive abilities that typically rely heavily on auditory and verbal coding skills.

However, some of these questions are not easy to answer because cochlear implants do not simply restore hearing to normal. Rather, they provide listeners with direct electrical stimulation of the auditory nerve and its afferents that must be translated into identifiable auditory percepts and used appropriately for whatever cognitive task is currently required (Rauschecker & Shannon, 2002). Therefore, a child with a cochlear implant must determine what sounds represent and mean and must learn to link these sounds to the visual and auditory events occurring around him or her. This complex perceptual learning task is also important to understand in order to successfully assess the speech, language, attention, learning, and memory skills of profoundly deaf children who have received cochlear implants.

Profoundly deaf children with cochlear implants are also an ideal population in which to study the effects of different *types* of early linguistic experience on language development. The amount and nature of aural-oral experience received after cochlear implantation differs substantially from child to child (Connor, Hieber, Arts, & Zwolan, 2000). The auditory-oral training and educational placement that a deaf child receives after cochlear implantation is typically referred to as his or her communication mode. Communication modes for such children fall along a continuum between exclusively oral communication that uses only speech and total communication that uses a form of signing such as signed exact English or cued speech in addition to spoken language. Although American Sign Language (ASL) does fall within this continuum, it is rarely used by deaf children using cochlear implants.

Differences in each child's communication mode after cochlear implantation allow for comparisons between groups of children based on the richness and robustness of their exposure to spoken language and their experience using primarily oral-aural communication. Such comparisons are informative because they can provide solid behavioral evidence of the degree to which the amount and quality of spoken language exposure received by deaf children with cochlear implants has an effect on the development of their speech, language, and other cognitive abilities. However, one caveat in

examining effects of communication mode on speech and language development in deaf children with cochlear implants is that placement into a communication mode or educational program is not random, and children who fail to thrive in oral communication programs are often put into total communication programs.

Although the development of the speech and language skills of deaf children after cochlear implantation has been the primary area of interest to most clinicians who are interested in measuring benefit and outcome in this population, several recent studies have begun to study other cognitive skills of these children such as attention, learning, and memory. However, this new interest in cognitive processes should not be viewed as a divergence from research focused on speech and language in deaf children using cochlear implants. Rather, recent investigations of learning and memory processes in deaf children using cochlear implants may provide new insights into speech and language development and provide principled explanations for the enormous individual differences in outcome and benefit that have been observed in this clinical population (Pisoni, Cleary, Geers, & Tobey, 2000).

An extensive body of literature examining normally-hearing populations has shown that attention, learning, and memory processes are all intertwined and closely related to vocabulary development and language learning. Attention, learning, and memory account for a large amount of variability that is observed in the language skills of normally-hearing adults and children (Baddeley, Gathercole, & Papagno, 1998; Cowan, 1996; Cowan, Nugent, Elliott, Ponomarev, & Sults, 1999; Gupta, 2003). For example, differences in working memory have been found to be closely related to vocabulary knowledge and the development of spoken and written language abilities in normally-hearing adults and children (Cowan, 1996; Gathercole & Baddeley, 1989; Gathercole, Willis, Emslie, & Baddeley, 1992; Gupta, 2003). In addition, working memory processes have also been linked to language proficiency in deaf children who do not use cochlear implants (Bebko, Bell, Metcalfe-Haggert, & McKinnon, 1998). Thus, in addition to providing vital knowledge about the role of early auditory and linguistic experience in learning and memory, the study of memory processes in deaf children with cochlear implants may also yield new fundamental knowledge about speech and language development.

Direct links between working memory performance and the development of speech and language skills have recently been documented in deaf children using cochlear implants. Pisoni and Cleary (2003) found that immediate memory capacity, measured by forward digit span, was strongly correlated with deaf children's scores on several different word recognition tasks. In addition, serial recall has also been found to be related to the receptive vocabulary of deaf children using cochlear implants (Dawson, Busby, McKay, & Clark, 2002). However, only recently have some of the more intricate aspects of memory processing abilities in deaf children with cochlear implants been explored to uncover how they may influence speech and language development.

The following sections review recent research examining several memory processes that may be intimately connected to speech and language development. Specifically, we summarize findings on working memory capacity, verbal rehearsal, and serial scanning processes in profoundly deaf children using cochlear implants and discuss how they are related to the basic cognitive skills that have been shown to be important to traditional speech and language outcome measures used to assess benefit with a cochlear implant. The usefulness of measuring temporal characteristics of speech, such as speaking rate and interword pause durations, to index the speed of subvocal verbal rehearsal and serial scanning in deaf children using cochlear implants is also discussed. We present the results of these speech-timing studies and consider their implications for the development and the use of subvocal verbal rehearsal and serial scanning in deaf children with cochlear implants and discuss why these two fundamental memory processes contribute to the shorter immediate memory spans observed in these children. Overall, the

findings presented here indicate that, in addition to perceptual difficulties related to their hearing impairment and the encoding of degraded auditory input, atypical development of subvocal verbal rehearsal and serial scanning also contribute to the decreased memory spans of deaf children using cochlear implants. Interestingly, these results are similar to what has been found in deaf children who do not use cochlear implants (see Marschark & Mayer, 1998 for a review).

In addition to research on immediate memory and scanning, several recent findings on the nonword repetition skills of deaf children with cochlear implants are described. These new results suggest that some deaf children with cochlear implants have substantial difficulties in rapidly encoding, rehearsing, and repeating novel phonological patterns. Such difficulties indicate that deaf children with cochlear implants have developed atypical phonological processing skills. Finally, we discuss the influence of communication mode and early oral-aural experience on memory and nonword repetition performance. These differences in communication mode suggest that early linguistic experiences and activities after cochlear implantation play a substantial role in perceptual and cognitive development. Taken together, the findings presented here suggest that fundamental linguistic and phonological processing skills used in memory and nonword repetition tasks may play a foundational role in the development of speech and language skills following cochlear implantation. In addition, these findings reveal that basic memory processes such as encoding, subvocal verbal rehearsal, and serial scanning of short-term memory are atypical in deaf children using cochlear implants and appear to be closely related to the nature and amount of early auditory and linguistic exposure received by these children after cochlear implantation.

Memory Abilities in Deaf Children without Cochlear Implants

Prior to the recent interest in deaf children using cochlear implants and their aural rehabilitation, much research focused on deaf children communicating with manually signed visual-spatial language such as ASL or one of the signing systems created to accompany spoken language. Research concerning the acquisition of signed language and its influence on cognitive and social development encouraged a series of investigations of memory development in this population (e.g., Bebko, 1984; Campbell & Wright, 1990; Liben & Drury, 1977; Marschark & Mayer, 1998). The early work on the memory processes of deaf children who use manual signs and lack a fully developed native spoken language was an important precursor to the current investigations of the memory of deaf children using cochlear implants (Marschark & Mayer, 1998). Several studies have shown that when confronted with a specific language processing task that relies on memory, many deaf children, like their normally-hearing peers, use covert verbal rehearsal as a strategy to maintain items in short-term memory (Bebko, 1984; Liben & Drury, 1977). Covert verbal rehearsal is assumed to involve the repeated cycling of verbally coded memory representations within the phonological loop of working memory in order to prevent memory decay (Baddeley et al., 1975).

One of the strongest pieces of evidence that deaf children use covert verbal rehearsal strategies came from a study by Campbell and Wright (1990). They found that deaf children, like normally-hearing children and adults, are susceptible to the word length effect. Word length effects are observed when the number of lexical items that can be recalled from immediate memory is determined by the length of the words in the list. Word length effects occur because longer words take more time to articulate and subvocally rehearse and cannot be refreshed as quickly and efficiently within the phonological loop. As a result of the decreased rate of subvocal verbal rehearsal, memory spans for lists of longer words will be shorter. Evidence of the word length effect and covert verbal rehearsal strategies in deaf children suggests that they are capable of processing and repeatedly recycling linguistic input within the short-term memory store (Baddeley et al., 1975).

Despite utilizing memory strategies that are similar to their normally-hearing peers, deaf children behave atypically on a wide variety of memory tasks. In particular, phonological memory tasks appear to be the most difficult for deaf children to carry out, especially when they involve encoding and retrieval of sequential information (Banks, Gray, & Fyfe, 1990; Waters & Doehring, 1990). Early onset deafness can also produce substantial differences in performance on memory tasks that require the management and manipulation of phonological or linguistic information. However, what has previously remained unknown is whether, after a prolonged period of auditory and spoken language deprivation, cochlear implantation can ameliorate or even prevent some of these disadvantages and allow deaf children who receive a sensory aid to perform more like their normally-hearing peers on a wide range of language and memory tasks.

Working Memory Capacity in Deaf Children with Cochlear Implants

Several recent studies have shown that deaf children with cochlear implants have shorter immediate memory spans than their normally-hearing, age-matched peers. The first evidence of shorter memory spans in deaf children using cochlear implants was obtained using the WISC-III auditory digit span task which provided a measure of immediate memory capacity (Pisoni et al., 2000; Pisoni & Geers, 2000). The WISC-III auditory digit span task is administered to children live-voice with lip reading cues available and involves two different recall conditions. In forward digit span recall, children are simply asked to repeat back a sequence of digits in their exact order of presentation. In the backward digit span task, children are required to repeat the digits in the reverse order of their original presentation.

In both the forward and backward digit span tasks, deaf children with cochlear implants performed worse than their normally-hearing peers. Figure 1, adapted from Pisoni and Cleary (2003), displays the forward and backward digit spans obtained from 176 deaf children using cochlear implants obtained over a four year period along with a comparison group of 44 age-matched, normally-hearing children. All children were between 8- and 9-years-old and the deaf children had around 4 to 7 years of experience with their implant (Geers et al., 1999). Subsets of this sample of children were used for all of the subsequent studies discussed in this chapter that were conducted by our lab. The top panel of this figure shows that the digit spans of all four groups of deaf children using cochlear implants were significantly shorter than the digit spans of the normally-hearing children who are shown on the right.

The bottom panel of Figure 1 shows that, in addition to memory span differences found between normally-hearing children and deaf children using cochlear implants, deaf children with cochlear implants who used oral communication methods had longer forward digit spans than children who used total communication. These results provided the first evidence that the quality and quantity of aural and oral exposure can have a systematic effect on immediate memory span capacity for sequential patterns in deaf children using cochlear implants. Specifically, as has been suggested in deaf individuals without cochlear implants, the quality and quantity of oral and aural experience of deaf children with the devices may mediate or influence memory processing strategies such as perceptual and phonological encoding, subvocal verbal rehearsal, and serial scanning (Bebko & Metcalfe-Haggert, 1997).

Given that digit span recall requires the verbal repetition of auditory stimuli, it is reasonable to ask whether perceptual encoding or articulatory difficulties may have substantially contributed to the shorter digit spans observed in the deaf children using cochlear implants, particularly those who used total communication. If a deaf child using a cochlear implant cannot detect and accurately perceive what digit was spoken or has such unintelligible speech that even when the correct response is known it cannot be articulated in any identifiable form, memory capacity may be underestimated. It is also important to consider the role of perceptual or articulatory difficulties in memory performance, because in some

memory tasks using only visual stimuli and nonverbal responses, deaf children with cochlear implants perform as well as their normally-hearing peers. For instance, in memory tasks requiring recognition memory for faces or the reproduction of a pattern of visually and spatially arranged dots, deaf children with cochlear implants fall within the normative range of scores obtained for normally-hearing children (Cleary & Pisoni, 2004). Not surprisingly, this result is similar to what has been found in deaf children who do not use cochlear implants (Bellugi, O’Grady, Lillo-Martin, O’Grady-Hynes, Van-Hoek, et al., 1990; Campbell & Wright, 1990; McDaniel, 1980; Olsson & Furth, 1966).

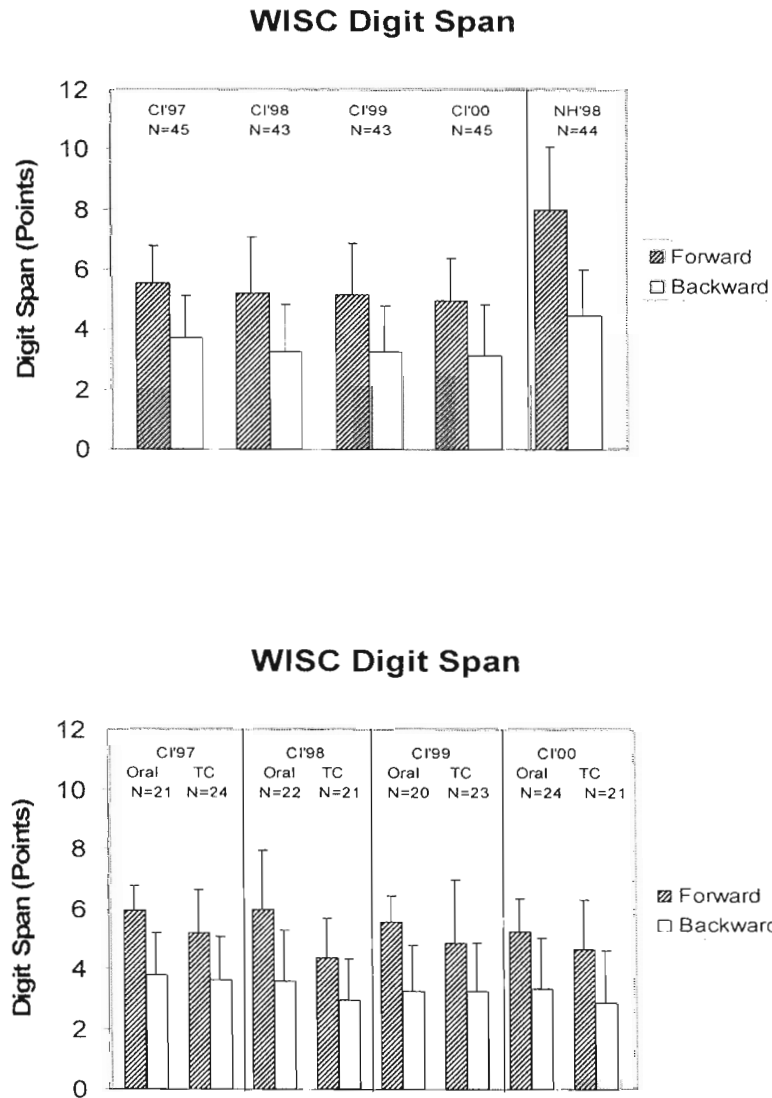


Figure 1. Mean WISC-III digit spans from four groups of 8- and 9-year-old deaf children with cochlear implants and normally-hearing children. The top panel shows the digit spans of all deaf and normally-hearing children, and the bottom panel shows the group of deaf children with cochlear implants split according to communication mode. Error bars represent standard error of the mean. (Adapted from Pisoni & Cleary, 2003)

However, deaf children using cochlear implants have been found to have shorter memory spans than their normally-hearing peers in visual memory tasks in which the stimuli are presented sequentially. Using a customized version of the popular memory game “Simon” by Milton Bradley, Cleary, Pisoni, and Geers (2001) reported that deaf children using cochlear implants had shorter reproductive visual memory spans than their normally-hearing peers. Figure 2 shows a version of the Simon apparatus that is nearly identical to the one used to measure memory span in the deaf and normally-hearing children. The Simon memory task used in this study involved presenting randomly generated patterns of colored lights to the children. All patterns were combined using four possible colors (blue, green, red, yellow) and got progressively longer during the task. Children were required to reproduce the patterns by manually pressing the colored and illuminated response buttons on the Simon apparatus which was interfaced to a computer that recorded all responses.

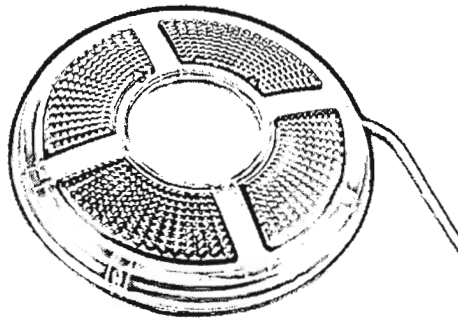


Figure 2. Simon memory span game adapted for use with deaf and normally-hearing children.

Cleary et al.’s findings suggest that problems with memory processes other than the early auditory encoding of linguistic input may also contribute to the shorter digit spans of deaf children who use cochlear implants. They reasoned that deaf children using cochlear implants performed poorly even on a visual memory span task because they had difficulty in coding visual sequences verbally and were slower at subvocally rehearsing the verbally coded sequential information in working memory (Cleary et al., 2001). Thus, although the Simon memory task is ostensibly based on visual information (the colors of buttons) the most successful strategy to complete the task is to use some form of verbal coding and subvocal verbal rehearsal of color names rather than relying exclusively on visual cues.

Although the deaf children with cochlear implants are able to use subvocal verbal rehearsal, they are at a disadvantage relative to their normally-hearing peers because of their lack of early linguistic experience and aural-oral activities which would ordinarily facilitate rapid execution of this rehearsal strategy. However, the effects of deafness and lack of sensory input on memory performance appear to dissipate when stimuli in memory tasks are not as likely to be verbally encoded (Cleary & Pisoni, 2004; Dawson et al., 2002). For instance, in several serial short-term memory tasks using either tones or hand gestures as stimuli, Dawson and colleagues found that deaf children using cochlear implants performed just as well as their normally-hearing peers.

Taken together, these recent results indicate that verbal encoding problems most likely prevent deaf children with cochlear implants from performing as well as their normally-hearing peers on both auditory and visual memory tasks. However, verbal encoding is not the only underlying memory process required to perform a digit span recall or serial short-term memory task. As mentioned earlier, subvocal

verbal rehearsal is also an important component of working memory. To gain a better understanding of how working memory functions in this clinical population, we explored the verbal rehearsal process in much greater detail using several different measures of speech timing.

Speech Timing and Memory Processes in Deaf Children with Cochlear Implants

In normally-hearing children, several fundamental memory components have been successfully delineated by examining temporal aspects of speech production using speech timing measures. Measures of speech timing during memory tasks completed by normally-hearing children have been used to index both subvocal or covert verbal rehearsal as well as serial scanning of items in short-term memory (Cowan, 1992; Cowan, Wood, Wood, Keller, Nugent et al., 1998). One basic form of speech timing that Cowan and colleagues have measured is overt speaking rate. Measures of overt speaking rate can be used to estimate the rate of subvocal verbal rehearsal in immediate memory. The idea that overt speaking rate is an appropriate measure of subvocal verbal rehearsal is based on a large body of memory research that has found a consistent and strong linear relationship between speaking rate and memory span in both normally-hearing children and adults (Baddeley, Thompson, & Buchanan, 1975; Hitch, Halliday, & Littler, 1989; Hulme & Tordoff, 1989; Kail & Park, 1994; Schweickert, Guentert, & Hersberger, 1990). In general, these studies have found that speakers who articulated faster also had longer digit spans. According to Baddeley and his colleagues (1975), the relationship between speaking rate and immediate memory span occurs because the faster an individual speaks and thus rehearses subvocally, the more frequently items can be refreshed within the phonological loop. A faster rate of rehearsal through this loop will facilitate the recall of more items and ultimately result in a longer memory span.

The finding that speech-timing measures may reflect basic memory processes was explored further by Cowan and his colleagues (1992; 1994) using measures of serial scanning. Scanning is the process by which each item in a list is individually located in short-term memory. This process is carried out by retrieving the items within a list serially during each interword pause taken during the period of recall (Sternberg, 1966). In contrast to measures of overt speaking rate that are frequently derived from sentence repetition or speeded articulation tasks, measures used to estimate serial scanning speed are made during the actual recall process of immediate serial recall tasks. Memory scanning activities can be conveniently indexed by measuring the durations of the interword or inter-item pause durations that occur during digit span recall. Figure 3, adapted from Burkholder and Pisoni (2003b), shows a schematic representation of how interword pauses are measured from speech production samples made during digit span recall.

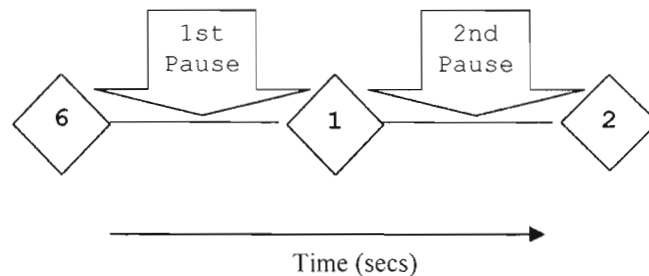


Figure 3. Schematic representation of interword pause duration measures made on WISC-III forward digit span responses. Example of a three digit list (6 1 2).

The serial scanning process begins with the onset of the first pause taken during recall and continues until the next item on the list is determined. Thus, during the first pause in serial recall, between the first and second items on the list, scanning occurs until the second item in the list is located and articulated. Similarly, during the pause between the second to last and last items, nearly the entire list has to be scanned until the final item to be recalled is located. Cowan (1992) observed that the pause durations during immediate recall increase as later digits are recalled. This increase in duration occurs because more items from the list must be scanned through in serial order as the final items of the list are recalled.

Cowan and colleagues (1994) also examined maturational effects on speech-timing in normally-hearing children. They found that 8-year-olds spoke significantly faster and had shorter interword pause durations in immediate recall than 4-year-olds. These findings suggested developmental increases in speed of subvocal verbal rehearsal and serial scanning. Increases in subvocal verbal rehearsal speed and serial scanning rates appeared to facilitate immediate memory span recall in the children Cowan examined. In addition to having faster speaking rates and shorter pause times in recall, the 8-year-old children also displayed significantly longer memory spans than the 4-year-old children.

Based on Cowan's findings that speech-timing measures in recall can be used as an index of covert memory processes that influence the immediate memory spans in normally-hearing children, Burkholder and Pisoni (2003b) conducted a speech-timing analysis on the digit span responses of 37 profoundly deaf children using cochlear implants. The children were between 8- and 9-years-old and had 4.5 to 7 years of experience with their cochlear implants. In our study, both the overt speaking rates and pause durations of profoundly deaf children with cochlear implants were compared to a set of measures obtained from a group of 36 age-matched, normally-hearing controls. Speaking rate was obtained from the two groups by measuring the durations of short sentences taken from the McGarr Sentence Intelligibility task (McGarr, 1981).

The McGarr stimulus materials consisted of 36 sentences of 3-, 5-, and 7-syllables, each with 12 sentences at each syllable length. The sentences were elicited by simply asking the children to listen to each sentence as it was read by the clinician or experimenter and then providing them with the written text of the sentence. With the text of the sentence placed in front of them, the children were asked to repeat the sentence at their usual speaking rate. Providing the written text of the sentences reduces the memory load involved in the task and also guards against errors in repetition due to misperception of the spoken sentence. Further assurance that the deaf children with cochlear implants repeated the sentences correctly was achieved by allowing them up to three chances to repeat each sentence. All sentences spoken by both groups of children were digitally recorded and measured using waveform editing software.

Figure 4, adapted from Burkholder and Pisoni (2003b), displays the McGarr sentence durations obtained from the 8- and 9-year-old deaf children with cochlear implants and their aged-matched, normally-hearing peers. The mean durations of the 3-, 5-, and 7-syllable sentences are each shown separately on the abscissa. In addition, the mean duration of all sentences combined together is shown in this figure. The top panel of this figure clearly illustrates that deaf children using cochlear implants had significantly slower speaking rates than their normally-hearing peers on these sentences. In addition, the bottom panel of the figure shows that children who use total communication spoke significantly slower than children who use oral communication methods.

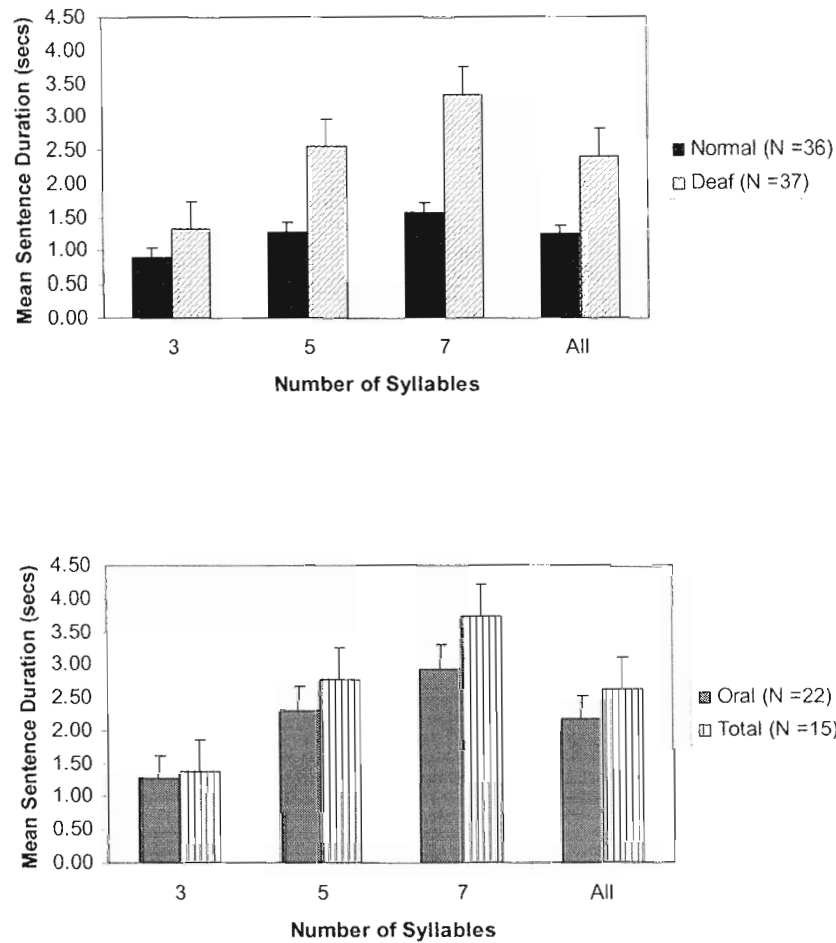


Figure 4. Mean sentence durations of normally-hearing children and deaf children using cochlear implants. The top panel shows sentence durations of normally-hearing children and deaf children using cochlear implants, and the bottom panel shows the sentence durations of the deaf children with cochlear implants split according to communication mode. Error bars represent standard error of the mean. (Redrawn from Burkholder & Pisoni, 2003b)

Slower speaking rates have been documented in deaf individuals previously and are attributed in part to the lack of auditory feedback while speaking (Bochner, Barefoot, & Johnson, 1987). However, even with the newly provided auditory feedback from a cochlear implant, deaf children still appear to be unable to produce speaking rates within normal ranges. Based on the findings obtained in previous research examining speaking rate and memory, the pediatric cochlear implant users' inability to overtly articulate at rapid paces may underlie differences in covert verbal rehearsal and result in these children having shorter digit spans than their normally-hearing peers.

The proposal that slower speaking rates and subvocal rehearsal speeds may contribute to the shorter memory spans of the deaf children with cochlear implants was further confirmed through analyses showing a robust correlation between their speaking rates and digit spans (Burkholder & Pisoni, 2003b; Pisoni & Cleary, 2003). Figure 5, adapted from Pisoni and Cleary (2003), displays the correlation between sentence durations and forward digit spans of 176 deaf children using cochlear implants. The

log-based transformation of McGarr sentence durations appears on the abscissa and WISC-III digit span points appear on the ordinate.

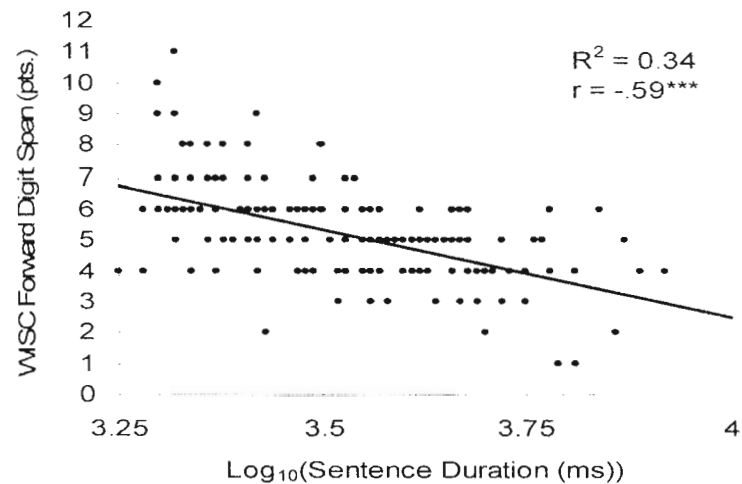


Figure 5. Scatterplot illustrating the relationship between average sentence durations for the seven-syllable McGarr Sentences and WISC-III forward digit span scored by points. The sentence durations were log-transformed. R-squared values indicate percent of variance accounted for by the linear relation. (Adapted from Pisoni & Cleary, 2003)

Based on this robust correlation between sentence duration and memory span, it appears that deaf children with cochlear implants and those deaf children without perform worse than their normally-hearing peers on serial recall tasks such as digit span recall because they are not able to subvocally rehearse the digits fast enough. In addition, the correlations between forward digit spans and speaking rate obtained within both the normally-hearing children and deaf children using cochlear implants were of a similar magnitude. These results indicate that basic subvocal verbal rehearsal processes operate similarly in these two different populations and may contribute in comparable ways to immediate memory span for spoken digits.

Although both the pediatric cochlear implant users' shorter forward digit spans and their strong correlation with speaking rate were expected, one other result from this study was unexpected and interesting. Correlations conducted between backward digit span and speaking rate revealed a strong relationship for the group of deaf children with cochlear implants. However, the group of normally-hearing children did not display a correlation between backward digit span and speaking rate (Burkholder & Pisoni, 2003b). This result suggests that the deaf children with cochlear implants may be using the same subvocal verbal rehearsal strategy to complete the backward digit span task that they used in the forward digit span task. This strategy may not be as efficient as the executive planning and organizational strategies that normally-hearing children use to perform the same memory task. Thus, not only may some of the pediatric cochlear implant users' subvocal verbal processing strategies suffer because they are carried out more slowly than normally-hearing children's, but the subvocal verbal rehearsal strategies could also be inappropriately engaged during certain tasks, such as backward digit span recall, in which other planning, rehearsal, and recall strategies would be more useful (Thomas, Milner, & Haberlandt, 2003).

In addition, it is also possible that the shorter digit spans observed in the deaf children with cochlear implants may be due to their inability to scan test items in memory as fast as normally-hearing children. Following the same procedures that Cowan et al. (1994) used, scanning rates during the digit span task were obtained by measuring the interword pause durations taken from digital audio recordings of pediatric cochlear implant users and normally-hearing children completing the actual recall portion of the task. Figure 6, adapted from Burkholder and Pisoni (2003b), displays mean interword pause durations produced by deaf children with cochlear implants and normally-hearing children during WISC-III forward digit span recall. Mean interword pause durations are shown for digit span lists of three and four digits and the longest list recalled by each child which is denoted as the list limit.

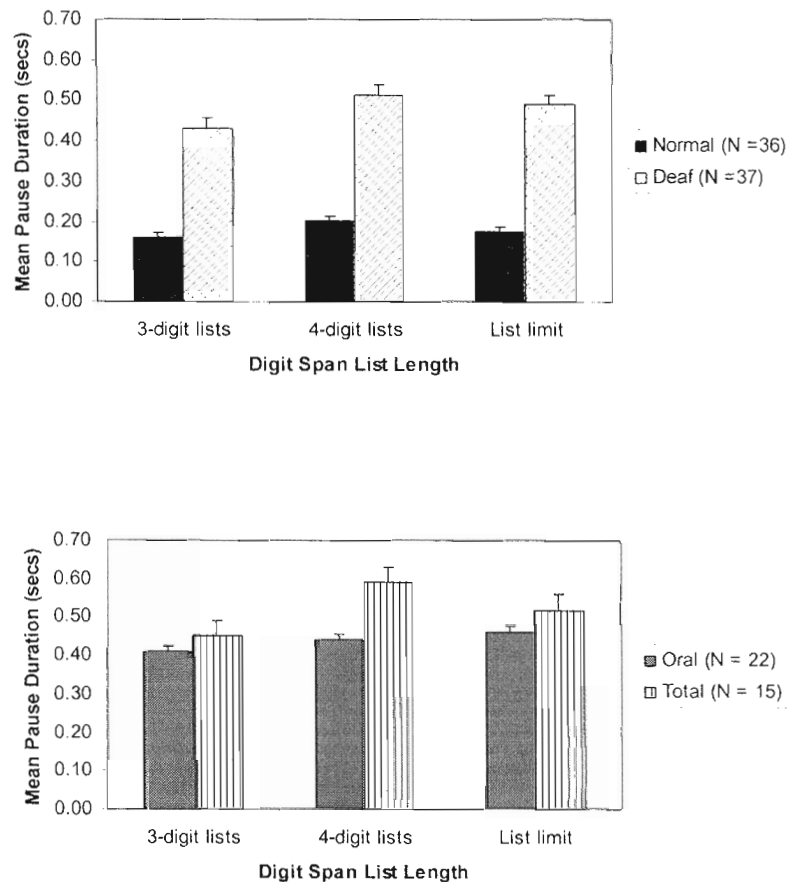


Figure 6. Mean interword pause durations taken during WISC-III forward digit span recall for list lengths of 3 and 4 digits and the span limiting list or longest list correctly recalled. The top panel shows the pause durations of both normally-hearing and deaf children using cochlear implants and the bottom panel shows the pause durations of deaf children using cochlear implants split according to communication mode. Error bars represent standard error of the mean. (Redrawn from Burkholder & Pisoni, 2003b)

The top panel of Figure 6 illustrates that the deaf children using cochlear implants were significantly slower than their normally-hearing peers while scanning items during digit span recall. In fact, the pediatric cochlear implant users' interword pause durations taken during digit span recall were

nearly twice as long as the normally-hearing children's interword pause durations when recalling lists of three and four digits and in the longest list they were able to correctly recall. These slower serial scanning rates may also be responsible for the shorter memory spans of deaf children using cochlear implants.

Subvocal verbal rehearsal and serial scanning processes both rely on phonological or linguistic encoding. Thus, the lack of early auditory sensory input and linguistic stimulation in the deaf children is likely to be another important factor affecting subvocal verbal rehearsal speed and serial scanning rates resulting in shorter digit spans. When considered together with Cowan et al.'s (1994; 1999) earlier findings on speech timing and memory, the speech-timing study in deaf children using cochlear implants suggests that maturation of subvocal verbal rehearsal and serial scanning not only depends on chronological age but also on the amount and type of early linguistic exposure that children receive. The role that linguistic information plays in these memory processes also explains why the children who used communication methods that stress auditory-oral training performed better than the children who used total communication. The richer auditory-oral exposure and experience that the children using oral communication receive likely facilitates their performance on a wide range of linguistic tasks that use subvocal verbal rehearsal and serial scanning of short-term memory because they are able to rapidly decompose and linguistically represent auditory-verbal sensory information. In addition, children using oral communication methods may have an advantage on auditory memory tasks because they have less difficulty retrieving these items and reassembling them into an intelligible spoken response.

Memory Recall Errors in Deaf Children Using Cochlear Implants

Recently, additional evidence has been collected suggesting that the pediatric cochlear implant users' shorter auditory digit spans are primarily related to memory processing problems such as subvocal verbal rehearsal and serial scanning. Burkholder and Pisoni (2004) examined and categorized the errors made during digit span recall by deaf children using cochlear implants to determine whether their errors were primarily due to encoding item or order information incorrectly. Each individual error made during spoken recall was classified as one of four types of errors. Errors caused by the recall of digits in an incorrect order were considered to be order errors. Errors caused by the recall of a digit or digits that were not present in the original list were considered to be item errors. Errors in digit span recall caused by the failure to repeat one or more digits were considered to be omissions. Finally, errors that represented both item and order errors were considered to be combination errors.

The two types of errors with the most relevance in this analysis were item and order errors (Conrad, 1965). Order errors result from the loss of temporal order information during encoding or spoken recall. In a serial recall task, encoding sequential order and maintaining this information until recall is a complex process. Therefore, errors in order are most likely related to mistakes in processing due to increased cognitive load. In contrast, item errors result in the replacement of an individual digit in the list with a digit that was not presented in the original list. In a group of deaf children using cochlear implants, item errors are likely indicative of encoding problems rather than slowed or inefficient rehearsal or scanning. Therefore, it is important to dissociate these two types of errors from one another in memory recall.

Figure 7, adapted from Burkholder and Pisoni (2004), shows the proportion of each type of error made in the forward (top panel) and backward (bottom panel) digit span task for both the deaf children using cochlear implants and the group of age-matched, normally-hearing peers. By using this categorization process, Burkholder and Pisoni (2004) found that the proportion of order errors exceeded all other types of errors made by deaf children with cochlear implants during auditory digit span recall.

Although this was an auditory memory task, the performance of the deaf children with cochlear implants appeared to be more influenced by order errors rather than item errors.

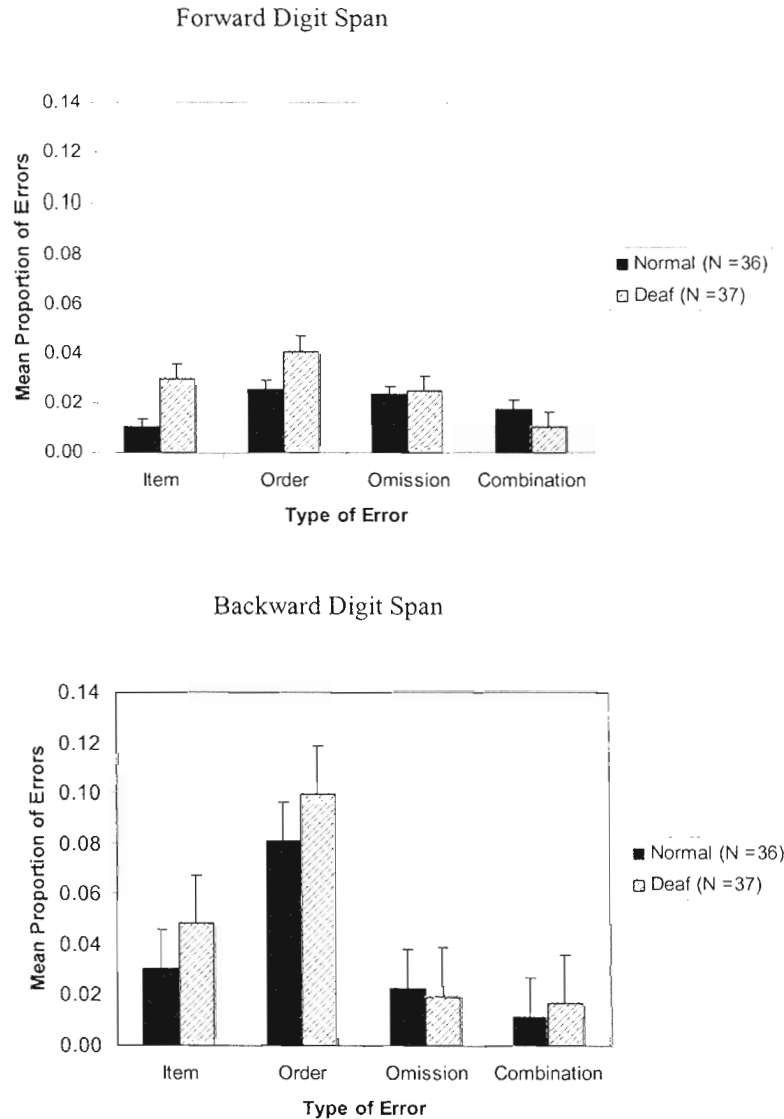


Figure 7. Mean proportion of error types made by normally-hearing children and deaf children using cochlear implants during digit span recall in forward (top panel) and backward (bottom panel) recall conditions. Error bars represent standard error of the mean.

The pattern of errors made by the deaf children using cochlear implants was similar to the results found for normally-hearing children. Both the deaf and normally-hearing children committed significantly more order errors than item errors during digit span recall. In addition, order errors were more numerous in backward digit span recall than in forward digit span recall. This result is not surprising because backward digit span is considered to be a more complex and demanding task requiring planning and recall strategies and executive function that may lead to an increased processing load (Li & Lewandowsky, 1995).

Taken together, three converging sets of findings suggest that deaf children with cochlear implants perform more poorly on memory span tasks because they covertly rehearse and scan items in short-term memory more slowly than normally-hearing children. First, deaf children with cochlear implants do poorly even on memory span tasks that do not require encoding of auditory stimuli and spoken responses (Cleary et al., 2001). This result provides support for the proposal that deaf children with cochlear implants not only have difficulty perceiving and encoding auditory stimuli, but they have other memory processing problems that are not tied exclusively to input modalities used in the memory assessments.

Second, Burkholder and Pisoni's (2003b) speech-timing analysis found that the pediatric cochlear implant users' sentence and interword pause durations were significantly longer than the sentence and interword pause durations of their normally-hearing peers. These results suggest that the memory processes reflected in these measures, subvocal verbal rehearsal and serial scanning, also operate more slowly in the deaf children with cochlear implants. Finally, by directly examining the nature of the errors in digit span recall, Burkholder and Pisoni (2004) found a greater proportion of order errors than item errors made in immediate serial recall by deaf children using cochlear implants. This result suggests that deaf children with cochlear implants not only have difficulty in perceiving spoken digits but they frequently fail to encode and maintain the correct serial order of the digits in a test sequence. Therefore, a solid body of evidence suggests that encoding order information may be more difficult for deaf children with cochlear implants than correctly perceiving the degraded stimuli received through their cochlear implant.

Nonword Repetition in Deaf Children with Cochlear Implants

In addition to measures of immediate memory capacity using digit span, nonword repetition has also been a useful methodology to examine phonological working memory skills in normally-hearing children. Differences in nonword repetition performance have been found to be related to novel word learning in both adults and children (Gathercole & Baddeley, 1989; Gathercole et al., 1992; Gupta, 2003). The relationship between novel word learning and nonword repetition should come as no surprise, because in any word learning task, whether in an experimental or real-world setting, words originally begin as nonwords for those trying to learn them. Therefore, measures of nonword repetition may be useful in assessing the fundamental operation of word learning ability in deaf children using cochlear implants. Unlike spoken word recognition or sentence repetition tasks, nonword repetition is one method that can be used to measure both speech perception and production skills in the absence of higher-level contextual and lexical influences.

However, there are numerous other information processing skills that play a role in successfully completing a nonword repetition task. Although the task of repeating a nonword may intuitively sound as if it is a fairly easy task, successful nonword repetition requires the completion of a complex sequence of sensory, perceptual, and linguistic processes that are executed rapidly in a short period of time. To complete nonword repetition, a listener must encode a novel sound pattern in an auditory-only mode, retain and rehearse the pattern within the phonological loop, and then reassemble the sound pattern into an articulatory motor program for speech. This complex sequence of tasks may be particularly difficult for deaf children who use cochlear implants. Therefore, by examining pediatric cochlear implant users' nonword repetition skills, valuable information can be gathered on several important processes of speech, language, and memory to provide new insights into how these children apply phonological processing skills to novel nonword patterns.

The nonword repetition task utilized in our research was adapted from the stimulus materials developed by Gathercole and her colleagues (1994). The original nonword list included 40 nonwords that sounded like plausible English words. From the original set of 40 nonwords, 20 were selected for use as stimuli for the nonword repetition task conducted with the deaf children who use cochlear implants. These 20 nonwords were selected because of the high degree of variability that was observed when they were repeated by normally-hearing children (Carlson, Cleary, & Pisoni, 1998).

Unlike the McGarr sentence intelligibility task used to elicit small samples of connected speech to measure speaking rate, the nonword repetition task is not administered via live voice and does not involve providing the deaf children with the written text of each nonword. Rather, in the nonword repetition task, the prerecorded stimuli are played back at a comfortable listening level over a loudspeaker placed directly in front of the child. The auditory-only administration method used in the nonword repetition paradigm is significant because no visual cues from the speaker's face are available to the children during the task.

To evaluate the nonword repetition skills of deaf children with cochlear implants, we employed several analysis methods. Detailed and time consuming methods for evaluating the accuracy of the deaf children's nonword repetitions involved the use of both segmental and suprasegmental scoring procedures carried out by several trained transcribers (Carter, Dillon, & Pisoni, 2002; Dillon, Cleary, Pisoni, & Carter, 2004). In these initial analyses, children were scored on their ability to correctly reproduce a number of aspects in each nonword, such as the number of syllables, stress pattern, and phonemes. When scored using traditional segmental and suprasegmental methods, the deaf children correctly produced a nonword only 5% of the time, which indicates a floor performance. Such strict scoring criteria make it difficult to examine any variation in the nonword repetition skills of these deaf children. However, an alternative nonword repetition scoring method using perceptual ratings made by naïve listeners has been useful to quantify the nonword repetition skills of deaf children with cochlear implants.

In the perceptual ratings paradigm that we developed, normally-hearing adult listeners were first presented with one of the same target nonwords, spoken by an adult female, originally presented to the deaf children with cochlear implants. After hearing the nonword target, the listeners were presented with the repetition of that same nonword by one of the deaf children using a cochlear implant. The listeners were told to rate the utterances produced by the children using a scale from 1 to 7 according to how accurate they believed the child's response was, ignoring differences in pitch, when compared to the target pattern that preceded it.

In contrast to the segmental and suprasegmental scoring methods, results from the perceptual ratings task revealed a wide range of variability in nonword repetition skills within the group of deaf children using cochlear implants (Dillon, Burkholder, Cleary, & Pisoni, in press). While most of the children were able to complete the nonword repetition task, a small number of children appeared to be overwhelmed with the task and performed nearly at floor. Communication mode also affected performance on this task. Children who used oral communication received higher nonword ratings than the children who used total communication.

In a sample of 69 deaf children using cochlear implants, Dillon and colleagues (2004) also found that subvocal verbal rehearsal speeds, measured by overt speaking rate, accounted for the most variance in nonword repetition ratings. The results of a regression model fit to the nonword repetition ratings of the deaf children using cochlear implants are shown in Table 1. Along with overt speaking rate, closed-

set speech perception, speech intelligibility, and communication mode were also considered in the regression analysis.

The standardized coefficients listed in the far right column indicate the degree of variance in nonword repetition ratings accounted for by each independent variable. The analysis indicated that the speed of subvocal verbal rehearsal, as measured by the durations of overtly articulated sentences, was negatively related to nonword repetition skills in deaf children with cochlear implants. This measure accounted for the most variance in nonword repetition ratings assigned by normally-hearing listeners. This result is consistent with a large body of earlier work on normally-hearing children and adults showing that working memory is strongly correlated with nonword repetition performance (Gathercole & Baddeley, 1989; Gathercole et al., 1992; Gupta, 2003). The present results are particularly interesting because they suggest that processing speed of the subcomponent processes required to complete nonword repetition is the factor that accounts for the most variance in the task when compared to traditional end-point measures of speech perception and production.

Factors Contributing to Nonword Repetition Performance	Standardized coefficient
<hr/>	
Overt speaking rate: Subvocal verbal rehearsal speed	
Mean sentence duration of McGarr 7-syllable sentences (log, msec)	- .34***
Closed-set word identification: Speech Perception	
Word Intelligibility by Picture Identification (WIPI)	+.29***
Speech Production: Speech Intelligibility	
McGarr Sentence Intelligibility	+.28**
<hr/>	
Degree of exposure to oral-only communication	
Communication Mode score	+.16*

* $p < .05$, ** $p < .01$, *** $p \leq .001$

Table 1. Results of the regression model fit to the nonword repetition ratings of 69 pediatric cochlear implant users.

Nonword Repetition Duration and Response Latency Measurements

In addition to the data on nonword repetition collected from perceptual ratings and segmental and suprasegmental analyses, Burkholder and Pisoni (2003a) also measured nonword durations and response latencies of the deaf children using cochlear implants. Similar to the speech-timing measures obtained from the deaf children's sentence repetitions and digit span recall responses, the duration and response latency measurements have been informative about the speed of processing in deaf children using cochlear implants. Response latencies provided measures of how long it took each child to plan and initiate his or her response while durations of the nonwords indicated how long it took each child to completely utter a nonword.

The results of this study indicated that the nonword repetition response latencies of the deaf children with cochlear implants were nearly twice as long as the response latencies of a group of age-matched, normally-hearing children. In addition, the durations of the nonword responses of the deaf children with cochlear implants were significantly longer than the durations of the nonwords spoken by

normally-hearing children. Taken together, these two results suggest that the deaf children with cochlear implants require significantly more processing time than their normally-hearing peers to encode, rehearse, and articulate novel nonword patterns. Because nonword repetition is frequently conceptualized as a measure of phonological working memory, these results provide additional support concerning the limited working memory capabilities of deaf children who use cochlear implants. Overall, the recent studies on the immediate memory capacity of deaf children with cochlear implants suggested that the lack of early experience with auditory and linguistic input has profound effects not only on speech perception and sensory encoding but also on the children's ability to encode, rehearse, and recall sequential information whether it is presented in the form of visual patterns, highly familiar digits, or novel nonwords.

Summary and Conclusions

In this chapter, we presented a summary and discussion of several recent studies that assessed the working memory processes and abilities of deaf children with cochlear implants. Although most of the clinical research examining deaf children using cochlear implants has focused on traditional audiological outcome measures of speech and language skills to assess benefit, important new knowledge about speech and language development has come from recent studies on memory processing abilities in this population. These studies have shown that subvocal verbal rehearsal and serial scanning operate much more slowly in deaf children with cochlear implants and contribute to their shorter memory spans. It appears that slower processing speeds may even play a greater role in the deaf children's memory performance than the initial encoding problems related to their current hearing impairment and use of a cochlear implant.

In addition, these studies suggest that the amount and/or nature of the auditory exposure that children receive after implantation can influence their performance on immediate memory tasks that require the encoding, verbal rehearsal, and serial scanning of phonological information in working memory. As in earlier studies, we have found that deaf children with cochlear implants who use oral communication methods consistently performed better than deaf children who use total communication methods on a wide range of tasks (Dillon et al., 2004; Pisoni et al., 2000). However, in these studies, individual differences due to communication mode were reflected in both processing speed and accuracy in tasks assessing immediate memory. Although it might seem reasonable that having a system of visual-manual cues to assist deaf children in communicating would serve as an advantage, the findings presented here suggest that processing additional manual input during communicative exchanges, in addition to having poorer speech skills, may influence the strategies and speed of memory encoding and rehearsal by children using total communication.

This interpretation is consistent with what has been observed in deaf individuals not using cochlear implants. For instance, deaf students who used sign and had poorer speech skills have been found to rely on both verbal and visual encoding strategies during memory tasks (Lichtenstein, 1998). In addition, deaf children and adults using cued speech visually encode hand shape and placement during serial order tasks rather than only verbally encoding the phonological information that cued speech is designed to disambiguate (Leybaert & Lechat, 2001). A similar reliance on both verbal and visual encoding during sequential memory tasks may be a disadvantage to deaf children with cochlear implants who use total communication relative to their orally communicating peers who likely use only verbal or speech-based encoding and rehearsal strategies.

An alternative and perhaps more controversial idea is that manual input may not only influence memory processing strategies used by children using total communication but could create competition

for limited resources in auditory-visual modalities used for both hearing and seeing important speech cues during auditory memory span tasks (Bergeson & Pisoni, 2004; Pisoni, 2000). Thus, when a child with a cochlear implant using total communication methods such as signed exact English or cued speech is confronted with manual signs, his or her attention will be drawn to the hand(s) of the speaker in addition to the lips on the speaker's face. It has been well documented in normally-hearing and hearing-impaired adults and children both with and without cochlear implants that speech cues obtained from a speaker's face can provide reliable complementary information about the linguistic content of the speech signal that is equivalent to having a 15 dB increase in the speech signal (MacLeod & Summerfield, 1987; Sumbly & Pollack, 1954; Tyler, Fryauf-Bertschy, Kelsay, Gantz, Woodworth, & Parkinson, 1997; Tyler, Parkinson, Woodworth, Lowder, & Gantz, 1997).

In deaf children using cochlear implants, the amount of information extracted from visual speech cues and the audio-visual gain demonstrated in speech perception tasks is related to communication mode. Children in total communication programs are less adept at combining auditory and visual sources of speech and do not perform as well in visual-only speech perception conditions relative to their peers who use oral communication (Lachs, Pisoni, & Kirk, 2001; Bergeson, Pisoni, & Davis, 2003). This result suggests that use of signing strategies in addition to speech may prevent children using total communication from fully seeing and processing the articulatory gestures of a speaker's face which provide vital information about the speech signal and may influence the strategies used in the encoding, rehearsal, and recall of verbal information.

In addition to the specific role that linguistic experience has on the development of speech, language, and memory performance in deaf children using cochlear implants, experience-dependent plasticity associated with profound deafness may also contribute to differences in speech and language outcome measures in deaf children using cochlear implants. Neuroplastic effects of auditory deprivation have been well documented in areas ranging from the peripheral auditory system to the cerebral cortex (Shepherd & Hardie, 2001). Recently, it has been suggested that neural plasticity may be associated with postoperative performance with a cochlear implant. Using preoperative PET scan measures, Lee and colleagues (2001) found that deaf children with hypermetabolism within visual pathways performed worse after receiving a cochlear implant than children with reduced metabolism in visual pathways that neighbored auditory cortex. These neural imaging results indicate that the recruitment and reorganization of unused auditory cortex by visual pathways has consequences for the later development of auditory-based language.

Associations between preoperative PET scans in deaf children and their subsequent performance on speech and language tasks after cochlear implantation have also been reported recently by Lee, Oh, Sun, Joo, and Soo (2004). They found that children who go on to be more successful users of cochlear implants had more metabolic activity in cortical areas that are suspected to be active in working memory tasks. This is a theoretically significant finding because it suggests that memory not only affects the abilities and mechanisms of language acquisition directly but also may affect it indirectly by playing a more general neuro-cognitive role in how a deaf child using a cochlear implant learns to encode and derive meaning from the degraded auditory signals provided by the device.

Thus, a continuing problem facing researchers interested in how deaf children using cochlear implants develop speech and language is to more clearly determine how these children learn to use the auditory signals provided to them through an implant in the first place. In addition to relying on working memory processes, the task of encoding and interpreting the new sounds processed by a cochlear implant may also make use of specific perceptual learning abilities, attention, and multimodal audio-visual integration skills. Therefore, in addition to further considering the relationship between memory and

language in deaf children using cochlear implants, new research efforts should focus on other important cognitive processes such as perceptual learning, long-term memory, selective attention, and executive function if we are to gain a more detailed picture on both neural and behavioral levels of how deaf children develop speech and language skills while using a cochlear implant.

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