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Speech Timing and Working Memory in Normal-Hearing Children and Deaf Children with Cochlear Implants[1]

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Abstract. The relationship between articulation rate and working memory has been investigated extensively in normally developing children to understand how they access phonological information and rehearse it effectively through the articulatory control processes of working memory. Little, if any, research has examined articulation rate and working memory in children who receive highly degraded speech signals because of profound deafness. In the present study, 37 profoundly deaf children between 8 and 9 years of age who use cochlear implants (CI) were studied to measure their speaking rates, digit spans and assess the magnitude of the relationship between the two variables. Measurements from a group of normal-hearing (NH) age-matched children were also obtained to assess differences in speaking rate and digit spans between the two groups. Additional speech timing measures, including articulation rates, pause durations, and response latencies were obtained from recordings made during the recall portion of the WISC-III (Wechsler, 1991) auditory digit span task. The results showed that articulation rates, measured from sentence durations, were strongly related to immediate memory span in both NH and deaf children with CIs. In addition, pauses during recall were negatively correlated with memory span when both groups of children were considered together. These results replicate earlier findings on NH children reported by Cowan et al. (1994; 1998) and suggest that both subvocal verbal rehearsal speed, which is dependent on overt articulation, and serial scanning, which is carried out during recall pauses, contribute to immediate memory span in NH children as well as deaf children who have received CIs. The deaf children displayed significantly longer sentence durations and pauses during recall, and shorter digit spans compared to the NH children. This pattern indicates that slower subvocal rehearsal and scanning processes may contribute to their shorter digit spans. Such findings in a group of deaf children with CIs suggest that subvocal rehearsal and scanning processes are not just dependent on chronological development. Instead, in this clinical population, it appears that the absence of early auditory experience and phonological processing activities before implantation has measurable effects on the working memory processes that rely on verbal rehearsal and serial scanning of information in short-term memory.

Introduction

Current models of working memory generally include a component that is considered to act both as a storage medium and as a mechanism for rehearsal of phonological information (Baddeley, 1992). This component is called the *phonological* or *articulatory loop* and is a cognitive process that integrates speech-based information into working memory. The articulatory loop integrates phonological information into memory by using two components: the *phonological store* and the *articulatory control process*. The integration of information carried out by the phonological loop is assumed to occur through subvocal repetition or verbal rehearsal of phonological information. This repetition and verbal rehearsal occurs in a cyclic or looping fashion within the articulatory control process (Baddeley, 1986; 1992; Baddeley, Gathercole & Papagno, 1998).

Studies considering the repetition or rehearsal portion of the phonological loop have provided valuable information about the relationship between immediate memory span and vocal and subvocal repetition of items that are maintained in memory. It is generally accepted that items requiring less time for vocalization and, therefore, less time for subvocalization (Landauer, 1962) will be remembered more easily than longer words. Shorter words can be rehearsed faster than longer words. A faster rate of rehearsal is beneficial because it reduces memory decay. Memory decay ordinarily occurs if items are not refreshed within a two second time frame. This interval of two seconds has been suggested as the time limit of phonological working memory (Baddeley, 1986; Hulme & Tordoff, 1989; Standing, Bond, Smith & Isely, 1980).

The relationship between speaking rate and working memory in adult populations has often been examined by considering differences in word length and pronunciation rate. Word length is traditionally measured by the number of syllables in a word. Pronunciation rate is usually measured by how many syllables or words can be overtly articulated per second. Various spoken languages have been compared and assessed with regard to word length and pronunciation rate. Such comparisons have been useful in analyzing the differences in the memory spans observed in native speakers of different languages (Elliott, 1992; Naveh-Benjamin & Ayres, 1986; Powell & Hiatt, 1996).

A common method used to assess the relationship between word length, speaking rate, and the capacity of the phonological memory in individuals speaking different languages has been the digit span task. This task is used frequently because it is considered a reliable and valid way to tap into the mechanisms of working memory. Results of cross-language studies using the digit span task have shown that native speakers of languages that contain fewer syllables per digit name have longer memory spans (Elliott, 1992; Ellis & Hennelly, 1980; Naveh-Benjamin & Ayres, 1986). Again, shorter words are rehearsed more quickly. Within-subjects designs using bilinguals have shown that these speakers generally have longer digit spans in the language that has shorter digit names. These findings have been obtained even when experience and aptitude between the two languages have been taken into account (Chincotta & Underwood, 1996).

Other studies have also shown that shorter words are more easily recalled than longer words. This *word length effect,* similar to the bilingual digit span effect explained above, also occurs because shorter words require less time to articulate and subvocally rehearse than longer words (Baddeley, Thomson & Buchanan, 1975; Hulme & Tordoff, 1989). Research using nonwords has provided additional support for this proposal as well. These studies have shown that subvocal rehearsal of shorter words is faster, even in circumstances where context, meaning, and familiarity are stripped away from the words (Gathercole, Willis, Baddeley & Emslie, 1994; Hitch, Halliday & Littler, 1991). However, when articulatory suppression intended to prevent subvocal rehearsal has been included in these experiments, word length effects and language related digit span advantages are eliminated (Baddeley, Lewis & Vallar, 1984; Murray & Roberts, 1968). These findings provide support for the hypothesis that subvocal rehearsal plays a critical role in determining phonological memory span.

Other research has focused on the effects of presentation rate on memory recall. It is generally accepted that faster rates of presentation produce better recall of phonological information (Mackworth, 1964; Murray & Roberts, 1968). This research also examines the effects of self-presentation rate, or overt articulation speed, on working memory. However, differences in articulation rate are not likely to be dependent on the characteristics of the language but rather on attributes of the speakers. Individuals that speak more rapidly than others, when given the same speech stimuli, generally display longer memory spans in verbal short-term memory tasks (Cowan et al., 1998; Elliot, 1992). These findings suggest that individual variability may also play a role in controlling overt speaking rates and immediate memory span.

In addition to individual differences, developmental effects have been associated with variability in speech rate (Cowan, 1992; 1994; Cowan et al., 1998; Hulme & Tordoff, 1989; Kail & Park, 1994). As children develop, their articulation rates increase. This increase in speaking rate likely contributes to an increase in covert verbal rehearsal speed. Enhanced covert rehearsal speeds will then, in turn, contribute to an increase in immediate memory span.

The positive relationship between articulation rate and working memory span is a reliable finding in the literature. Memory span can be predicted linearly from measures of overt speaking rates of words (Baddeley et al., 1975; Baddeley, 1992) and nonwords (Hulme, Maughan & Brown, 1991) in adults and children (Hulme & Tordoff, 1989). Several recent studies of children have shown that these memory span predictions are based on the maximal rate at which children can repeat various lists of words (Cowan et al., 1994; Hulme & Tordoff, 1989; Kail, 1997). Repetition tasks using word lists are commonly used to analyze children's articulation rates and to examine these rates' influence on children's memory spans. The results of these tasks have generally demonstrated that there is a positive correlation between speaking rate and memory span.

However, developmental differences in the relationship between speaking rate and memory span have been found when children of different age ranges are compared. One example of these striking differences was a negative correlation found between speeded articulation rates and working memory in four-year-old children (Cowan et al., 1994). In this study, Cowan and his colleagues used rapid repetition of word pairs to assess the speaking rates of four- and eight-year-old children. As was expected, eight-year-old children displayed the typical relationship between speaking rate and memory span. That is, eight-year-old children able to speak faster had longer memory spans. In contrast, the opposite relationship was observed in the four-year-old children studied. This finding is surprising because children at this age are assumed to be in the early stages of developing subvocal rehearsal strategies (Flavell, Beach & Chinsky, 1966; McGilly & Siegler, 1989). Such counter-intuitive results suggest that the influence of speaking rate on working memory may depend on development. These results also suggest that the relationship between speaking rate and immediate memory should be studied more extensively to establish more consistent conclusions about its role in the development of speech and language skills.

The relationship between speaking rate and working memory capacity in children is of particular importance because of the implications it has for language acquisition and other areas of cognitive development, such as reading. Strong links have been found between phonological processing, reading, and language in NH children (Kail & Hall, 1994; Williams, 1984; Zifcak, 1981), as well as in deaf children (Daneman, Nemeth, Stainton & Huelsmann, 1995). At all ages and hearing abilities, working memory is likely to be quite important for language processing. First, working memory serves to maintain sensory information, making immediate language comprehension possible. Second, working memory stores and organizes additional information, allowing language production to occur effectively (Cowan, 1996).

In several studies, Gathercole and her colleagues (1994) reported a direct causal relationship between phonological working memory skills and vocabulary acquisition in children age 4 and 5. At this time in development, the knowledge and the ability to utilize subvocal rehearsal strategies begins to emerge (Flavell, Beach & Chinsky, 1966; McGilly & Siegler, 1989). Such co-occurring phenomena accentuate the importance of the relationship between verbal rehearsal rates, working memory, and milestones in cognitive development.

In addition to traditional measures of speaking rate, other speech timing measures obtained through different methodologies have been examined for possible influences on working memory. Research examining speaking rates and working memory in children has been expanded to include additional speech timing measures obtained during the actual recall portion of memory span tasks (Cowan, 1992; Cowan et al., 1994; 1998). These new measures include individual articulation times and interword pause durations, as well as the preparatory intervals preceding list recall. Like pre-test or non-recall based measures of speaking rate, speech timing measures taken from the actual recall process have contributed new insights into the relationship between temporal characteristics of speech and working memory.

In a study examining speech timing measures during recall, Cowan et al. (1994) suggested that interword pause times may be crucial determinants of phonological working memory. The importance of pause times in recall is based on the assumption that they reflect the operation of retrieval or scanning processes during recall (Cowan, 1992). This mechanism is taken to be developmentally linked because older children have been found to have shorter pause durations than younger children (Cowan et al., 1998). Additionally, Cowan et al. (1994; 1998) and other researchers examining memory development have shown that older children have longer memory spans than younger children. Cowan et al. (1998) also found that children with shorter interword pauses had longer memory spans than their peers.

Taken together, the recent findings by Cowan et al. (1994; 1998) suggest that the memory span increase in older children might be associated with shorter interword pauses during serial recall tasks. These shorter interword pauses, according to Cowan, demonstrate that scanning mechanisms are being executed faster and more efficiently in the older children. Additionally, from the same body of research, Cowan and his colleagues observed that interword pauses increased as children reached their span-limiting list length. This is the point at which the digit span task is assumed to be the most cognitively demanding. This result suggests that pauses during recall might play an important role in the memory retrieval process during development by serving as an index of the serial scanning period.

The shorter interword pauses observed in older children with larger memory spans may reflect the maturation of covert rehearsal and scanning mechanisms. This maturation may result in more effective and rapid serial scanning processes in older children than in younger children (Cowan, 1999; Hale, 1990). This factor, along with increases in articulation speed, may enhance the ability to engage in efficient memory recall as children develop. These findings have led Cowan and colleagues (1998) to conclude that there may be two processing methods used by children that contribute to working memory capacity. These two processes are serial scanning or retrieval and subvocal rehearsal of phonological information. Not only are these processes important in memory development per se, they are also important because they appear to become operative during different stages in development. Such asynchronies during development illustrate the intricate organization and acquisition of working memory and attention abilities in children (Cowan et al., 1998; Cowan, 1999).

Prior to Cowan's work examining speech-timing measures during serial recall, most studies that have investigated speech rates and working memory in children have used the same basic methodologies. The similarities in previous methodologies have caused some concern that there may be additional dimensions of this relationship yet to be found (e.g., pause time, as suggested by Cowan, 1999). In the majority of research that preceded studies measuring speech timing during recall, children's speech timing was evaluated in speeded articulation tasks. Speeded articulation tasks are designed to obtain maximal articulation rates by requiring participants to vocalize lists of words, letters, or numbers as fast as they can (Cowan et al., 1994; Hitch, Halliday & Littler, 1989; Hulme & Tordoff, 1989; Kail, 1997). Although there has been concern expressed that repeating lists may be confounding because of memory demands imposed by the task (Henry, 1994), it is still a common method of measuring the articulation rates of children (Ferguson, Bowey & Tilley, 2002).

Few research designs outside of a recall task have measured articulation rates of children by using more natural yet still experimentally controlled methods. Such methods previously used with adults, like reading short passages (Naveh-Benjamin & Ayres, 1986) or meaningful sentences, may be applicable to developmental populations as well. These methodologies may be useful because they provide a more consistent and representative measure of speaking rate exhibited in children on a regular basis. Maximal speaking rates, in contrast, may never be revealed in the same manner outside the laboratory setting. In addition to being ecologically valid, non-speeded articulation designs would be useful to determine the generality of research that has linked speeded articulation rates to working memory span.

To our knowledge, there have also been few research designs examining the relationship between speaking rate and measures of working memory in clinical populations of children. Developmentally delayed children with mental handicaps are one population in which links between phonological processing and working memory have been examined. Early research on this population suggested that atypical verbal rehearsal and encoding strategies contribute to digit span recall disadvantages (Ellis & Anders, 1969). However, other more recent research indicates deficiencies in central executive functioning (Conners, Carr & Willis, 1998). Unfortunately, such conclusions concerning executive or verbal rehearsal deficits in this population are likely confounded by other factors related to cognition and intelligence.

In order to avoid confounds related to cognition and intelligence, developmental populations that exhibit normal intelligence yet have an articulatory or phonological disadvantage for other reasons should be studied. Children with specific language impairment (SLI) meet these criteria. Significant amounts of research have shown that children with SLI exhibit deficits in working memory (Gathercole & Baddeley, 1990; Leonard, 1998; Sussman, 1993). However, such deficits are not thought to be related to problems that characterize SLI (Cowan, 1996). Similarly, working memory deficits in SLI children are not thought to be associated with sensory processes or speech sound discrimination (Gathercole & Baddeley, 1990; Sussman, 1993). However, it would be interesting to examine rehearsal and working memory in a clinical child population in which overt and covert rehearsal capabilities may be attenuated due to a deficit in speech discrimination and articulation. Profoundly deaf pediatric cochlear implant users manifest these characteristics ideally making them a particularly suitable population in which to study covert rehearsal and working memory.

The speech of the deaf has been studied for a number of years because of its relevance to the quality of communicative abilities in deaf individuals. One distinguishing characteristic of deaf speech is its reduced rate of articulation. Reduced speaking rates have been found in deaf individuals prior to the availability of cochlear implants (Nickerson, 1975), as well as in cochlear implant candidates (Leder et al., 1987). In addition to speaking rate, intelligibility of deaf speech is another common assessment used to evaluate the quality of language production in deaf individuals (McGarr, 1981; 1983; Osberger, Maso & Sam, 1993; Osberger, Robbins, Todd & Riley, 1994).

The intelligibility of deaf speech refers to how well short speech samples can be understood by naïve, normal-hearing, adult listeners. The McGarr Sentence Intelligibility Test (McGarr, 1981) was one of the first instruments constructed to assess the speech intelligibility of deaf speakers, and was specifically designed to evaluate the intelligibility of the speech in deaf children. McGarr (1983) found that deaf children display atypical speech production strategies and often fail to provide the same speech information that is ordinarily provided by normal-hearing adults.

A more recent study using the McGarr Sentence Intelligibility Test has found that the quality of speech production exhibited by deaf children using cochlear implants is closely linked to their speech intelligibility (Tobey & Hasenstab, 1991). Additionally, it has been shown that decreased speech intelligibility in cochlear implant users may be related to their slow articulation rate. Using the McGarr Sentence Intelligibility Test, Pisoni and Geers (1998) found that the intelligibility of speech was related to the speed at which it was articulated by children using CIs. This relationship indicates that the longer the duration of the McGarr sentences, the less intelligible they were to naïve normal-hearing listeners who were asked to transcribe them.

These results suggest that there are communicative advantages for pediatric cochlear implant users who are able to articulate faster. One such advantage is simply being more intelligible than their slower speaking peers. An additional advantage fast-talking CI users is that they may be more capable of planning and maintaining their speech output in memory with less effort. Such decreased working memory demands during speech planning likely improve the fluidity and clarity with which speech output is articulated.

One factor that is important to both articulation rate and intelligibility of speech in children using cochlear implants is the nature of the early sensory and linguistic experience used to develop these abilities. Within the CI population, communication environments can vary measurably according to what kind of strategies are utilized by each child. Communication strategies used by deaf children with CIs vary across a continuum ranging from exclusive oral communication (OC) to total communication (TC), a method utilizing oral communication supplemented with manual sign and lip reading strategies. By assessing where children fall on this continuum, a classification into either the OC or TC group is usually made. This classification method has allowed for comparisons of the two groups on a variety of communicative and cognitive measures based on the nature of the early auditory and linguistic experiences of the children.

In their studies of speech intelligibility of OC and TC children, Osberger et al. (1993; 1994) found that the most intelligible deaf children used oral communication. Based on the relationship of intelligibility to speaking rate, it follows that OC users speak faster than their TC counterparts. An ability to speak faster and more intelligibly in OC children may be a direct result of their early communicative experiences after implantation. The most beneficial early experiences that the OC users have are oral-aural activities. In addition to encouraging the ability to produce speech, oral-aural activities provide the necessary auditory feedback to deaf children using CIs. Auditory feedback is crucial for these children because it provides a mechanism for them to self-monitor and improves their speech output and intelligibility.

In addition to displaying higher speech intelligibility than TC users, OC users have also been found to have longer phonological working memory spans exhibited by significantly longer WISC-III (Wechsler, 1991) forward digit spans. This finding suggests that their phonological working memory capacities and/or capabilities may be directly benefiting from increased articulation rates (Pisoni, 1999). More direct support for this relationship has been shown in a recent study in which CI users with faster articulation rates had longer WISC-III digit spans (Pisoni, Cleary, Geers & Tobey, 2000). Given this relationship between articulation rate and working memory in children, the working memory advantage displayed by OC children may be related to both overt articulation and covert verbal rehearsal abilities; both of these abilities are crucial to a phonological memory task such as digit span recall.

The CI children can be expected to utilize covert rehearsal strategies because verbal rehearsal strategies have been measured in deaf children without cochlear implants (Bebko, 1984; Liben & Drury, 1977). In addition, it has been shown that deaf children, like their NH peers, display word length effects in memory tasks (Campbell & Wright, 1990). More importantly, in a study examining verbal and spatial working memory in a sample of deaf children using CIs, Cleary, Pisoni and Geers (2001) found evidence of verbal rehearsal and encoding in the CI users. In some cases, the verbal rehearsal strategies of the children with CIs were as efficient as in a control group of NH children. Based on these findings, it is reasonable to expect that CI users in the present study will utilize covert rehearsal as well. Since covert rehearsal can be assumed, it follows that those CI users able to utilize covert rehearsal at a faster pace because of faster overt articulation rates will have longer memory spans. In addition, we expect that the fastest speaking NH children will have the longest memory spans.

The present study was designed to expand on the results described above and to complete the missing link currently observed in the relationship between speech timing measures and working memory in CI children. To establish such links, both speaking rate and verbal memory retrieval timing were examined in relation to working memory in a CI sample. Such examinations were conducted on the CI group as a whole and separately according to communication mode. Articulation rate measures were made by examining sentence durations from a non-speeded McGarr sentence repetition task. Speech timing measures were made by examining articulation and pause times embedded within WISC-III digit span recall. In addition to seeking replication of the relationship between articulation rates and WISC-III digit spans in pediatric CI users, this study further examined this relationship in a group of age-matched NH children. The magnitude of the relationship between articulation rate and working memory in each group of children was compared to determine how the characteristics of the relationship vary between the two different populations.

The comparison between speaking rate and working memory performance in pediatric cochlear implant users and NH controls seems appropriate based on earlier research comparing the memory capabilities of deaf and NH children. This earlier research has shown, not surprisingly, that there are large differences in phonological memory performance between deaf children and their NH age-matched peers. In one study examining phonological memory in deaf and NH children, Banks, Gray and Fyfe (1990) found that deaf children had more difficulties recalling details read in written text. In phonological memory tasks dependent on sequential information similar to the digit span task, deaf children have also been found to lag behind NH children (Waters & Doehring, 1990).

These results have been corroborated by studies of juvenile CI users. In a recent study, Cleary, Pisoni and Geers (2001) found that deaf children using CIs had significantly shorter working memory spans for both verbal and spatial patterns than do NH children. In addition, it has been determined that CI users have shorter forward and backward digit spans than their NH peers (Pisoni, 1999; Pisoni et al., 2000). The present investigation also seeks to replicate the finding that CI children have shorter working memory spans than their NH peers. Because of the close relationship between working memory spans and articulation rate, we also expect that deaf CI users will have longer McGarr sentence durations than a group of NH age-matched peers. In addition, we predict that within the CI group, TC users will have longer sentence durations than the OC users. Longer sentence durations are also expected to co-occur with shorter digit spans in the TC group.

Finally, for the first time in a CI population, speech-timing measures were obtained from the recall portion of the WISC-III auditory digit span task. To assess the timing of the spoken recall, response latencies, durations of individual articulations, and interword pauses in WISC-III digit span lists were obtained from both the CI and NH groups. These measures were evaluated according to what influences they exert on recall capabilities, paying close attention to the role of pause durations. Based on the recent findings reported by Cowan (1999), using a similar methodology with NH children, both articulation rate, obtained from the McGarr sentence task and the interword pauses obtained from the spoken recall of the WISC digit span task should be related to memory spans in the current NH group of children.

Of greater interest in this study is how these two processing rates function in the CI group. The importance of these two timing measures stems from the general hypothesis that articulation rate reflects the rate of subvocal verbal rehearsal and that pause durations in recall reflect the time spent scanning and retrieving information from short-term memory. Close evaluation of the CI children's speech timing measures were made to determine if their relationship to digit spans are equivalent to that observed previously in NH children and the current NH control group. The relationship between speech timing and memory span is considered in order to determine how it influences the digit spans of CI and NH children and within the TC and OC users. We predict that both of the processes reflected in speech timing, subvocal rehearsal and serial scanning are atypical in the CI population, particularly the TC users. These differences are expected to be observable through decreased articulation rates in McGarr sentences and longer interword pauses during the recall portion of the WISC-III forward digit span task.

Method

Participants

Thirty-seven deaf 8- to 9-year-old children (*M* = 8.70, *SD* =.51) who use cochlear implants were studied. Twenty-five of the children were male and 12 were female. The deaf children were tested at Central Institute for the Deaf (CID) in St. Louis, Missouri as part of a larger ongoing study called "Cochlear Implants and Education of the Deaf Child" (see Geers, 2000). Most of the subjects had congenital profound hearing loss. Five of the children lost their hearing after birth, between the ages of 9 and 18 months (*M* = 14.00, *SD* = 4.58). The average age of onset of deafness for all children was approximately two months of age. Implantation of the device occurred between 1.72 and 5.03 years (*M* = 3.04, *SD* = .88). The duration of deafness before implantation ranged from 0.60 to 5.03 years (*M* = 2.88, *SD* = 1.13). The duration of implant use for this group of children ranged from 4.46 to 6.87 years (*M* = 5.66, *SD* = .64). Prior to their inclusion in the CID study, the deaf children were evaluated through intelligence testing to ensure that they fell within reasonable limits expected for their appropriate age range. Only children that met these criteria were tested at CID and included in the present study.

The CI users were classified into two different communication groups based on whether they used primarily oral (OC) or total communication (TC). Total communication refers to a training mode utilizing manual sign and lip reading strategies, in addition to speech. The classification into TC or OC groups was based on scores assigned to the children just prior to implantation and three consecutive years after implantation. Additionally, their communication training programs were evaluated at the time of testing. The scores used in this evaluation ranged from "1," signifying a program primarily stressing the use of sign and lip reading (generally in the form of signed exact English or cued speech, not American Sign Language (ASL)) to "6," representing an oral-only regime. Each score assigned at each year of evaluation was then summed producing communication mode scores that could range from 5 to 30. This summed score determined the mode of communication that the CI children had most consistently used for a four-year period and at testing. Children with summed scores of 15 and below were considered to be TC users. Those children with scores above 15 were considered to be OC users. This method of division is based on the original scoring scale in which the lower scores (1-3) most accurately represent total communication and the higher scores (4-6) most accurately represent oral communication.

The actual range of scores obtained by these children was between 6 and 30 (*M* = 18.92, *SD* = 7.32). Children classified into the OC mode were determined to have been communicating primarily through oral communication during the four years prior to testing and at the time of testing. Children determined to be communicating orally with the supplement of manual sign and lip reading during the four years prior to testing and at testing were considered to be using TC strategies. Twenty-two children fell into the classification of OC users while the remaining 15 were considered to be TC users. All CI children were administered the Wechsler Intelligence Scale for Children (WISC-III) (Wechsler, 1991) forward and backward digit span tasks, the McGarr Sentence Intelligibility Test, and a variety of speech perception and comprehension tests.

A comparison group of 36 age- and gender-matched NH children was also included in this study (M = 8.75, SD = .69). An independent sample test of the mean ages of the control and CI group showed no difference in the ages of the children, ($t(71) = -.399$, $p = .691$). The NH group of children consisted of 24 males and 12 females. All children were reported by their parents to be monolingual native speakers of American English. Parental report also indicated that the children had no known speech, hearing, or attentional disorders at the time of testing.

This group of children was determined to be normal hearing by results of a brief hearing screening given by the researcher prior to beginning the experimental procedure. Using a standard portable pure-tone audiometer (Maico Hearing Instruments, MA27) and TDH-39P headphones, each child was tested at tone pulses of 250, 500, 1000, 2000, and 4000 Hz at 20 dB in first the right ear and then the left ear. All testing of the normal-hearing children was done in a small, quiet testing room at the Speech Research Laboratory that was equipped with a closed-circuit television camera. The NH children were also administered the WISC-III digit span and McGarr Sentence Intelligibility tests. Additionally, the NH children, but not the CI children, were administered a speeded articulation task and the Peabody Picture Vocabulary Test- Third Edition, Form A (PPVT-III; Dunn & Dunn, 1997).

Stimuli and Materials

The McGarr Sentence Intelligibility Test that was completed by both the NH and CI using children included a set of visual stimuli used to elicit short sentences from the children. A set of 36 McGarr sentences (McGarr, 1981) were printed in 36 point Times New Roman font and each sentence was affixed to a three by five inch note card. The 36 sentences included 12 each at 3-, 5-, and 7- syllables. The utterances of the sentences spoken by both groups of children and the NH children's utterances from all other tasks were recorded onto digital audiotape (Sony Walkman TCD-D8) via a uni-directional headset condenser microphone (Audio-Technica ATM75). This apparatus did not physically or mechanically interfere with the deaf children's usage or placement of their cochlear implant.

Auditory stimuli used in a speeded articulation task administered only to the NH children were recorded digitally by the experimenter, a female native speaker of American English, from a similar geographical region as the participants. Audio recordings were made using the Speech Acquisition Program (SAP; Hernandez, 1995) in a sound booth. All stimuli were equated for amplitude as a batch to 70 dB. The stimuli were transcribed by four NH listeners to insure that they were highly identifiable in isolation before they were used. The stimuli for the rapid articulation task were four pairs of digits (1-6; 2-9; 7-4; 5-8) and four pairs of words (book-glove; car-spoon; fish-pig; leaf-egg) (Kail, 1997). Each pair was recorded as a separate token and presented to the children individually over a high quality tabletop loudspeaker (Advent AV570).

Additional testing materials were used to obtain vocabulary measures from all children and speech perception measures from the CI users. The PPVT (Dunn & Dunn, 1997) was given to the NH children. The Test of Auditory Comprehension of Language-Revised (TACL-R; Carrow-Woolfolk, 1985) was administered to the CI children. The CI children were also tested using the open-set spoken word identification Lexical Neighborhood Test (LNT) for easy (LNTe), hard (LNTh), and multisyllabic words (mLNT) (Kirk, Pisoni & Osberger, 1995). The Word Intelligibility by Picture Identification (WIPI; Ross & Lerman, 1979) provided a means for testing closed-set spoken word identification in the CI users. Sentence perception was measured in the CI group by administering the open-set Bamford-Kowal-Bench Sentence List Test (BKB; Bench, Kowal, & Bamford, 1979). Speech-feature discrimination was evaluated using the VIDSPAC. VIDSPAC is a video game test of speech contrast perception, specifically designed for use in hearing-impaired children (Boothroyd, 1997). All performance tests for the deaf children were also administered at Central Institute for the Deaf as part of the larger, ongoing study.

Procedure

Digit Span Task. The WISC forward and backward digit span test was administered to both the deaf and hearing children. The CI children were administered the task using live voice presentation, with lip reading available, from a trained clinician at CID. Following standard administration procedures, one digit per second was read from the list by the experimenter. There were two lists at each length. List lengths of the forward digit span task began with two digits and increased to a maximum of nine digits. List lengths of the backward digit span task began with two digits and increased to a maximum of eight digits. Two practice lists were also administered in the backward digit span task. Testing concluded when both lists at the same length were incorrectly recalled or not attempted by the child. The task was administered in the same way to the NH children by the experimenter in the Speech Research Laboratory at Indiana University in Bloomington, Indiana. The entire administration procedure of the digit span task was recorded in both groups of children.

Analog audiotape recordings of the deaf children's digit span responses were made via a lavaliere clip-on microphone worn by the clinician during administration. The sessions were originally recorded in order to verify that the digit presentation rate was approximately one digit per second. The presentation rate was verified to be consistent through examinations made by a research assistant at the Speech Research Laboratory.

The analog recordings of each deaf child's WISC-III digit span response were digitized and stored separately as ".wav" sound files in the CoolEdit Pro Limited Edition (LE) (Syntrillium Software Corporation, 1996) digital waveform editing program. These responses were used in this study to obtain the speech timing measures of articulation rates, response latencies, and pause durations within the spoken digit span responses. During the digitizing process, the recordings were sampled at 44.1 KHz with a 16-bit resolution. Forty-five CI children were originally recorded and digitized in this manner. However, eight children were later eliminated from the study. The recordings were judged to be too poor to measure accurately from a visual waveform. The digit span responses of the NH children were also all digitized and segmented into separate lists and stored using CoolEdit Pro LE in the same manner as the CI children's recordings. Once recordings were digitized, they were measured using CoolEdit LE to determine the latencies of response and articulation and pause durations in the verbal recall portion of the task.

The acoustic measurements made on all of the children's usable recordings of each list of digits included responses latencies, articulation times, and pause times. All measures were made in seconds to the nearest millisecond using simultaneous waveform and spectrogram views. Measurement was conducted in CoolEdit Pro LE by selecting beginning and end points of the desired speech or pause segment with a computer mouse cursor. Response latencies were measured from the end of the clinician's or experimenter's concluding utterance in a list to the initiation of the first digit uttered in the child's response. Any response preceded by extraneous utterances by a child was not included in the analysis of response latency. If a child began to verbally recall the list before the experimenter was done administering it, response latency measures were also disregarded. However, articulation time and pause duration measures were still made on these responses.

Individual articulation times were measured for each digit uttered in each list by locating the start and finish of the vocalization of the digit. Pauses were measured similarly from the end point of a digit to the beginning of the next digit in the list. The individual measures made within one list were averaged to give the mean individual interword pauses and mean individual articulations in lists of 2, 3, and 4 digits. Articulation and pause measures within each list were also summed to give a total articulation time and pause duration time. In addition, all articulations and pauses were included in one measure of the entire utterance duration. The average of each measure was calculated if two lists at one length were correctly recalled and measured. (See Figure 1 for a schematic representation of the measuring points that were made on the digit span lists.)

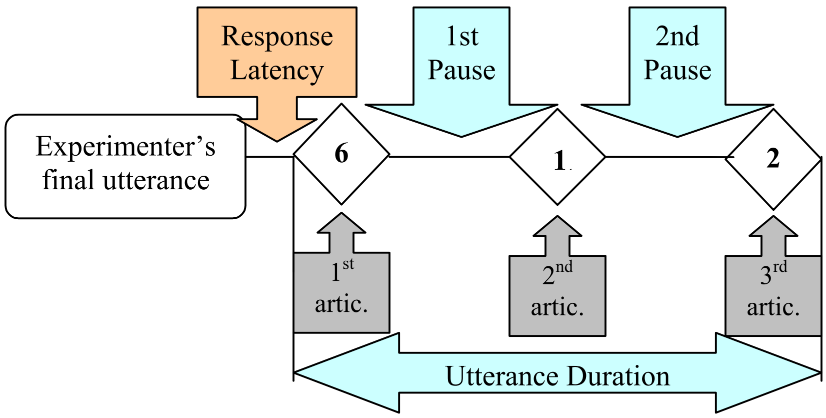

Figure 1. Schematic representation of speech timing measures made on WISC-III digit span responses. Example of list length three (6 1 2).

Only the measurement data from correctly recalled lists were used in the final analysis. Any measurements made on incorrect lists or lists with additional vocalizations or repetitions of correct numbers were disregarded. Correct responses from two practice items preceding the backward digit span task were also measured. Although all responses meeting these criteria were measured for the CI group, measurements of the NH children's digit span recall were only made up to lists of digit length four in both the forward and backward task. This limitation was made because few CI children could progress past lists of length four. Therefore, making most measures in lists longer than length four was unnecessary for the NH children. However, additional measures were made and considered at the list length limit (the longest list correctly recalled) for both groups of children. Recordings were measured by the primary researcher and a research assistant to determine inter-rater reliability. Correlations between the two rater's measures were determined to be between .88 and .97 when all the measures of response latencies, articulation durations, and pause durations were considered separately. The primary researcher's measurements were used in the final analysis.

McGarr Sentence Repetition Task. Both NH and CI children were presented with the 36 McGarr sentences in verbal and printed forms and asked to repeat them in their "best speaking voice." Sentences were presented randomly by shuffling the index cards with the sentences' written text prior to testing. The clinician or experimenter first read a sentence and then placed the index card with a printed version of the sentence in front of the children. The clinician also manually signed the sentences to the CI users if they required it. Access to lip reading was also available to all children.

Upon seeing the sentence to be spoken, the children were asked to reproduce the sentence in their best speaking voice. For the CI children, the quality of the speech recorded was closely monitored during testing. If the clinician noted any incomplete or incorrect portions of the sentences, the child was asked to repeat it up to a maximum of three times. This procedure was followed in order to elicit the best speech sample possible from the CI children.

Digital audiotape recordings were made of the utterances from both groups of children completing the McGarr Sentence Intelligibility Test. The sentences spoken by the NH children were digitized and stored as separate tokens in CoolEdit Pro LE. Duration measurements of the entire spoken sentences were then made on each group. The average durations of sentences at each syllable length (3, 5, 7) and the average total duration of all sentences were calculated for the two groups. The measurements of the CI group were completed at Callier Advanced Hearing Research Center at the University of Texas, Dallas, in cooperation with CID. The measurements of the NH group were completed at the Speech Research Laboratory using CoolEdit Pro LE.

In addition, the sentence durations of the 36 NH participants used in this study were compared to the durations of another group of 26 age- and sex-matched NH children whose data were collected at CID. This comparison was made to address the issue of possible testing effects caused by different speakers administering the test to the CI and NH children. Comparisons of the two groups of NH children showed no differences in speaking rate at syllable lengths 3 and 5 and at all lengths averaged overall. However, at syllable length 7, the children tested in the Speech Research Laboratory were found to speak at a significantly faster rate ($p = <.05$). See Figure 2 for all NH average McGarr durations. As a whole, these results show that the speaking rates between the two groups of NH children are fairly consistent. This finding was desirable because it provides some confidence that the speaking rates of children completing the McGarr repetitions were not globally influenced by the test administrators' speaking rates.

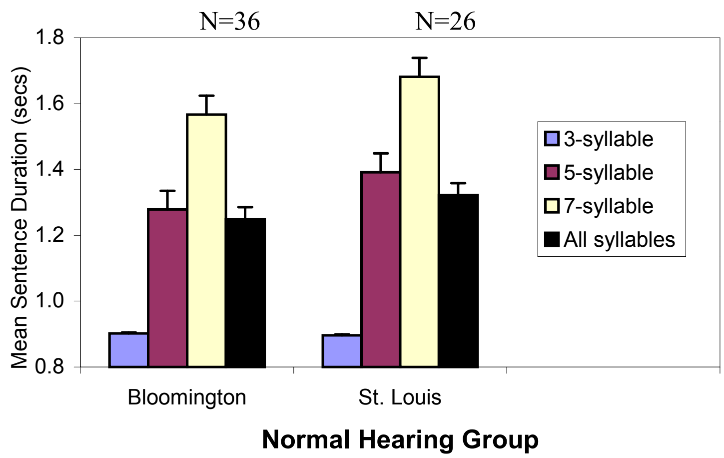

Figure 2. McGarr sentence duration comparison in two normal-hearing groups of children. Error bars represent the standard error.

After examining the distributions of the durations of the CI children and the NH children tested in Bloomington, one NH and one deaf child were eliminated from the final data analyses involving speaking rate. These children, both males, were excluded because their average McGarr sentence durations deviated significantly from the mean at all syllable lengths. For example, at syllable length seven, the NH child, the fastest speaker in the group, was more than two standard deviations below the mean when the average of the 7-syllable sentences measured in seconds was calculated ($M = 1.06$, $z < -2$). The CI user eliminated was the slowest speaking ($M = 8.23$, $z > 3$) and was an OC user. The decision to eliminate the CI user was made independent of the communication group classification.

Rapid Articulation Task. Normal-hearing participants were told that they would hear pairs of two words or two numbers together and that they needed to repeat them as quickly as possible, in pairs, until they were told to stop. The pairs were presented to all the children in the same order through the tabletop speaker at 70 dB SPL. Number pairs were presented first followed by the word pairs. Each child was prompted by the experimenter to stop after completing ten repetitions of each of the pairs. The children were permitted to rest between each set of pairs repeated if desired.

The audio recordings of the rapid articulation of word and number pairs were then digitized and segmented into their own sound files and stored in CoolEdit Pro LE where they were later measured. Measurements were made to determine both the duration of the entire repetition sequence and the rate of articulation. The average duration of each utterance, measured in seconds, was calculated for each child. From this measurement, the number of words uttered per second was determined, serving as another measure of articulation rate.

Results

WISC Digit Span Scores. Previous results regarding digit spans in CI and NH children were replicated in the present study. As we expected, CI children displayed shorter WISC-III digit spans than their NH peers. Additionally, TC users showed shorter forward digit spans than OC users. These results suggest that the CI children, particularly those using TC programs, are atypical in their phonological working memory abilities as indexed by traditional digit span measures.

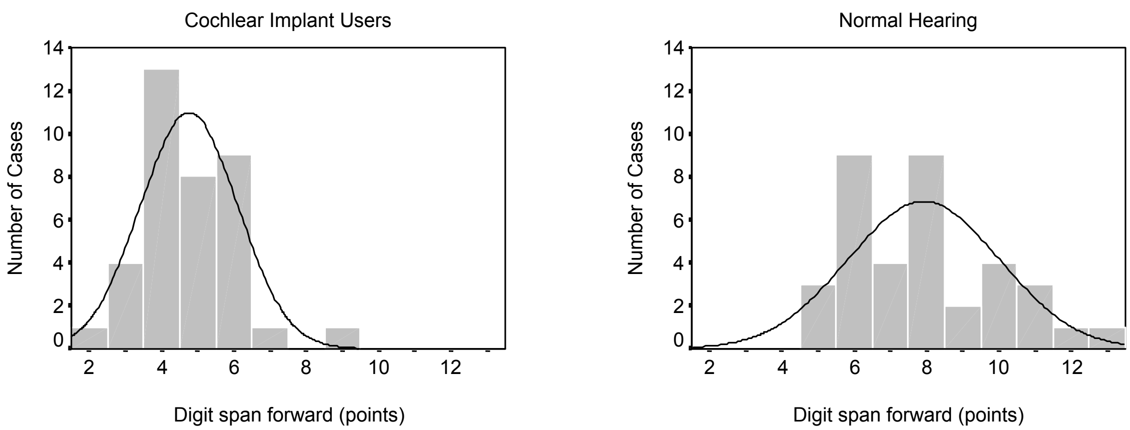

Figure 3. Distribution of forward digit span scores in CI and NH groups.

Digit span scores reflect the number of lists correctly recalled, not including practice items of the backward digit span condition. A point was awarded for each list correctly repeated to obtain the digit span scores. The range of possible scores on the forward digit span task is 0 to 16. The possible scores in the backward task range from 0 to 14. The significant difference ($t(59.43) = -7.71$, $p < .001$) in forward digit span between the NH ($M = 7.9$, $SD = 2.09$) participants and the CI users ($M = 4.8$, $SD = 1.34$) was just over 3 points. The distributions of these digit span scores are shown in Figure 3.

In addition, NH children ($M = 4.6$, $SD = 1.25$) had longer backward digit spans ($t(64.30) = -3.86$, $p < .001$) than the CI users ($M = 3.2$, $SD = 1.80$). Figure 4 illustrates the distribution of the scores for each group on backward digit span. Within the CI group, there were only significant differences between the forward digit spans ($t(35) = 2.19$, $p = .035$) of the 22 OC ($M = 5.1$, $SD = 1.32$) and 15 TC ($M = 4.2$, $SD = 1.21$) users. The distribution of forward digit span scores in the CI groups is shown in Figure 5. Backward digit spans between the TC ($M = 3.1$, $SD = 1.73$) and OC ($M = 3.3$, $SD = 1.88$) groups were nearly identical ($t(35) = .229$, $p = .821$) as shown in Figure 6. Figure 7 illustrates the mean score of all groups in the forward and backward digit span condition.

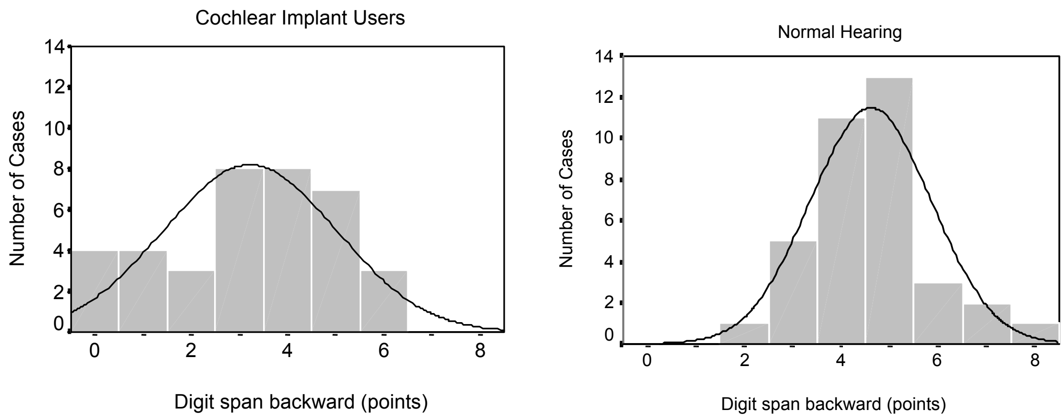

Figure 4. Distribution of backward digit span scores in CI and NH groups.

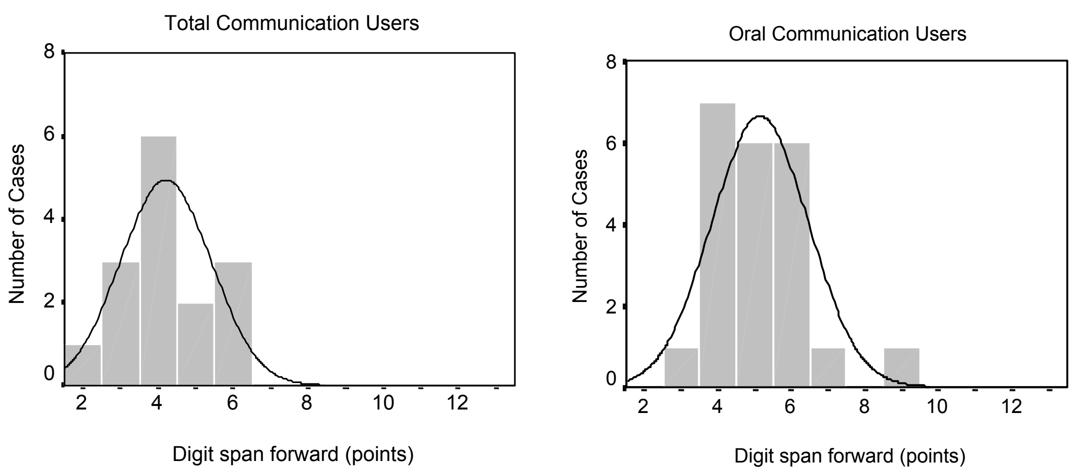

Figure 5. Distribution of forward digit span scores in TC and OC groups.

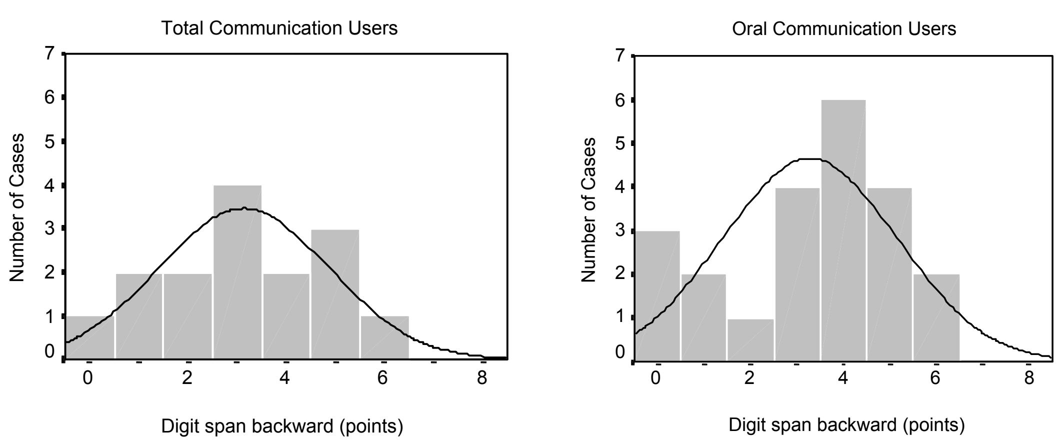

Figure 6. Distribution of backward digit span scores in TC and OC groups.

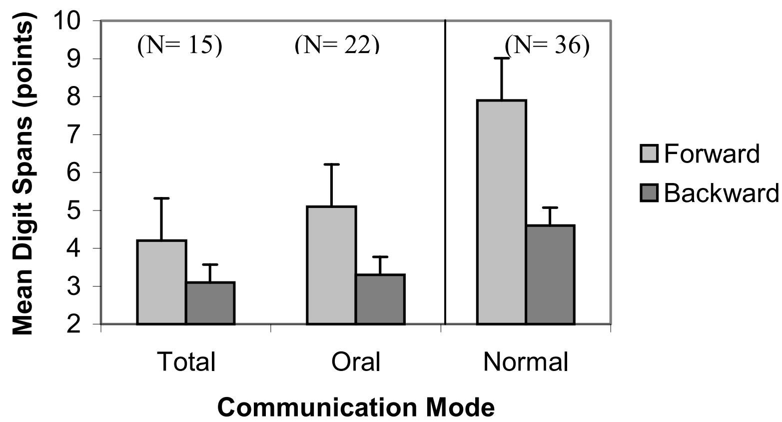

Figure 7. Average forward and backward WISC-III digit span scores in points. Error bars represent the standard error.

Limiting Span Measures. In addition to the conventional scoring system of the digit span task, all participants were evaluated based on their maximum span or memory limiting list length (Cowan et al., 1994; Cowan, 1999). The limiting span length is the longest list that could be recalled correctly in the task. At the maximum list length, it is assumed that children are at their information processing capacity where the task is most cognitively taxing. Obtaining this measure for every child provides an opportunity for a comparison of performance when each child is most challenged with the task and at the capacity of their immediate memory span.

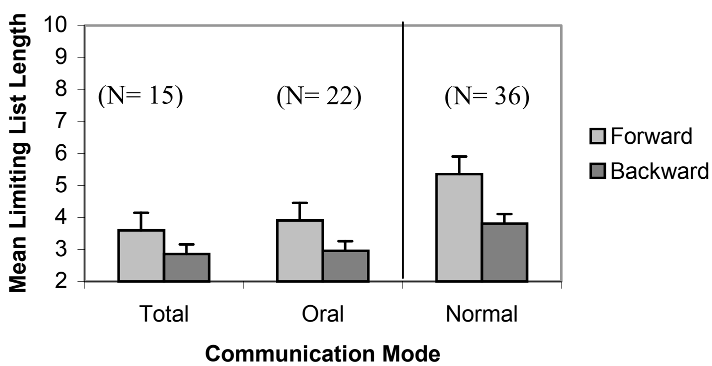

Figure 8. Average forward and backward WISC-III digit span limiting list lengths. Error bars represent the standard error.

Consistent with the point-based scoring system, we also observed differences in limiting list length between the NH and CI children. NH children had longer span limiting list lengths on average in both the forward ($M = 5.36$, $SD = 1.22$) and backward ($M = 3.81$, $SD = .749$) conditions ($t(57.81) = -6.62$, $p < .001$) than the CI children did in the forward ($M = 3.78$, $SD = .750$) and backward ($M = 2.92$, $SD = 1.18$) conditions ($t(70) = -3.82$, $p < .001$). However, there were no significant differences between the maximum list length recalled by the OC and TC groups in either the forward ($t(35) = 1.239$, $p = .223$) or backward ($t(35) = .238$, $p = .813$) condition. In fact, the mean limiting list length of the forward condition was nearly the same in the OC (M = 3.91, SD = .750) and TC (M = 3.60, SD = .737) groups, although the OC users had a slight advantage. The limiting list length of the backward digit span tasks were also slightly longer in the OC (M = 2.96, SD = 1.29) group than in the TC (M = 2.86, SD = 1.03) group. Figure 8 shows the means of the limiting list lengths of each group relative to the others.

McGarr Sentence Durations. As predicted, we observed significant differences in the speaking rates of all the groups at each of the three syllable lengths of the McGarr sentences. A post-hoc analysis utilizing Tukey's HSD procedure showed that NH children speak the fastest at all syllable lengths, TC children the slowest, and OC children display intermediate levels of speaking rate. The durations of all groups were significantly different from each other at all syllables lengths and overall when all syllable lengths were considered together, according to post-hoc analysis. Figure 9 illustrates these differences.

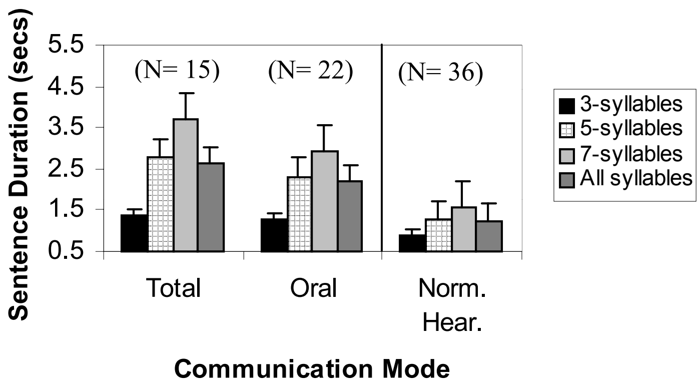

Figure 9. Mean McGarr sentence durations. Error bars represent the standard error.

Consistent with previous studies examining the relationship between working memory and speaking rate, the McGarr sentence durations were found to be negatively correlated with WISC-III forward digit spans in both the CI and NH groups. Syllable length seven of the McGarr sentences was chosen as the best measure of speed of articulation because the greater amount of syllabic content it provided allowed for more variance within the groups. In both the CI and NH groups, spoken durations of the McGarr sentences at syllable length seven were related to WISC-III forward digit spans using Pearson product correlational analysis. For this analysis, a natural log transformation of the raw durations that were measured in seconds was used. This transformation was necessary to normalize the slightly skewed raw data.

Hearing Ability	Log McGarr 7-Syllable Duration
Deaf DS Forward	-.516**
DS Backward	-.629**
NH DS Forward	-.369*
DS Backward	-.036

Communication Mode	Log McGarr 7-Syllable Duration
Oral DS Forward	-.376
DS Backward	-.648**
Total DS Forward	-.693**
DS Backward	-.712**

Tables 1-2. Relationship of McGarr 7-syllable sentences and WISC-III forward and backward digit spans in the CI and NH groups and the OC and TC groups. *$p < .05$, **$p < .01$

In the entire CI group, speaking rate was negatively correlated with forward digit spans. However, in the OC group, the correlation between speaking rate and forward digit spans failed to reach significance (p = .077). In addition, the correlation between backward span and speaking rate was strong in both CI groups but nonexistent in the NH group. Only the CI children showed a relationship between articulation rate and backward digit span while the relationship was absent in the NH children. See Tables 1 and 2 for the values of these correlations.

Partial correlations between the average McGarr 7-syllable duration and WISC-III digit spans were conducted on the CI group to control for the possible influences that speech perception, word recognition and language abilities may have on speaking rate. Three separate partial correlations were carried out controlling for scores obtained on a closed-set word identification task (WIPI), an open-set task of sentence repetition (BKB) and a test of speech feature discrimination (VIDSPAC). To control for language comprehension related to intelligence, the scores of an auditory language comprehension test (TACL-R) were also partialled out of the correlation. Table 3 shows a summary of the correlations that resulted from partialling out these measures individually.

Partialled out Variable	**Digit Span Condition**	**Log McGarr 7 Durations**
VIDSPAC	Forward	-.490**
Speech feature discrimination	Backward	-.526**
WIPI	Forward	-.362*
Word identification	Backward	-.443**
TACL Age	Forward	-.285*
Auditory language comprehension	Backward	-.450**
BKB	Forward	-.403*
Open set sentence repetition	Backward	-.399*

Table 3. Correlations of McGarr 7-syllable sentence durations and WISC-III forward digit spans in CI children with speech perception and comprehension measures partialled out of analysis.
*$p < .05$, **$p < .01$

The strengths of the correlations between speaking rate and digit span were reduced somewhat after these analyses. However, the overall relationship between speaking rate and digit spans in the CI group still remained strong and significant. Chronological age was not related to either digit span or speaking rate in any of the groups. Therefore, no adjustment was made to control for this factor in either the CI or NH groups.

Speeded Articulation Task. Although the speaking rates obtained using the McGarr Sentence Intelligibility Task were related to forward digit span in the NH group (r = -.37, $p < .05$), there was no relationship between the speeded articulation of either the word pairs (r = -.21, p = .251) or the digit pairs (r = -.25, p = .164) and digit span. Figure 10 shows scatterplots of these relationships. Despite the finding that speeded articulation and digit span did not correlate, the speeded articulation rates of word pairs did correlate with the McGarr sentence durations at all syllable lengths. This correlation is not surprising given that both repetition tasks involved similar speech stimuli. However, the speeded articulation of digit pairs was only related to the McGarr sentence durations at syllable length seven. This indicates that the children's speaking rate performances, relative to the rest of the group, were fairly consistent in both a speeded and non-speeded articulation task. These correlations are shown in Table 4. Figure 11 shows the relationship of the speeded articulation rate of word and digit pairs to the mean McGarr durations at syllable length seven, the measure taken to represent non-speeded articulation in this study.

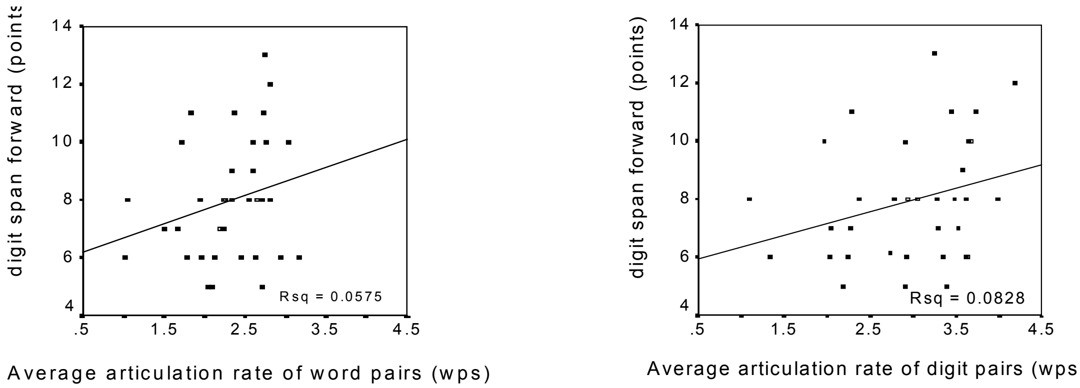

Figure 10. Correlation between rapid articulation rate and WISC-III forward digit span scored in points in the NH children.

<u>**Syllables**</u> *Stimulus Pairs*	<u>**3**</u>	<u>**5**</u>	<u>**7**</u>	<u>**All McGarr**</u>
Words	-.338*	-.359**	-.468**	-.410*
Digits	-.212	-.312	-.349*	-.311
Both	-.250	-.327	-.399*	-.346*

Table 4. Correlations between mean rapid articulation rate of words and digits with McGarr sentence durations for the NH children. *p < .05, **p < .01

Speech Timing Measures During Digit Recall: Articulation Durations. For the analysis of the speech timing measures during recall, only the responses from the digit span forward condition were considered and reported here. Analysis of the speech timing measures obtained during recall revealed no differences between the three groups in the average articulation of individual digits in any of the list lengths (2 (F (2, 66) = .262, p = .771), 3 (F (2, 68) = .689, p = .506), and 4 (F (2, 55) = 1.005, p = .373)) or the limiting list lengths (F (2, 68) = .818, p = .446) considered from the digit span forward condition. No relationship was found between the average articulations and digit span forward at any of the list lengths or the limiting list length when all children were considered together or when evaluated in groups according to hearing ability or communication mode.

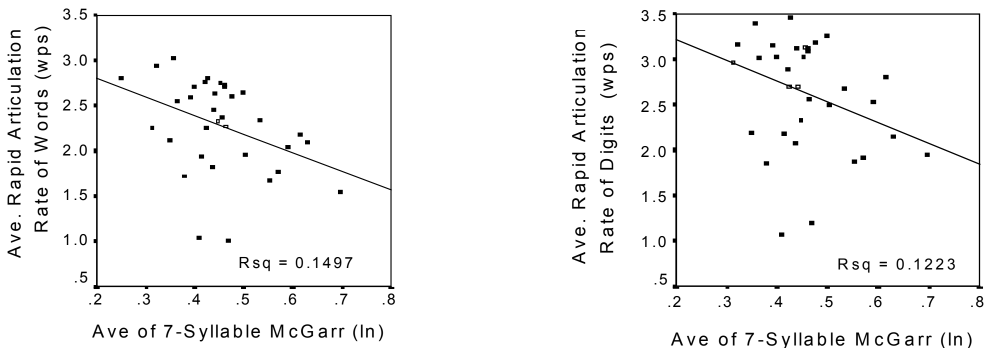

Figure 11. Correlations between mean speeded articulation rate of word and digit pairs and McGarr 7-syllable sentences in NH children.

Speech Timing Measures During Digit Recall: Response Latencies. The average response latencies of all the correct forward digit span lists did show a weak negative relationship (r = -.294, p = .014) with forward digit span, scored in points, when both the deaf and NH children were considered together. This relationship is plotted in Figure 12.

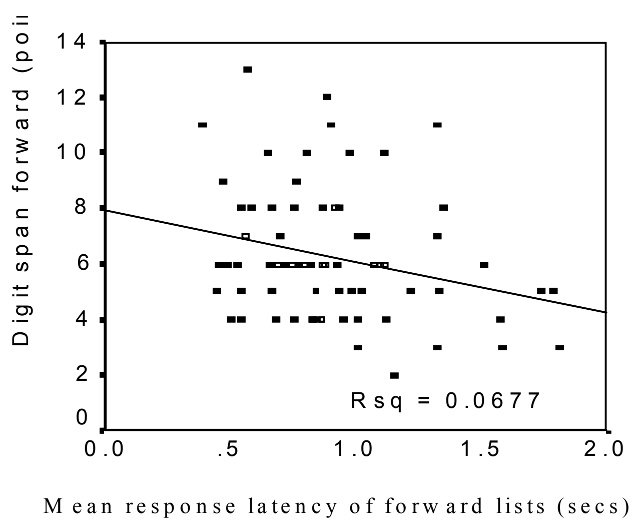

Figure 12. The correlation between mean response latency of all correctly recalled WISC-III forward digit span lists and digit span forward scored in points in both deaf and NH children.

However, this relationship appears to be driven by the TC group only. The correlation between the average response latencies of the forward lists and digit span forward points in the TC group was significant (r = -.599, p = .023). There was also a strong negative correlation between the average forward response latencies and the limiting list length in the TC group (r = -.722, p = .004). Scatterplots illustrating this relationship are shown in Figures 13 and 14.

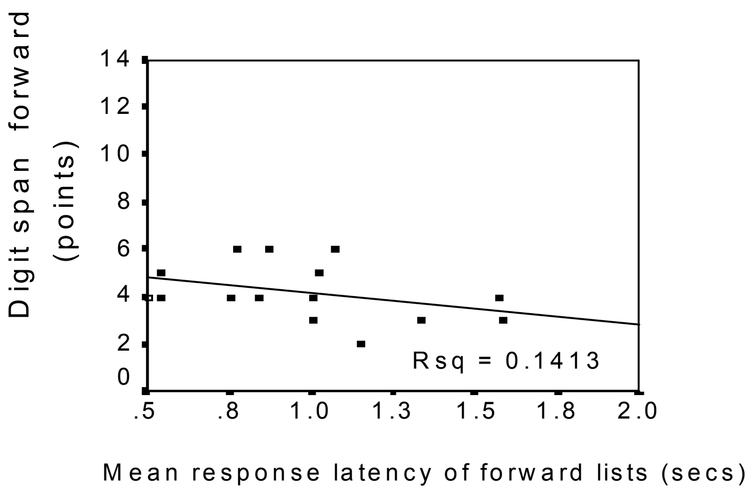

Figure 13. Correlation between mean response latency in digit span forward lists and digit span in TC cochlear implant users.

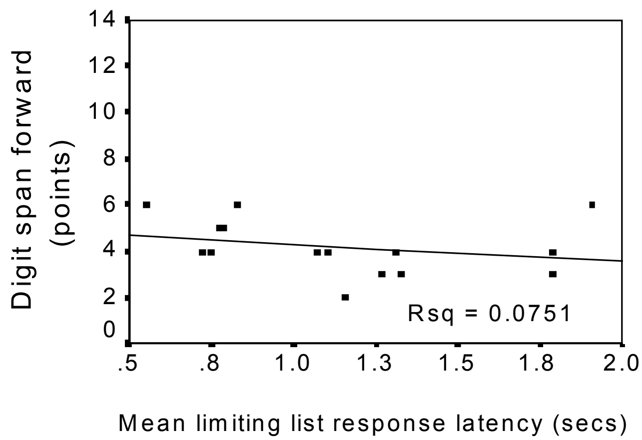

Figure 14. Relationship of mean response latencies in limiting list lengths to WISC-III forward digit span in TC cochlear implant users.

A significant correlation between the average response latency at the list limit and the length of the list limit was found in the NH group (r = .346, p = .045), although it is the inverse of the relationship observed in the TC group. See Figure 15 for an illustration of this relationship. Although the relationship of response latencies and forward digit span was particularly salient in the TC children and an unexpected relationship between span limiting response latencies and span length was found in the NH group, there was no difference in the mean response latencies observed between the three groups in the forward lists or at the span limiting list.

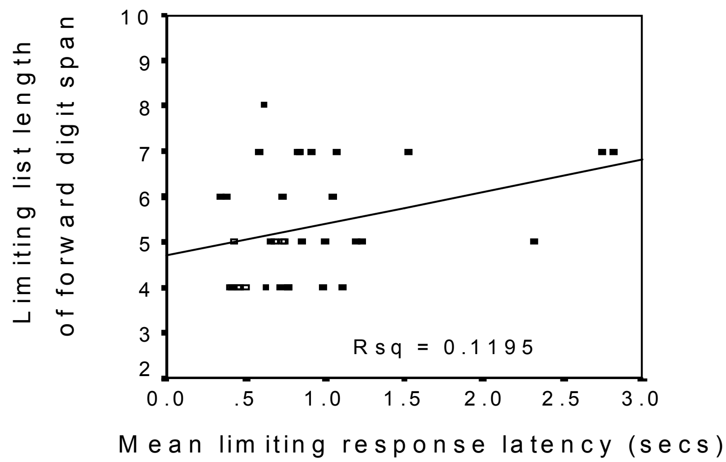

Figure 15. Relationship of mean response latency at forward limiting list length and the limiting list length of WISC-III digit span forward in normal hearing children.

Speech Timing Measures During Recall: Pause Durations. One speech timing measure that was shown to display differences among the groups was average pause duration. The average of individual pauses taken during recall in the forward condition were longer in both of the CI groups than in the NH children at list lengths three ($F(2, 66) = 18.583$, $p < .001$) and four ($F(2, 59) = 15.261$, $p < .001$). In addition, the average pauses taken from each child's own limiting list length were longer ($F(2, 68) = 17.109$, $p = .000$) in the TC ($M = .518$, $SD = .312$) and OC children ($M = .459$, $SD = .241$) than in the NH children ($M = .175$, $SD = .157$). Within the CI group, post-hoc analyses showed there was no difference between OC and TC users in the average pause durations at any forward list length, although there was a tendency for the pauses taken by the TC users to be longer than those taken by the OC users. See Figure 16 for an illustration of the average pause lengths in all groups at lists with three and four digits and at the limiting list length.

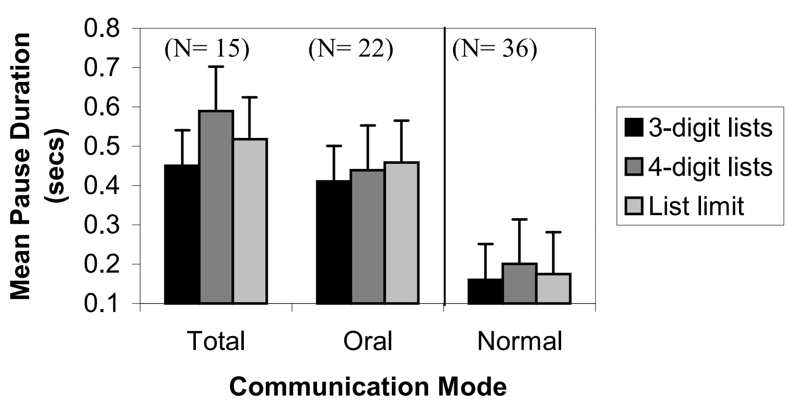

Figure 16. Average single pause durations during WISC-III forward digit span recall. Error bars represent the standard error.

The correlation of pause durations in forward digit lists of length three and four with forward digit span was found to be significant when the entire sample of children was considered together. See Table 5 for the values of these correlations. Figure 17 is an example illustration of the relationship between mean pauses and forward digit span in the group of all 72 children. This figure plots the mean interword pause taken during the limiting list length against digit span forward. There was no correlation between pause duration and digit span when each group was considered separately.

List Length	Digit Span Forward
2 Digits	-.234*
3 Digits	-.412**
4 Digits	-.323*
Span List	-.403*

Table 5. Correlations between mean pause duration during WISC-III forward digit span recall and forward digit span scores in all children. *p < .05, **p < .01

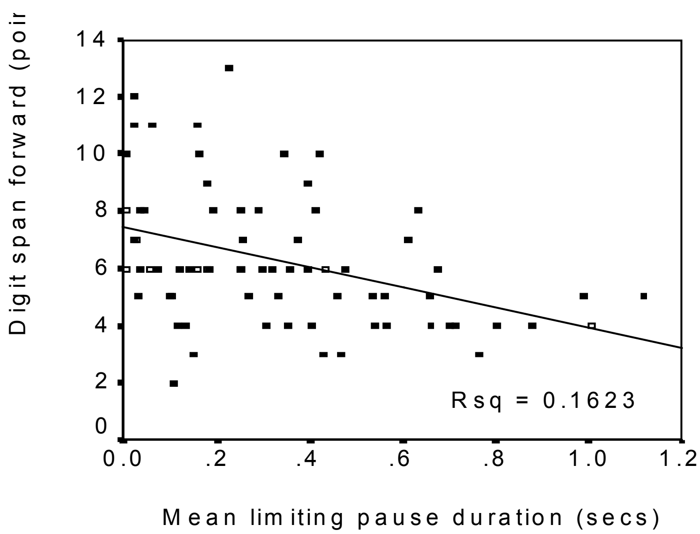

Figure 17. Correlations between mean interword pause duration in span limiting list and WISC-III digit span forward in all children.

Discussion

As expected, the results of this study replicated previous studies showing that profoundly deaf children with cochlear implants have shorter digit spans and slower speaking rates than their NH peers. Additionally, within the CI group, TC users displayed slower speaking rates and shorter forward digit spans than did OC users. These results provide additional support for the proposal that speaking rate and working memory are closely related in this clinical population. It is assumed that slower speaking rates reduce or impede subvocal verbal rehearsal processes and, therefore, the maintenance of phonological information in working memory. Both of these differences are probable causes for the shorter digit spans observed in the CI group.

More direct confirmation of this hypothesis was obtained correlationally. However, bi-directional influences between the measures of speaking rate and memory can never be completely disregarded. By this account, it is assumed that speaking rate has a causal influence on phonological memory and not vice versa. The magnitude of the relationship between speaking rate and digit spans in the NH and CI groups and within the CI group should also not be disregarded. In comparing the relationship between speaking rate and digit span in these groups, several variations in the magnitude of the relationship were observed. These variations could be useful in determining why there are differences in the digit spans of the CI and NH children and the OC and TC children.

It is particularly interesting that the relationship between speaking rate and backward digit spans was observed in the CI group but was absent in the NH group. This finding suggests that deaf children with CIs may have used a different coding strategy to carry out this immediate memory task. The strong correlation of speaking rate with backward digit span in the CI users suggests that these children are using rehearsal strategies similar to what they are using in the digit span forward condition to complete the task. This strategy may, in fact, not be as efficient as the coding strategies that NH children typically use in tasks such as this. The differences in the correlations between backward digit spans and articulation rates in the CI and NH groups warrant further consideration. Additional research on executive functions of memory, such as organizing and planning recall mechanisms, are needed in order to determine why such differences are observed in the relationship between backward digit span and speaking rate in deaf children using CIs.

The differences in the correlations between speaking rate and digit span in the OC and TC groups are also important. Both the OC and TC groups showed robust correlations between the speaking rate and backward digit spans. However, the correlation between speaking rate and forward digit spans failed to reach significance in the OC group. In contrast, the correlation between speaking rate and forward digit span was particularly strong in the TC group. This discrepancy may be related to the differences observed in the two groups' forward digit span scores. The longer sentence durations observed in the TC group and the negative correlation with forward digit span suggest that slower speaking rates are more detrimental to digit span recall in the TC children than in the OC children. The TC children's speaking rates were also significantly slower than the OC children's speaking rates at all sentence lengths, a finding that provides additional support for this proposal.

The particularly strong relationship between speaking rate and forward digit span in the TC group suggests that the TC children's decreased rates of speaking and, therefore, rehearsing may adversely affect their phonological memory abilities relative to both the OC and NH children. In addition, the forward digit-span scores and span limits of the TC group appear to be closely tied to their response latencies. This relationship may also play a role in the shorter digit spans observed in this group. As the response latencies or *preparatory intervals* (Cowan et al., 1994) in the TC group increased, digit span scores and the maximum span decreased. This pattern indicates that the TC group may be receiving the least amount of benefit from the preparatory interval.

The preparatory interval is the final period of time in which items in the digit span lists can be actively rehearsed or refreshed in their entirety before response output. Instead of being assisted by this final opportunity, it appears that the TC users may be adversely affected by rapid memory decay that takes place during this time. This disadvantage may be related to the TC children's slower speaking rates. Because the TC users are unable to articulate quickly, they may be unable to subvocally rehearse fast enough during response preparation to counteract memory decay.

The OC group did not exhibit the same relationship between response latencies and digit spans. This finding indicates that their subvocal rehearsal rates may be fast enough to avoid the memory decay that could be hindering the TC group during response preparation. Although faster overt articulation likely contributes to the digit span difference observed within the CI group, faster overt articulation by the OC users was not directly related to their forward digit spans. This finding suggests that OC users may have an additional strategy or ability that benefits forward digit span recall. This additional processing strategy used in a phonological recall task may facilitate the longer forward digit spans observed in OC children.

One additional advantage that OC users may have over their TC counterparts is related to their memory scanning abilities exhibited during digit span recall pauses. Although not statistically significant, the interword pause durations observed in the OC children were consistently shorter than those found for the TC group. The shorter pause times indicate that the OC children were scanning items in short-term memory faster than the TC children. Faster scanning by OC children may have reduced the time during recall in which items could be forgotten, therefore facilitating their immediate memory in comparison to the TC children.

Clearly, the NH children had the advantage of faster scanning abilities during digit span recall. The NH children's interword pauses during recall were much shorter than those of the CI users. This suggests that the NH children were much more efficient at memory scanning. The differences in interword pause time measured in the NH and CI children's digit span responses may be partly responsible for the digit span differences observed between the groups. Faster scanning rates and the ability to speak and rehearse at faster speeds may be the primary factors responsible for the digit span differences observed between the NH and CI groups.

The overall pattern of results found in both the CI and NH groups is quite similar to those reported recently by Cowan et al. (1998) in NH children. Both studies suggest that covert verbal rehearsal and serial scanning speed of short-term memory processes are important factors affecting immediate memory span in NH children. Cowan et al. found that those children who were fastest at the two processes had longer memory spans. However, this study was restricted to NH children that differed only in chronological age.

Comparable results were observed in the present study using children with similar chronological ages but quite different developmental histories relating to early auditory experience. The similarities of the results between this study and Cowan's studies with NH children indicate that speed of articulation, rehearsal, and memory scanning (i.e., retrieval from short term memory) may be closely linked to early auditory experiences and activities involving speech and spoken language processing. The contribution of early auditory and speech experience found in this study suggests that subvocal rehearsal and serial scanning processes may not be exclusively related to developmental milestones that are more cognitively or metacognitively centered, such as the ability to effectively organize and utilize the two processes in tasks requiring immediate recall. Rather, efficient subvocal rehearsal and scanning may be strongly dependent on underlying mechanisms of auditory perception and speech production that contribute to the development of phonological processing skills and the active use of verbal rehearsal strategies in working memory.

Because the group of deaf children were found to fall within the normal range of intelligence prior to being recruited for the current study, the most probable developmental influence on their decreased speaking rehearsal speed, scanning rates and shorter digit spans is their early period of sensory deprivation. The majority of the CI users in this study were congenitally deaf or deafened shortly after birth, causing their early developmental experiences to be quite different from the NH children's experiences. The most obvious and influential difference in the developmental experiences of normal-hearing and deaf children is the sensory deprivation endured by deaf children. This sensory deprivation likely results in widespread developmental brain plasticity, further differentiating deaf children's development from that of normal-hearing children. Such brain plasticity affects the central auditory system, as well as other cortical areas, both before and after cochlear implantation (Ryugo, Limb & Redd, 2000). The breadth of cortical plasticity that is possible during a period of sensory deprivation may also play a role in the CI children's atypical performance on cognitive tasks such as digit span recall. In addition, it should be emphasized here that cochlear implantation itself does not remediate the hearing of deaf children to normal. Rather, children with cochlear implants must learn to use an altered electrical signal to perceive and produce speech (Balkany, Hodges, Miyamoto, Gibbin & Odabasi, 2001; Miyamoto & Kirk, 1999). This unique form of auditory perception is also a hallmark difference in the developmental course experienced by deaf children after cochlear implantation.

Taken together, all previously mentioned factors prevent profoundly deaf children with CIs from simply initiating a delayed "normal" course of auditory, speech, and language acquisition. Instead, deaf children with CIs may follow a somewhat different developmental pattern of speech and language acquisition that may play a major role in the speed at which speech is perceived and produced and how effectively it is subvocally represented, rehearsed and retrieved. Such differences are likely the primary influences contributing to the differences in immediate memory span that were observed in this study. These differences may also propagate and cascade up the information processing system to affect other cognitive domains, such as reading, learning and allocating attention to surroundings. For this reason, these domains should be included in future investigations of the perceptual and cognitive development of profoundly deaf children using cochlear implants.

Summary and Conclusions

In summary, an examination of articulation rates obtained from a sentence repetition task revealed that deaf children with CIs are much slower at producing overt speech than their NH peers. Additionally, measures made on the verbal recall portion of the WISC-III auditory digit span task showed that interword pauses taken during digit span recall are longer in deaf children using CIs than in NH children. Both sentence durations and interword pause durations displayed during recall were also longer in TC children than in OC children. The differences observed between the TC and OC children demonstrate the robust effects of early oral-aural experiences on covert and overt verbal rehearsal. The decreased rehearsal rate and retrieval speed from short-term memory are likely contributing to the shorter digit spans observed in the TC group. The atypical working memory performance observed in the deaf children with CIs suggests that their slower speeds of overt articulation result in slower covert verbal rehearsal processes which are crucial for maintaining information in short-term memory. Additionally, the longer pauses taken during recall reflect slower serial scanning and retrieval in the CI users, particularly those children who are placed in total communication environments.

The differences observed in verbal rehearsal and scanning speed in deaf children with CIs replicate recent findings in NH children who were studied at different points in development (Cowan et al., 1992; Cowan et al., 1994; Cowan et al., 1998; Cowan, 1999). Contrary to being broad developmental influences related to chronological age and maturation, the longer articulation times and slower scanning speeds observed in the present study with deaf children who use CIs may be the consequences of different early auditory and linguistic experiences caused by a period of auditory deprivation as well as the unusual electrical stimulation provided by a cochlear implant. The unique developmental experience of auditory deprivation prompting the intervention of cochlear implantation is the most likely influence preventing these children from developing the same proficient and highly automatic skills to process, produce, rehearse and retrieve verbal information from working memory that their NH peers have developed over the same time period.

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