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Speech timing and working memory in profoundly deaf children after cochlear implantation

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Abstract

Thirty-seven profoundly deaf children between 8- and 9-years-old with cochlear implants and a comparison group of normal-hearing children were studied to measure speaking rates, digit spans, and speech timing during digit span recall. The deaf children displayed longer sentence durations and pauses during recall and shorter digit spans compared to the normal-hearing children. Articulation rates, measured from sentence durations, were strongly correlated with immediate memory span in both normal-hearing and deaf children, indicating that both slower subvocal rehearsal and scanning processes may be factors that contribute to the deaf children's shorter digit spans. These findings demonstrate that subvocal verbal rehearsal speed and memory scanning processes are not only dependent on chronological age as suggested in earlier research by Cowan and colleagues (1998). Instead, in this clinical population the absence of early auditory experience and phonological processing activities before implantation appears to produce measurable effects on the working memory processes that rely on verbal rehearsal and serial scanning of phonological information in short-term memory.

Keywords

Articulation rate; Cochlear implants; Deafness; Digit span; Speech timing; Verbal rehearsal; Working memory

Introduction

Working memory in normal-hearing children has been widely investigated for several decades, and the findings have been linked to several important developmental changes in reading and language (Henry, 1994; Hulme & Tordoff, 1989; Kail, 1988, 1997; Kail & Park, 1994; Murray & Roberts, 1968). These investigations have provided some initial clues to which memory processes are most influential in initiating developmental increases in memory span. Several researchers have suggested that increases in articulation rate may be one of several important maturational changes contributing to developmental increases in memory span because of the influence articulation rate may have on the speed of subvocal verbal rehearsal (Cowan, 1999; Ferguson, Bowey, & Tilley, 2002; Hitch, Halliday, & Littler, 1989; Hulme & Tordoff, 1989; Kail, 1988, 1997; Kail & Park, 1994). In addition, Cowan and his colleagues have proposed that developmental increases in serial scanning processes may also contribute to memory span in normal-hearing children (Cowan, 1992, 1999; Cowan et al., 1994, 1998). However, little, if any, research has examined the development and utilization of these processes in clinical populations of children that have slower rates of speech articulation and difficulties in perceiving speech, both of which may

affect memory span. Examination of verbal rehearsal and scanning in a unique clinical population of children, such as profoundly deaf children who use cochlear implants could yield valuable information about the role that early sensory deprivation, degraded phonological information, and slowed speech output have on immediate memory span and provide new knowledge about the development of memory processes.

The relation between articulation rate and immediate memory span has been explained through one of the earliest and most influential models of working memory proposed by Baddeley (1986, 1992). In his model, two components, the *phonological store* and the *articulatory control process* maintain phonological information in working memory through cyclically controlled subvocal repetition or verbal rehearsal. The speed and efficiency of this hypothesized covert verbal rehearsal process appears to be directly related to overt articulation rates (Landauer, 1962). Support for the relation between overt articulation, covert verbal rehearsal, and memory span has come from numerous studies examining the word length effect (Baddeley, Thomson, & Buchanan, 1975; Hulme & Tordoff, 1989), digit spans in bilinguals (Elliot, 1992; Powell & Hiatt, 1996), and articulatory suppression effects (Baddeley, Lewis, & Vallar, 1984).

The relation between articulation rate and working memory span is a reliable finding in the literature. Memory span is linearly related to measures of overt speaking rates for words (Baddeley, 1992; Baddeley et al., 1975) and nonwords (Hulme, Maughan, & Brown, 1991) in both adults and children (Hulme & Tordoff, 1989). Several recent developmental studies have shown that immediate memory span can be predicted based on the maximal rate at which children can repeat lists of words aloud (Cowan et al., 1994; Kail, 1997).

However, other research findings have questioned the relation between speaking rate, rehearsal, and memory and the role memory decay may play in adults (Lovatt, Avons, & Masterson, 2002; Nairne, 2002; Service, 1998). The standard model of working memory, proposed by Baddeley, suggests that subvocal verbal rehearsal must occur at a pace rapid enough to prevent memory decay in order for items to be preserved in memory (Baddeley, 1992). However, this memory “decay” may actually be linked to temporal changes in stimulus presentation or output interference rather than just the speed of subvocal rehearsal or may not occur at all (Crowder, 1993; Nairne, 2002; Neath & Nairne, 1995).

These considerations may also be relevant to memory processes in children, making it important to further study developmental differences in speaking rate and memory span. Previous studies have found differences between speaking rate and memory span when children of different ages are compared. Cowan et al. (1994) found differences in the speaking rates and memory spans of 4- and 8-year-old children. As expected, 8-year-old children showed the same relation between speaking rate and memory span observed in adults. That is, 8-year-olds who spoke faster displayed longer memory spans. However, the opposite relation was observed in the 4-year-old children. This finding was surprising because children at this age are assumed to be in the early stages of developing subvocal verbal rehearsal strategies (Flavell, Beach, & Chinsky, 1966; McGilly & Siegler, 1989). Such counterintuitive results suggest that the influence of speaking rate on working memory may be an important and significant developmental process to study and understand. Results such as these also suggest that the role of speaking rate and verbal rehearsal on memory span may have been overestimated in the standard model of working memory and that cue driven retrieval or recall processes may also be responsible for the reported developmental differences in memory span (Nairne, 2002).

Recently, memory recall processes in children have been examined in greater detail to determine their role in memory development (Cowan, 1992; Cowan et al., 1994, 1998).

More specifically, recall processes have been indexed by measures of speech-timing such as preparatory intervals preceding list recall and interword pause durations within recall. Like pre-test or non-recall based measures of speaking rate, speech-timing measures taken during actual spoken recall have provided several new insights into the relation between temporal characteristics of speech and working memory processes (Cowan, 1992; Cowan et al., 1994, 1998).

In one study of speech-timing measures during immediate recall, Cowan et al. (1994) found that interword pause times may provide a reliable index of the dynamics of the memory scanning and retrieval process during development. Cowan et al. found that children's interword pauses within spoken recall increased as list length increased. This result supports Cowan's earlier (1992) suggestion that serial scanning may be carried out during the pauses, because longer lists require that more items be serially scanned, prolonging interword pause time. Additional evidence demonstrating that items in short-term memory are scanned during interword pauses was found in another study by Cowan et al. (1998), who reported that children with shorter interword pauses also had longer memory spans than their peers.

In addition to memory span, recall mechanisms also appear to be developmentally linked. Cowan reported that older children have shorter pause durations in immediate recall than younger children (Cowan et al., 1998). Taken together, the recent findings by Cowan et al. (1994, 1998) suggest that memory span increases observed in older children might be associated with both shorter interword pauses during serial recall and faster speaking rates. According to Cowan, shorter interword pauses demonstrate that scanning mechanisms used to retrieve items from short-term memory are being executed faster and more efficiently in the older children. This factor, along with increases in articulation speed, may enhance the ability to engage in efficient memory recall as children develop. These new findings on speech timing have led Cowan and his colleagues (1998) to propose that two processing operations are used by normally developing children that affect measures of working memory—serial scanning or retrieval of items from short-term memory and subvocal verbal rehearsal of phonological information (Cowan, 1999; Cowan et al., 1998).

To our knowledge, however, there have been very few studies that have examined scanning and rehearsal processes in clinical populations of children. Early research on developmentally delayed children with mental handicaps suggested that atypical verbal rehearsal and encoding strategies were responsible for differences in digit span in this population (Ellis & Anders, 1969). Other more recent research suggests differences in central executive functioning (Conners, Carr, & Willis, 1998). Unfortunately, such conclusions concerning executive or verbal rehearsal deficits in these populations are likely to be confounded by other factors related to differences in cognition and general intelligence.

To avoid confounds related to cognition and intelligence, developmental populations that exhibit normal intelligence yet have articulatory or phonological delays for other reasons should be studied. Children with specific language impairment (SLI) are one clinical population that meets these criteria. Numerous studies have shown that children with SLI exhibit a range of deficits in working memory (e.g., Gathercole & Baddeley, 1990; Gillam & Cowan, 1995; Leonard, 1998; Sussman, 1993). These deficits are thought to be related to inefficient encoding of phonological and temporal information about speech and spoken language (Gillam & Cowan, 1995; Gillam, Cowan, & Marler, 1998) rather than discrimination and perception of speech sounds (Gathercole & Baddeley, 1990; Sussman, 1993). However, it would be interesting to examine the development and operation of working memory processes in a clinical population in which overt and covert rehearsal capabilities may be compromised and delayed due to early deficits in speech discrimination,

articulation, and phonological encoding. Profoundly deaf pediatric cochlear implant users display these characteristics ideally, making them a particularly suitable clinical population in which to study verbal rehearsal and speech-timing measures in working memory in comparison to normal-hearing children.

A comparison between speaking rate, speech timing, and working memory performance in pediatric cochlear implant users and normal-hearing controls should be informative based on earlier research comparing the memory capabilities of deaf and normal-hearing children. Previous research on this clinical population has revealed, not surprisingly, large differences in phonological memory performance between deaf children and their normal-hearing age-matched peers. In one study examining phonological memory in deaf and normal-hearing children, Banks, Gray, and Fyfe (1990) found that deaf children had more difficulties recalling details previously read in written text. In phonological memory tasks that depend on encoding and retrieval of sequential information, deaf children have also been found to lag behind normal-hearing children (Waters & Doehring, 1990).

Similar results have been found more recently in deaf children using cochlear implants. In a study from our laboratory, Cleary, Pisoni, and Geers (2001) reported that deaf children using cochlear implants had significantly shorter working memory spans for both verbal and spatial patterns than normal-hearing children. Other studies have found that pediatric cochlear implant users have shorter forward and backward digit spans than normal-hearing children (Pisoni et al., 2000; Pisoni & Cleary, 2003). However, no research has been carried out to compare the speaking rates and speech timing of deaf children with cochlear implants to their normal-hearing peers. Given the relation between speaking rate and memory span found earlier in developmental populations, this comparison may provide some new insights into why deaf children with cochlear implants display shorter immediate memory spans and why they show an enormous amount of variability on a large number of clinical outcome measures of speech and language.

The speech of deaf children has been studied for a number of years because of its importance to assessing the communicative abilities of these children (McGarr, 1981, 1983; Osberger, Maso, & Sam, 1993; Osberger, Robbins, Todd, & Riley, 1994; Tobey & Hasenstab, 1991). In contrast, little research has examined the speech of deaf children to explore the possible influences on cognitive abilities such as memory (Pisoni et al., 2000). One of the most distinctive characteristics 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 users (Leder et al., 1987). These results suggest that overt speaking rate and subvocal verbal rehearsal speed could be responsible for the shorter immediate memory spans observed in deaf children with cochlear implants.

Speaking rate has also been linked to differences in communicative abilities such as speech intelligibility in deaf individuals (Pisoni & Geers, 2000). 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 developed to assess and evaluate the speech intelligibility of deaf children. Using the McGarr sentences, Pisoni and Geers (2000) found that measures of speech intelligibility in deaf children with cochlear implants were related to the speed at which the test sentences were articulated. Longer sentence durations (i.e., slower speaking rates) were associated with less intelligible speech, as measured by naïve normal-hearing listeners who were asked to transcribe test sentences.

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 of the cochlear implant users who can speak faster is that they may be more capable of planning and maintaining their speech representation in working memory with less effort. Such decreased working memory demands during speech planning may result in increases in verbal fluency and articulatory precision of speech production.

In addition to the communicative advantage of having more intelligible speech, children with cochlear implants who are able to speak faster show a cognitive advantage over their slower speaking peers. Pisoni et al. (2000) found that children with cochlear implants who were able to speak faster also displayed longer memory spans, suggesting a relation between speaking rate and working memory. One factor that was found to contribute to both the articulation rate and memory spans of children using cochlear implants was the nature of the early sensory, linguistic, and communicative experiences that these children were exposed to after receiving their cochlear implants.

Communication strategies used by deaf children with cochlear implants vary across a continuum. This continuum is often divided into oral communication, in which speech is the primary method of communicating, and total communication, a method utilizing oral communication supplemented with manual signing and lip reading. By assessing where children fall on this continuum, a classification into either the oral communication or total communication group can be made. This classification method has allowed for comparisons of deaf children on a variety of communicative and cognitive measures based on the nature of the early auditory and linguistic experiences of the children (Geers, 2000; Pisoni & Geers, 2000; Pisoni et al., 2000).

In their study of working memory in deaf children with cochlear implants, Pisoni and Geers (2000) reported that oral communication users speak faster, display more intelligible speech, and have longer immediate memory spans than total communication users. This finding suggests that oral communication users' working memory capacity is affected by linguistic and auditory experience and activities after receiving their implant and may reflect increased articulation rates (Pisoni et al., 2000). Thus, the digit span advantage displayed by oral communication children may be related to both overt articulation rate and covert verbal rehearsal abilities.

The ability of oral communication children to speak more intelligibly and more rapidly may also be a consequence of their early communicative experiences and linguistic activities after implantation. The most beneficial early experiences that the oral communication users have are undoubtedly those pertaining to oral-aural activities. Oral-aural activities are critical for speech and language development because of the role they play in helping deaf children with cochlear implants to develop efficient spoken language and phonological encoding skills. In addition to encouraging these children to produce speech, oral-aural educational environments also provide the necessary auditory feedback to deaf children using cochlear implants. Auditory feedback may be especially important for these children because it provides a direct mechanism for them to self-monitor and improve their speech articulation, speech motor control, and speech intelligibility. These differences may then affect overt articulation speed and subvocal rehearsal speed, which in turn could affect their working memory spans.

Deaf children with cochlear implants who use either communication mode are likely to rely on covert verbal rehearsal strategies in many language processing tasks because such mechanisms have been measured in deaf children without cochlear implants (Bebko, 1984;

Liben & Drury, 1977). In addition, it has been shown that when carrying out memory tasks, deaf children, like their normal-hearing peers, display word length effects which are assumed to reflect speed of articulation (Campbell & Wright, 1990). More importantly, in a recent study examining verbal and spatial working memory in a sample of deaf children using cochlear implants, Cleary et al. (2001) found evidence of verbal rehearsal and encoding in the cochlear implant users. In some cases, the verbal rehearsal strategies of the children with cochlear implants were as efficient as the strategies used by normal-hearing children. Based on these earlier findings, it is reasonable to expect that the cochlear implant users in the present study are capable of some kind of covert verbal rehearsal as well. Previous findings also suggest that covert verbal rehearsal in cochlear implant children may be related to speaking rate (Pisoni & Geers, 2000). If this hypothesis is correct, we would expect that both the cochlear implant users and the normal-hearing children in the present study who speak at faster rates should display longer immediate memory spans.

The present study was designed to investigate and expand on the earlier results showing a relation between speaking rate and memory span in deaf children with cochlear implants. In addition, we were interested in examining speech-timing measures during memory span recall in this clinical population. Measures of speaking rate and speech timing during recall were examined in a group of deaf children who use cochlear implants and in an age-matched control group of normal-hearing, typically developing children. Measures of articulation rate and subvocal rehearsal speed were obtained by examining sentence durations from a non-speeded sentence repetition task. The strength of the relation between articulation rate and working memory in each group of children was compared to determine how rehearsal processes might differ between the two populations. To assess speech timing during spoken recall, response latencies, articulation durations of the test items, and interword pauses in digit span lists were measured in both the cochlear implant and normal-hearing groups of children.

The importance of these speech-timing measures to understanding the processes used in immediate memory is based on Cowan's recent proposal that articulation rate in recall reflects subvocal verbal rehearsal speed and that pause durations in recall reflect the time spent scanning and retrieving items from short-term memory (Cowan, 1999). Speech-timing measures obtained during the deaf children's digit span recall were examined to determine if the differences in scanning information in short-term memory would be comparable to the findings observed previously in normal-hearing children and the current normal-hearing control group. The relation between speech timing and memory span was also investigated to determine how it influences the digit span differences between cochlear implant and normal-hearing children and between total communication and oral communication users. These comparisons are critical in order to uncover the reasons for the shorter memory spans exhibited by profoundly deaf children with cochlear implants. We hypothesized that the observed differences in immediate memory span are related to a reduced efficiency of verbal rehearsal and/or scanning processes and ultimately derive from the early period of sensory and linguistic deprivation that these children experienced prior to receiving their cochlear implants.

We predicted that both measures of speech timing, subvocal rehearsal speed and rate of serial scanning, would be atypical in the deaf children with cochlear implants, particularly the total communication users because of their reduced exposure to spoken language. These differences were expected to be observable through decreased articulation rates in the sentence repetition task and longer interword pauses during the recall portion of the digit span task. We assume that such results would be related to the nature of the deaf children's unique developmental history and the early absence of linguistic experience and activities which attenuate or prevent the efficient verbal encoding, rehearsal, and retrieval of

phonological information from working memory that normal-hearing children routinely experience in the typical language learning environment.

Method

Participants

Thirty-seven deaf 8- to 9-year-old children ($M = 8.70$, $SD = 0.51$) who use cochlear implants were recruited for this study. 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 (Geers, 2000). Most of the deaf children had a 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 ($M = 2.39$, $SD = 4.11$). Implantation of the device occurred between 1.72 and 5.03 years ($M = 3.04$, $SD = 0.88$). 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 ($M = 5.66$, $SD = 0.64$). 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 age range. Only children that met this criterion were tested at CID and included in the present study.

The cochlear implant users were classified into two different groups based on whether they used primarily oral or total communication methods. Total communication refers to a training mode utilizing manual sign and lip reading strategies, in addition to speech, whereas oral communication is a method using primarily speech. The classification into total communication or oral communication groups was based on scores assigned to the children by parental report. Before participating in the CID study, parents rated what their child's communication regimen was just prior to implantation and what it was for the three consecutive years after implantation. Additionally, communication training programs were evaluated at the time of testing. The scores used in this evaluation ranged from "1," representing a program that primarily stressed the use of sign and lip reading (generally in the form of Signed Exact English or cued speech, not American Sign Language) 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 cochlear implant users had most consistently used for a four-year period and at the time of testing. Children with summed scores of 15 and below were considered to be total communication users. Children with scores above 15 were considered to be oral communication users. This method of classification was based on the original scoring scale in which the lower scores (1–3) most accurately represent total communication methods and the higher scores (4–6) most accurately represent oral communication methods.

The actual range of scores obtained by these children was between 6 and 30 ($M = 18.92$, $SD = 7.32$). Children classified into the oral communication mode used oral communication during the four years prior to testing and at the time of testing. Children 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 total communication strategies. Twenty-two children were classified as oral communication users while the remaining 15 were considered to be total communication users. All cochlear implant children were administered the Wechsler Intelligence Scale for Children (WISC-III) (Wechsler, 1991) forward and backward digit span task, the McGarr Sentence Intelligibility Test (McGarr, 1981), and a variety of speech perception and comprehension tests.

A comparison group of 36 age- and gender-matched normal-hearing children was also recruited for this study ($M = 8.75$, $SD = 0.69$). An independent sample test of the mean ages of the control and cochlear implant group showed no difference in the ages of the children, $t(71) = -0.40$, $p = .69$. The normal-hearing 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. The normal-hearing children were paid \$5.00 and received a lab T-shirt or hat for participating in the study.

A brief hearing screening was administered to the normal-hearing children by the first author 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. None of the children showed any evidence of a hearing loss. All testing of the normal-hearing children was done in a small, quiet testing room at the Speech Research Laboratory at Indiana University that was equipped with a closed-circuit television camera so parents could watch the procedure from an adjacent room.

Stimuli and materials

The McGarr Sentence Intelligibility Test was used to elicit recordings of the normal-hearing and cochlear implant children speaking short sentences (McGarr, 1981). The test materials included a set of 36 English sentences that were printed in 36 point Times New Roman font. Each sentence was displayed on a three by five inch note card. The 36 sentences included 12 each at 3-, 5-, and 7-syllables. The utterances spoken by both groups of children were recorded onto digital audiotape (Sony Walkman TCD-D8) via a uni-directional headset cardioid condenser microphone (Audio-Technica ATM75). The apparatus did not physically or mechanically interfere with the deaf children's usage or placement of their cochlear implant.

Additional testing materials were used to obtain vocabulary measures from all children and speech perception measures from the cochlear implant users. The PPVT (Dunn & Dunn, 1997) was given to the normal-hearing children to insure that their language development was age appropriate. The Test of Auditory Comprehension of Language-Revised (TACL-R; Carrow-Woolfolk, 1985) was administered to the cochlear implant users. The cochlear implant 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) test, (Ross & Lerman, 1979) provided a means for testing closed-set spoken word identification in the cochlear implant users. Sentence perception was measured in the cochlear implant 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, a video game specifically designed to assess speech feature contrast perception in hearing-impaired children (Boothroyd, 1997). All performance tests for the deaf children were also administered at CID as part of the larger, ongoing study.

Procedure

Digit span task—The WISC-III forward and backward digit span test was administered to both the deaf and hearing children. The cochlear implant children were administered the task using live voice presentation, with lip reading cues 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 normal-hearing children by the first experimenter. The entire administration procedure used in the digit span task was recorded onto audio tape in both groups of children.

Analog audiotape recordings of the deaf children's digit span responses were made via a lavalier 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 digit span response were digitized and stored separately as ".wav" sound files using the CoolEdit Pro Limited Edition (LE) (Syntrillium Software Corporation, 1996) digital waveform editing program. These utterances 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 16-bit resolution. Forty-five deaf children were originally recorded and digitized in this manner. However, eight children were later eliminated from the study for several reasons. These eight children were eliminated, because after observing high noise levels and/or low voice amplification levels, the recordings were judged to be poor and too difficult to measure accurately from a visual waveform. The digit span responses of the normal-hearing children were also all digitized and segmented into separate lists and stored in the same manner as the deaf children's recordings. Once recordings were digitized, measurements were made to determine the response latencies, articulation rates, 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 rates, and pause times. All measures were made in seconds to the nearest millisecond using simultaneous waveform and spectrogram views. Measurement was done 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 by a child. Any response preceded by extraneous utterances from 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 rate and pause duration measures were still made on these responses.

Individual articulation times were measured for each digit uttered in a list by finding 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. 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 total pause duration time. In addition, all articulations and pauses were included in one measure of entire utterance duration. The average of each measure was calculated if two lists at one length were correctly recalled and measured. Fig. 1 shows a schematic representation of the measuring points that were made on the digit span lists.

Only the measurement data from correctly recalled lists were used in the final speech-timing analysis. Any measurements made on incorrect lists or lists with additional vocalizations or

repetitions of correct numbers were disregarded. Although all responses meeting these criteria were measured for the cochlear implant group, measurements of the normal-hearing 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 cochlear implant users could progress beyond list lengths of four. Therefore, making most measures in lists longer than four digits was unnecessary for the normal-hearing 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 first author and a trained 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 first author's measurements were used in the final statistical analysis.

McGarr sentence repetition task—Both normal-hearing and deaf children were presented with the 36 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 child. The clinician also manually signed the sentences to the cochlear implant 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 cochlear implant children, the quality of the utterance was closely monitored during testing. If the clinician noted any incomplete or incorrect portions of the sentences, the child was asked to repeat the utterance up to a maximum of three times. This procedure was followed in order to elicit the best speech sample possible from the cochlear implant children. As expected, normal-hearing children had no difficulties in repeating the sentences accurately.

Digital audiotape recordings were made of the utterances from both groups of children completing the McGarr Sentence Intelligibility Test. The sentences spoken by the normal-hearing children were digitized and stored as separate files 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 utterances from the cochlear implant group were completed at Callier Advanced Hearing Research Center at the University of Texas, Dallas, in cooperation with CID. The measurements of the normal-hearing group were completed at the Speech Research Laboratory.

The sentence durations of the 36 normal-hearing participants used in this study were compared to the durations of another group of 26 age- and sex-matched normal-hearing children whose data were collected at CID. This comparison was made to address the issue of testing effects caused by different speakers administering the test to the deaf and normal-hearing children. Comparisons of the two groups of normal-hearing children showed no differences in speaking rate at 3- and 5-syllables and at all syllables averaged overall. However, at syllable length 7, the children tested in the Speech Research Laboratory were found to speak at a slightly faster rate ($p < .05$). As a whole, these results indicate that the speaking rates of the two groups of normal-hearing children are fairly consistent despite being tested in two different physical locations by two different experimenters. This finding was desirable, because it provides evidence that the speaking rates of children repeating the sentences were not globally influenced in any systematic way by the test administrators' speaking rates.

After examining the distributions of the durations of the deaf children and the normal-hearing children tested in Bloomington, one normal-hearing and one deaf child were eliminated from the final data analyses involving speaking rate. These two children, who both were male, were excluded because their average sentence durations deviated from the mean at all syllable lengths. For example, at syllable length seven, the normal-hearing 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 cochlear implant user that was eliminated was the slowest speaking ($M = 8.23$, $z > 3$) and was also an oral communication user. The decision to eliminate the cochlear implant user was made independently of the communication group classification.

Results

WISC-III digit span scores

Differences in digit span reported previously in deaf children with cochlear implants and normal-hearing children were replicated in the present study. As expected cochlear implant users displayed shorter digit spans than their age-matched normal-hearing peers. Additionally, total communication users showed shorter forward digit spans than oral communication users. Fig. 2 illustrates these differences. These results suggest that the deaf children with cochlear implants, particularly children from total communication programs, have atypical phonological working memory abilities as indexed by traditional digit span measures.

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 a measure of the total span score. The range of possible scores on the forward digit span task was 0 to 16. The possible scores in the backward task ranged from 0 to 14. The difference in forward digit span scores between the normal-hearing ($M = 7.92$, $SD = 2.09$) and deaf children ($M = 4.79$, $SD = 1.34$) was just over three points and was highly significant, $t(59.43) = -7.71$, $p < .001$.

In addition to the differences in forward spans, normal-hearing children also had longer backward digit spans ($M = 4.63$, $SD = 1.25$) than the cochlear implant users ($M = 3.21$, $SD = 1.80$), $t(64.30) = -3.86$, $p < .001$. Within the cochlear implant group, only the differences between the forward digit spans were significant for the 22 oral communication ($M = 5.14$, $SD = 1.32$) and 15 total communication ($M = 4.20$, $SD = 1.21$) users, $t(35) = 2.19$, $p = .035$. Backward digit spans between the total communication ($M = 3.13$, $SD = 1.73$) and oral communication ($M = 3.32$, $SD = 1.88$) groups were nearly identical, $t(35) = 0.23$, $p = .82$.

Limiting span measures

In addition to the conventional scoring system used to measure the digits spans, all participants were evaluated using their maximum span or limiting list length (Cowan et al., 1994; Cowan, 1999). The limiting list length span was the longest list correctly recalled 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 demanding. Obtaining a list length limiting span measure for each child provided an opportunity for a comparison of performance when each child is most challenged with the task and at the capacity of his or her immediate memory span.

Consistent with the earlier point-based scoring method using total span scores, we also observed differences in limiting list length spans between the normal-hearing and deaf children. Fig. 2 shows a summary of both the means of the digit span scores and the limiting list length spans of the normal-hearing and deaf children. Normal-hearing children had

longer limiting list length spans in both the forward ($M = 5.36$, $SD = 1.22$) and backward ($M = 3.81$, $SD = 0.75$) conditions, $t(57.81) = -6.62$, $p < .001$, than the deaf children did in the forward ($M = 3.78$, $SD = 0.75$) and backward ($M = 2.92$, $SD = 1.18$) conditions, $t(70) = -3.82$, $p < .001$. However, there were no significant differences between the limiting list length span of the oral communication and total communication groups in either the forward, $t(35) = 1.24$, $p = .22$, or backward condition, $t(35) = 0.24$, $p = .81$. In fact, the mean limiting list length span of the forward condition was nearly the same in the oral communication ($M = 3.91$, $SD = 0.75$) and total communication ($M = 3.60$, $SD = 0.74$) groups, although the oral communication users had a small advantage. The limiting list length of the backward digit span tasks were also slightly longer in the oral communication ($M = 2.96$, $SD = 1.29$) group than in the total communication ($M = 2.86$, $SD = 1.03$) group.

McGarr sentence durations

As expected, significant differences in speaking rate were observed for all three groups of children at each of the three sentence lengths. Fig. 3 displays a summary of these sentence durations. A post-hoc analysis utilizing Tukey's HSD procedure ($ps < .05$) showed that normal-hearing children had the fastest speaking rates at all three sentence lengths, total communication children the slowest and the oral communication children displayed intermediate levels. The durations of all three groups of children were significantly different from each other at all sentence lengths and overall when all sentence lengths were combined together, based on post-hoc tests.

Consistent with previous studies examining the relation between working memory and speaking rate, the sentence durations were negatively correlated with forward digit spans in both the cochlear implant and normal-hearing groups. Children who spoke more quickly had longer digit spans. A summary of these correlations is provided in Table 1. The 7-syllable sentences were chosen as the best measure of speed of articulation because they contained more syllables and therefore allowed for more variance to be obtained within the groups. In both the cochlear implant and normal-hearing groups, spoken durations of the sentences at syllable length seven were correlated with forward digit spans using Pearson product correlational analysis. The natural log transformation of the raw sentence durations, measured in seconds, was used for this analysis. This transformation was used to normalize the slightly skewed raw data.

For the entire cochlear implant group, speaking rate was correlated with forward digit spans. However, in the oral communication group, the correlation between speaking rate and forward digit spans just failed to reach significance ($p = .08$). In addition, the correlation between backward span and speaking rate was strong and significant in both cochlear implant groups but was not present in the normal-hearing group. The lack of the relation between speaking rate and backward digit span in the normal-hearing children may have been due to the very small variance observed in the normal-hearing children's backward digit span scores.

Partial correlations between the average 7-syllable sentence durations and digit spans were conducted on the cochlear implant group to control for influences that their speech perception and production, word recognition, and language abilities may have on speaking rate and the ability to verbally recall lists of digits. Table 2 shows a summary of the partial correlations that were obtained after these sources of variance were removed. Four separate partial correlations were done to control for the contribution of word identification (WIPI and LNTh), sentence repetition (BKB), and speech feature discrimination (VIDSPAC). These four tests assessed speech perception and word recognition abilities and when partialled out of the correlation between speaking rate and memory span control for influences of hearing ability on speaking rate and memory recall. 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. In addition, speech intelligibility of the McGarr sentences was partialled out to control for differences in speech production, which could affect both speaking rate and verbal recall in the immediate memory span task.

The strength of the correlations between speaking rate and digit span were moderated to different degrees after these analyses. However, the overall relation between speaking rate and digit spans in the cochlear implant group still remained strong and statistically 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 group.

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 analyzed and reported here. Table 3 displays the mean articulation durations, response latencies, and interword pause durations for the test items taken from the forward digit span lists containing three digits and the span limiting list. Analysis of the speech-timing measures obtained during digit recall revealed no differences between the three groups in the average duration of articulation of the individual digits at any of the list lengths (2, $F(2, 66) = 0.26, p = .77$, 3, $F(2, 68) = .69, p = .51$; and 4, $F(2, 55) = 1.00, p = .37$) or the limiting list lengths, $F(2, 68) = .82, p = .45$. No correlation was found between the average articulations taken from digit span forward and forward digit span scores when all children were considered together or when evaluated in groups according to hearing ability or communication mode.

Speech-timing measures during digit recall: Response latencies

Although the average response latencies did not differ between the groups (see Table 3), they were related to forward digit span. The average response latencies of all the correct forward digit span lists showed a weak negative relation, $r = -.26, p = .03$, with forward digit span, scored in points, when both the deaf and normal-hearing children were considered together. However, this relation reflects performance by the total communication group. Only the total communication children showed a correlation between response latency and forward digit span when considered separately from all the other children, $r = -.38, p = .02$. We also observed a weak negative correlation between the average response latencies at the limiting list length and forward digit spans in the total communication group, $r = -.27, p = .04$. No other relation was found between response latencies and forward digit span. However, a correlation between the average response latency at the list limit and the length of the list limit was found in the normal-hearing group, $r = .35, p = .05$, although it was the inverse of the relation observed in the total communication group and barely reached statistical significance. Despite the correlations between response latencies and digit spans found in the total communication and normal-hearing groups, there were no differences in the mean response latencies measured in the forward lists or the span limiting lists between the three groups of children.

Speech-timing measures during recall: Pause durations

As expected based on Cowan's earlier work, we found that interword pause durations within spoken recall differed significantly among the groups. Fig. 4 shows a summary of the average pauses in all groups at list lengths of three and four digits and at the limiting list length. The average of individual pauses that occurred during recall in the forward condition was significantly longer in both of the cochlear implant groups than in the normal-hearing children at list lengths three, $F(2, 66) = 18.58, p < .001$, and four, $F(2, 59) = 15.26, p < .001$. In addition, the average pauses taken from each child's own limiting list length span were longer, $F(2, 68) = 17.11, p < .001$, in the total communication ($M = 0.52, SD = 0.31$) and

oral communication children ($M = 0.46$, $SD = 0.24$) than in the normal-hearing children ($M = 0.18$, $SD = 0.16$). Within the cochlear implant group, post-hoc analyses showed no difference in the average pause durations at any forward list length, although there was a tendency for the pauses taken by the total communication users to be longer than those taken by the oral communication users.

Discussion

The results of this study replicated previous findings showing that profoundly deaf children with cochlear implants have shorter digit spans than their normal-hearing peers. As expected, deaf children with cochlear implants also displayed longer sentence durations than their normal-hearing peers. In addition, within the group of deaf children with cochlear implants, total communication users displayed slower speaking rates and shorter forward digit spans than the oral communication users. These results provide additional support for the proposal that speaking rate and working memory are closely related in this clinical population and may reflect the operation of verbal rehearsal processing mechanisms that are similar to those used by normal-hearing children. Slower speaking rates are assumed to reflect reduced speed and efficiency of subvocal verbal rehearsal processes and consequently affect the maintenance of phonological information in working memory (Baddeley, 1992; Baddeley et al., 1975).

In addition to having longer sentence durations than normal-hearing children, the deaf children also had much longer interword pause durations during digit span recall. Longer interword pauses are assumed to reflect slower serial scanning processes which may affect the retrieval of phonological information in working memory (Cowan, 1992; Cowan et al., 1994). Taken together, the pattern of results indicates that both slower subvocal rehearsal and serial scanning are possible causes for the shorter digit spans observed in the deaf children.

However, the relation between speaking rate and digit span in the normal-hearing and cochlear implant groups and within the cochlear implant group showed several interesting differences. These differences could be useful in determining the source of the variation in the digit spans of the cochlear implant and normal-hearing children and the oral communication and total communication children. First, the correlation between speaking rate and backward digit spans was absent in the normal-hearing group but was observed in the cochlear implant group. This difference may be due to a lack of variance in the backward digit span scores of the normal-hearing children. Alternatively, this finding suggests that deaf children with cochlear implants may be using somewhat different coding strategies to carry out this task. The strong correlations observed between speaking rate and backward digit span in the cochlear implant users suggests that these children are using verbal rehearsal and recall strategies that are similar to the strategies they used in the digit span forward condition to complete the task. This strategy may, in fact, not be as efficient as the coding and recall strategies that normal-hearing children typically use in tasks such as this. Recent findings on normal-hearing adults suggest that forward and backward memory span recall operates according to different timing patterns (Rosen & Engle, 1997; Thomas, Milner, & Haberlandt, 2003). A failure to differentiate the timing of recall in the forward and backward digit span conditions by the cochlear implant users may have contributed to this difference.

The differences in speaking rate and digit spans observed between oral communication and total communication groups are also important. The correlation between speaking rate and forward digit spans just failed to reach significance in the oral communication group. In contrast, this correlation was much stronger in the total communication group. The difference may be related to the differences observed in the forward digit span scores of both

groups. The longer sentence durations observed in the total communication group and the strong negative correlation with forward digit span suggests that slower rehearsal rates may be more detrimental to digit span recall in the total communication children than in the oral communication children.

In both the total communication and oral communication children, slower serial scanning processes, as indexed by the interword pauses during digit span recall, also appear to reduce their memory spans. Overall, the cochlear implant users' interword pauses during recall were much longer than the normal-hearing children's pauses. This finding suggests that the deaf children were much slower at actively scanning and retrieving items in short-term memory during the recall process. Differences in scanning time may also be responsible for the differences in digit span observed between the groups. Faster scanning rates, coupled with the ability to verbally rehearse at faster speeds may be the two primary factors that are responsible for differences in digit span observed between the normal-hearing and cochlear implant groups.

However, it is also possible that the pattern of results obtained in the present study could be due to other factors that are not related to verbal rehearsal or scanning processes. The current interpretation attributing deaf children's shorter memory spans to slower rates of verbal rehearsal and increased memory decay is based on Baddeley's (1992) model of working memory. However, several sources of evidence suggest that verbal rehearsal and decay processes may not be responsible for the differences in immediate memory span as the standard model suggests (Crowder, 1993; Nairne, 2002). The present results could be due to speech output difficulties, deficits or delays in phonological coding, attention or early auditory perceptual processing problems experienced by the cochlear implant children.

Articulatory motor planning and/or speech production problems could be responsible for both the slower speaking rates and poorer recall due to unintelligible speech. However, an examination of the articulation duration measures obtained in the present study does not support this hypothesis. The durations of the individual test items in the digit span recall test were similar for both the cochlear implant and normalhearing groups which would not be expected if speech production and articulation was more difficult for the cochlear implant users during recall. Another alternative is that the deaf children with cochlear implants may have phonological processing deficits that prevent them from completely encoding the spoken digits effectively at the time of perception. However, previous studies using nonword repetition have shown that many deaf children using cochlear implants are able to successfully carry out complex phonological processing tasks (Cleary, Dillon, & Pisoni, 2002; Dillon, Burkholder, Cleary, & Pisoni, 2002). Finally, although an attempt was made in this study to control for differences in the speech perception abilities of the cochlear implant users, their reduced memory spans could reflect the degraded or impoverished auditory input that they receive from their cochlear implant. This explanation of the observed differences also has problems. Cleary et al. (2001) have shown recently that deaf children with cochlear implants have shorter memory spans for visual sequences of colored lights as well as sequences of spoken words even when they do not have to respond verbally at the time of recall. Cleary et al. (2001) required their subjects to enter their responses by pushing a sequence of buttons on a response box. Their findings indicate that deaf children's memory span difficulties are not exclusively related to the auditory sensory modality or the processing of sound inputs and may in fact be due to encoding and subvocal verbal rehearsal of phonological and temporal-sequential information regardless of input modality or output response requirements.

Regardless of the underlying cause, the overall pattern of speech-timing results found in both groups of children is quite similar to the findings reported recently by Cowan et al.

(1998). Cowan et al.'s results suggest that covert verbal rehearsal and the speed of serial scanning of items in short-term memory are important processing factors that affect measures of immediate memory span in normal-hearing children. Cowan et al. also found that children who were faster at subvocal verbal rehearsal and serial scanning displayed longer immediate memory spans than children who executed these processes more slowly. However, his findings were restricted to typically developing normal-hearing children that differed only in chronological age.

Comparable results were observed in the present study using children of similar chronological ages but with quite different developmental histories that reflected the absence of sound and early auditory experience during critical periods of perceptual and cognitive development. However, one caveat in comparing the present study's results to previous studies examining speaking rate is that, in the present study, speaking rate was assessed using a non-speeded sentence repetition task, while previous studies have measured maximal speaking rate using a speeded word or list repetition task. This difference may affect the extent to which the present study adequately represents the traditionally accepted relation between speaking rate and memory span and how the present study relates to previous studies examining speaking rate and memory in developmental populations. However, despite the methodological variation in measuring speaking rate, the similarities of the results obtained in this study with deaf children and Cowan's studies with normal-hearing children suggest that speed of articulation, covert verbal rehearsal, and memory scanning (i.e., retrieval of phonological representations of test items from short-term memory) are fundamental information processing skills that are closely linked to early auditory experiences and linguistic activities involved in the development of speech and spoken language processing. The contribution of early auditory and linguistic experience found in this study suggests that subvocal verbal rehearsal and serial scanning processes used to retrieve information from short-term memory may not be exclusively related to maturationally based developmental milestones that are cognitively or metacognitively centered, such as the ability to effectively organize and utilize these two processes in tasks requiring immediate recall. Rather, efficient subvocal verbal rehearsal strategies and scanning abilities may be strongly dependent on underlying neural mechanisms of auditory attention, perception, and speech production that contribute to the development of phonological processing skills and the active use of verbal rehearsal and coding strategies in short-term memory.

Because the group of deaf children examined in our study fell within a normal range of intelligence prior to being recruited for this project, the most probable developmental influence on their decreased verbal rehearsal speed, scanning rates, and shorter digit spans is the presence of an early period of auditory and linguistic deprivation prior to receiving a cochlear implant. Sensory deprivation may result in wide-spread developmental brain plasticity and neural reorganization, further differentiating deaf children's perceptual and cognitive development from that of normal-hearing children (Kaas, Merzenich, & Killackey, 1983; Shepherd & Hardie, 2001). This brain plasticity affects not only the central auditory system but other cortical areas as well both before and after cochlear implantation (Ryugo, Limb, & Redd, 2000).

In addition to issues related to neural plasticity and development, it should be emphasized here that cochlear implantation itself does not restore the hearing of deaf children and return it 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 may also be an important difference in the development of deaf children after cochlear implantation and

may further contribute to cortical plasticity and variations in auditory perception that could influence memory span performance (Ryugo et al., 2000).

Taken together, exposure to a period of auditory deprivation combined with a unique form of sensory input from a cochlear implant may prevent profoundly deaf children with cochlear implants from simply initiating a delayed “normal” course of auditory, speech, and language acquisition. Instead, deaf children with cochlear implants appear to follow a somewhat different developmental pattern of speech and language development that affects the speed at which speech is perceived and produced and how it is effectively encoded, rehearsed, scanned, and retrieved in working memory. These basic information processing differences are likely the primary influences contributing to the differences in immediate memory span that were observed in this study. Differences in working memory may also propagate and cascade up the information processing system to affect other cognitive processes, such as reading, learning and allocating attention to other stimuli in the surroundings (Fry & Hale, 2000). These information processing domains should be included in future investigations of the perceptual and cognitive development of profoundly deaf children using cochlear implants to gain a better understanding of why some deaf children show large differences in a range of language and cognitive skills from their normal-hearing peers.

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

Fig. 2. Average forward and backward WISC-III digit spans (a) scored in points and (b) at limiting list length spans. Error bars represent standard error of the mean.

Fig. 3.
Mean McGarr sentence durations. Error bars represent standard error of the mean.

Fig. 4. Average single pause durations during WISC-III forward digit span recall for list lengths of 3 and 4 digits and the span limiting list. Error bars represent standard error of the mean.

Table 1

Correlations between McGarr 7-syllable sentences and WISC-III forward and backward digit spans in normal-hearing children and profoundly deaf children with cochlear implants using either oral or total communication methods

	Recall condition	<i>r</i> value
Hearing ability		
Normal hearing	Forward	-.37 *
	Backward	-.04
Profoundly deaf	Forward	-.52 **
	Backward	-.63 **
Communication mode		
Oral communication	Forward	-.38
	Backward	-.65 **
Total communication	Forward	-.69 **
	Backward	-.71 **

*
 $p < .05$.

**
 $p < .01$.

Table 2

Correlations between McGarr 7-syllable durations and WISC-III forward and backward digit spans in profoundly deaf children with cochlear implants after separately partialling out measures of speech perception and comprehension

Partialled out variable	Recall condition	Partial <i>r</i> value
VIDSPAC		
Speech feature discrimination	Forward	-.49 **
	Backward	-.53 **
WIPI		
Closed-set word identification	Forward	-.36 *
	Backward	-.44 **
LNT (hard)		
Open-set word identification	Forward	-.46 **
	Backward	-.52 **
TACL age		
Auditory language comprehension	Forward	-.29 **
	Backward	-.45 **
BKB		
Open-set sentence repetition	Forward	-.40 *
	Backward	-.40 *
McGarr sentence intelligibility		
Speech intelligibility	Forward	-.40 *
	Backward	-.42 *

*
 $p < .05$.

**
 $p < .01$.

Table 3

Mean (*SD* is in parentheses) interword pauses, individual articulations, and response latencies (secs) of forward digit span recall

List		Speech timing measure		
		Articulation duration	Response latencies	Interword pauses
Hearing ability				
Normal hearing	Three digit lists	.56(.14)	.63(.30)	.16(.15)
	List limit	.56(.18)	.92(.61)	.18(.16)
Deaf CI users	Three digit lists	.53(.09)	.77(.30)	.43(.20)
	List limit	.59(.13)	1.06(.57)	.49(.28)
Communication mode				
Oral	Three digit lists	.55(.09)	.74(.29)	.41(.22)
	List limit	.61(.11)	1.07(.65)	.46(.24)
Total	Three digit lists	.50(.09)	.82(.32)	.45(.19)
	List limit	.56(.17)	1.03(.42)	.52(.31)

Note. CI denote cochlear implant.