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Working Memory in Deaf Children with Cochlear Implants: Correlations Between Digit Span and Measures of Spoken Language Processing[1]

David B. Pisoni and Ann Geers[2]

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

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[2] Center for Applied Research on Childhood Deafness, Central Institute for the Deaf, St. Louis, MO 63110.

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Abstract. This correlational study investigated the role of working memory in speech intelligibility, speech intelligibility, language processing and reading in a group of 43 prelingually deaf children with cochlear implants. Using the digit span subtests of the WISC as a measure of working memory capacity, moderate to high correlations were obtained between forward auditory digit span and each of the four outcome measures. The overall pattern of correlations with digit span suggests the presence of a common underlying source of variance that is associated with the encoding, rehearsal, storage and retrieval of phonological representations of spoken words. Differences on these outcome measures may reflect differences in the speed and efficiency of encoding and rehearsal processes used in spoken language processing tasks.

Introduction

We are searching for the processes and mechanisms that can account for and explain the enormous individual differences observed among users of CIs. The work I report today began last year in NYC at the NYU meeting. Actually, the idea started at the Brooklyn Botanical Garden with me persuading Ann Geers to add some simple memory tests to the battery of speech and language tests she was already gong to use in her study of CI kids that started in July of 1997. I'd like to share the results of this joint effort with you today.

Dr. Geers has just summarized some of the major findings of her study of long-term CI users (Geers et al., 1998). The results demonstrate that compared to TC children, oral-only children display a wide range of benefits in speech perception, speech production and language. Although her two groups of children had equivalent IQ scores, and were closely matched on several of the important demographic variables, large and consistent differences still emerged between the two groups on a number of the language-related outcome measures.

What factor or set of factors underlies these differences in performance between Oral-only and TC children? It is very easy to say that children who "hear" better through their implant just learn language better and subsequently recognize words better. But it is much more difficult to explain the observed differences in <u>speech intelligibility</u> and <u>reading nonwords</u> on the basis of better hearing and language skills without a more detailed description of exactly what these <u>underlying skills</u> and <u>abilities</u> are and what specific cognitive processes they draw on.

To account for the differences in speech intelligibility performance, it is necessary to assume some <u>underlying linguistic structure and process</u> which mediates between speech perception and speech production. Without access to and use of a common underlying linguistic system—a "grammar," these separate abilities and skills would not be so closely coordinated and mutually dependent. Reciprocal links exist between speech perception, production and a whole range of language-related abilities and these links reflect the child's linguistic knowledge of phonology, morphology and syntax. Speech perception, spoken word recognition and language comprehension are not isolated autonomous abilities or skills that are independent of language and the child's developing linguistic system. The same observation is true for speech production, reading and lip-reading. An account framed in terms of hearing, audibility or sensory discrimination abilities cannot provide a satisfactory explanation of all of the results or an adequate description of the "process" of how early auditory experience affects speech perception and language development in these children.

In order to provide a unified account of these findings, it is necessary to obtain additional performance measures on how deaf children with cochlear implants actually "process" and "code" the sensory, perceptual and linguistic information they receive through their implants and how they store and retrieve this information from memory. We also need to learn more about the role of early auditory experience on perceptual and cognitive development, especially spoken word recognition, lexical development, language comprehension and speech intelligibility.

What is it about the oral-only language-learning environment and the interactions of the child in this environment that produces these consistent differences across many of the language-based outcome measures? Is it merely exposure to sound? Is it exposure to spoken language? Or is there something even more fundamental going on here in terms of how the sound patterns of speech are "processed" – that is, perceived, encoded, rehearsed, stored, retrieved, transformed and manipulated and how these language processing skills "emerge" and develop over time after implantation?

We believe that answers to these kinds of questions, fundamental questions about information processing and the flow and content of how the nervous system codes and uses sensory inputs, may hold the "key" to explaining the enormous individual differences observed among deaf children with cochlear implants (Pisoni et al., 1997). If we knew more about the reasons for the large individual differences among deaf children with cochlear implants, we might be able to introduce changes in the child's post-implant language-learning environment and modify the specific intervention methods used in aural rehabilitation and language therapy.

At the present time, without knowing how or why deaf children with cochlear implants differ in their speech perception and language skills, researchers and clinicians have no principled theoretical basis for recommending one communication method (oral) over another (total communication) for an individual child or adopting one procedure for aural rehabilitation and language therapy over another. Learning more about individual differences among pediatric cochlear implant users may therefore be very useful in helping poorer-performing children reach their potential and more generally increasing the "effectiveness" of cochlear implants in children. This may be particularly critical as younger and younger children are being implanted and candidacy criteria are modified. Moreover, new knowledge about the effectiveness of cochlear implants and the reasons for the large individual differences among deaf children may be particularly critical at this time with the development of new stimulation strategies which have the potential of providing even greater language-learning benefits over a shorter period of time after implantation.

To get a handle on these kinds of basic information processing problems, we have been looking very closely at short-term working memory in deaf children with CIs. Working memory serves as the primary "interface" between the initial sensory input and the stored knowledge systems that listeners have about their language (Baddeley et al., 1998). Working memory is the "critical" link between several component subsystems used in perception, production and action. Working memory is transient and very fragile and displays substantial capacity limitations in processing all kinds of sensory and perceptual information. Without rehearsal, elaboration and contact with long-term memory, information is quickly lost from short-term working memory.

Recent findings have suggested that differences in working memory capacity may be the primary "locus" of the large individual differences observed among normal-hearing children on a wide range of language-related abilities such as novel word learning, vocabulary knowledge, nonword repetition, comprehension and reading (Gathercole et al., 1997; Gupta & MacWhinney, 1997). Other findings on young children have demonstrated changes in the speed and efficiency of processing information in working memory with development. Thus, the study of working memory in deaf children with CIs may provide new ways of understanding the operation of the processing mechanisms that are used to encode, rehearse, store and retrieve linguistic representations of spoken language.

Methods and Procedures

Today, we wish to report the results of a correlational analysis of the auditory digit spans of the 43 children described in the previous paper by Dr. Geers. In addition to the battery of speech, language and reading tests described earlier, Dr. Geers and her staff also collected forward and backward auditory digit spans for each child using the digit-span subtests of the WISC. These digit spans were obtained using live voice in an auditory-only presentation mode. The child had to recall all of the digits in their correct temporal order to receive full credit for a given list length. Each child was run individually.

Several measures of memory span performance were obtained from these immediate recall scores. For purposes of the present analyses, digit span was defined as the longest length sequence of digits that the child could recall correctly two times in a row preserving both item and order information. This dependent measure was used in all of the analyses reported below. The digit spans ranged from zero to eight items correct with a mean of 5.3 for the 43 children in the study. Only one child failed to carry out the task at all and his data were not included in the correlational analyses.

Results

To investigate the use of working memory in deaf children with CIs, we correlated the forward digit span scores with the four sets of outcome measures that Dr. Geers had already collected from these children, speech perception, speech production, language and reading.

I. Speech Perception: For the speech perception measures, we correlated digit spans with isolated spoken word recognition (WIPI, LNT), word recognition in sentences (BKB), auditory-visual integration (Chive VE) and speech feature discrimination (VIDSPAC). Table I shows the correlations between forward digit span and these measures of speech perception performance. The correlations are all positive and generally moderate to strong, suggesting a common underlying source of variance.

In interpreting these first-order correlations, one could argue that the memory span results are simply due to audibility, to differences in sensory discrimination and to basic speech perception skills that "propagate" or "cascade" up the system. That is, the children who have longer auditory memory spans just perceive speech better and have more detailed initial sensory representations of the speech waveforms than children who have shorter auditory digit spans.

TABLE I

CORRELATIONS: SPEECH PERCEPTION

Forward Auditory Digit Span
(N=43)

	r
SPOKEN WORD RECOGNITION:	
WIPI	**+.71**
LNT	**+.64**
BKB	**+.59**
AUDITORY+VISUAL:	
Chive V (lip-reading)	**+.52**
Chive VE (visual enhancement)	**+.66**
SPEECH FEATURE DISCRIMINATION:	
VIDSPAC	**+.59**

To evaluate this proposal, we also computed a series of partial correlations using performance on the VIDSPAC, a test of speech feature discrimination, as a measure of speech discrimination performance. Table II shows the partial correlations and percent variance accounted for in these speech perception scores with variance due to speech discrimination partialed out. Even with the variance from the VIDSPAC removed, there are still moderate to strong correlations of auditory digit span with several of the speech perception scores and these partial correlations are still statistically significant.

TABLE II

PARTIAL CORRELATIONS: SPEECH PERCEPTION

Forward Auditory Digit Span
(w/VIDSPAC removed)
(N=43)

	r	Partial ***r***	Total Variance
SPOKEN WORD RECOGNITION:			
WIPI	**+.71**	**+.50**	**67%**
LNT	**+.64**	**+.37**	**62%**
BKB	**+.59**	**+.28**	**53%**
AUDITORY+VISUAL:			
Chive VE (visual enhancement)	**+.66**	**+.45**	**56%**

These initial findings demonstrate the presence of memory effects that are separate and independent of the effects due to audibility, sensory discrimination and speech feature perception. The partial correlations of these speech perception scores with auditory digit span suggest the presence of processing differences among children in the way they encode, represent and rehearse the sensory input they receive through their cochlear implants. These processing differences may reflect fundamental limitations on the capacity of working memory in terms of the speed and efficiency that sensory and perceptual information about spoken words can be coded, rehearsed and retrieved through their cochlear implants. These correlations also demonstrate that there is a large component of the variance in these tests that has to do with processing operations— that is what the child does with the sensory information he/she receives through the implant.

II. Speech Intelligibility: Table III shows the correlation of digit span with Speech Intelligibility scores obtained using the McGarr sentences. The correlation is +.69, again suggesting a close association between working memory and the underlying processes used in speech production. This particular correlation is especially important and informative because it demonstrates a reciprocal relationship , a form of "parity," between two very different aspects of language, perception and production, that draw on a common underlying resource related to the retrieval and rehearsal of the phonological representation of spoken words from lexical memory. Without assuming some common linguistic structure and process, it is difficult to imagine how audibility or sensory discrimination skills could account for these results.

TABLE III

CORRELATIONS: SPEECH INTELLIGIBILITY AND LANGUAGE

	Forward Auditory Digit Span (N=43) ***r***
SPEECH INTELLIGIBILITY:	
McGarr Sentences (transcription)	**+.69**
LANGUAGE:	
WISC SIM (vocab & abstract reasoning)	**+.52**
TACL (comprehension)	**+.54**

III. Language: The correlations of auditory digit span and two language measures, WISC SIM and TACL, are also shown in Table III. These tests were carried out using the child's "preferred" mode of communication. The WISC SIMILARITIES subtest measures vocabulary knowledge and abstract reasoning abilities with pairs of words. The TACL, Test of Auditory Comprehension, is a measure of receptive language skills that assesses comprehension of words, grammatical morphemes and complex sentences. The correlations of digit span with these two measures of language performance are positive and moderate suggesting a close association between working memory and the component processes used in language comprehension.

IV. Reading: The correlations between digit span and four different measures of reading performance are shown in Table IV. Reading comprehension was assessed using the PIAT, the Peabody Individual Achievement Test, which measures vocabulary knowledge and pronunciation and sentence comprehension. Both of these correlations were moderate (r= +.59 and +.41, respectively) and were statistically significant.

TABLE IV

CORRELATIONS: READING

	Forward Auditory Digit Span (N=43)
	r
READING:	
Woodcock WA (nonwords)	**+.62**
PIAT Vocabulary	**+.59**
PIAT Comprehension	**+.41**
RHYME (errors)	**-.48**

Phonological coding in reading was measured with two other tests, the Woodcock Word Attack subtest, which assesses the child's ability to read and pronounce novel nonwords aloud and a rhyme judgment task, which records how well a child can detect the presence of rhyme similarity in visually presented pairs of words. The correlation between auditory digit span and the Woodcock WA nonword reading task was +.62; the correlation between digit span and rhyme errors was -.48. Both correlations were statistically significant and both correlations suggest that working memory is also associated with several aspects of phonological coding used in reading and manipulating isolated printed words. Again, these findings suggest that working memory is used in the retrieval and processing of the phonological representations of printed words.

These two findings, one based on reading novel nonsense word patterns and the other based on metalinguistic judgments of rhyme in printed words, suggest that working memory makes use of and draws on abstract phonological representations of spoken words that are independent of input modality. Like the earlier findings on speech intelligibility and language comprehension, it is difficult to explain the correlations between digit span and reading performance on these particular tasks by appeal to some global factor related directly to audibility or sensory discrimination without assuming access and use of some underlying linguistic process and structure, specifically, the retrieval and manipulation of the phonological representations of words from lexical memory.

We believe these correlations with digit span are important new findings that tell us something about what children do with the sensory, perceptual and linguistic information they receive through their implant.

Discussion

The correlations between auditory digit span and the four sets of outcome measures obtained from these children demonstrate very clearly that the working memory component of the human information processing system is involved in some way in <u>mediating</u>, <u>modulating</u> and <u>controlling</u> performance across a wide range of language related tasks like speech perception, speech production, spoken word recognition, language comprehension and reading. Thus, processes related to the encoding, rehearsal and short-term storage of spoken words appear to play an important role in the component underlying abilities and skills that are actually being measured by the four different language-related outcome measures.

In doing these correlations, we also found a moderate but significant correlation between communication mode (CM) and digit span, r= +.38, which shows that early auditory experience has some influence on working memory and the fundamental/elementary information processing operations that language skills and abilities subsequently build on. Not only is there a positive correlation between communication mode and auditory digit span but an analysis of the group differences showed that the oral-only kids have significantly longer memory spans than the TC kids.

We suggest that this common underlying source of variance is related to the speed and efficiency of phonological coding in these children. Children from oral-only programs are not only exposed to more speech and language (see Hart & Risley, 1995) but they also engage in more meaningful processing activities that require them to build/create/construct more robust phonological representations of the sound patterns of words in their language. These findings in deaf children with cochlear implants demonstrate that spoken language and working memory are closely interrelated and share a common set of processing resources (Gathercole et al., 1997; Gupta & MacWhinney, 1997).

The finding that communication mode is also moderately correlated with auditory digit span and that oral-only children have longer digit spans that TC children further suggests that working memory abilities are not hardwired or rigidly fixed. Instead, working memory is dynamic and flexible and can be modified and shaped selectively depending on early auditory experience and the language learning environment that the child is immersed in and the specific kinds of language-related interactions the child has with his caregivers in this environment.

This working memory account not only explains the pattern of correlations of digit span with the language-based outcome measures but it also provides a "processing explanation" of the differences in performance between the Oral-only and TC children. Moreover, these new findings on auditory digit span help us to identify the "locus" of where the information processing differences in performance are located. The differences are due to the operation of working memory, specifically, the use of a subcomponent of the working memory system that is known as the "phonological loop." According to Baddeley, the phonological loop in the working memory system is responsible for the rehearsal and maintenance of the phonological representations of spoken words in memory and the learning of new words (Baddeley et al., 1998). The phonological loop is also assumed to play an important role in <u>speech production</u> by mediating access to retrieval of sensory-motor plans needed for speech motor control. And, the phonological loop is also used in reading, especially <u>reading unfamiliar words</u> or <u>novel nonword patterns</u>. All of these tasks draw on the same common set of phonological representations of spoken words and all of these tasks use the same processing resources in working memory, specifically, the "<u>phonological memory store</u>" and the "<u>articulatory subvocal rehearsal mechanism</u>" that serves as an interface between the initial sensory input and the representations of spoken words in lexical memory.

Conclusions

The present findings are also consistent with a large body of recent data on working memory and language development— word learning, vocabulary knowledge and nonword repetition in <u>normal-hearing children</u> (Gathercole et al., 1997; Gupta & MacWhinney, 1997). The correlations with auditory digit span demonstrate the importance of "processing variables" – fundamental information processing skills and abilities that have to do with the encoding, storage, retrieval and rehearsal of phonological representations of spoken words. These perceptual and cognitive variables go beyond simple audibility and discriminability of sensory inputs because they focus on what the deaf child <u>does</u> with the limited/degraded sensory information that he/she receives through the cochlear implant. The study of these particular processing variables provides us with a new approach and several new methodologies to study two of the long-standing research problems in the field of pediatric cochlear implants – (1) the enormous individual differences among CI users and (2) the role of early auditory experience in the language-learning environment. We propose that working memory is the processing mechanism that can account for the common underlying source of variance observed across a wide range of different language-based information processing tasks that require the encoding, rehearsal, storage and retrieval of spoken words. And, we propose that working memory is the processing mechanism that can be used to explain the effects of communication mode, specifically, how oral-only experience influences the four language-based outcome measures studied in these children. We suggest that the processing mechanism that is influenced and shaped by early auditory exposure and experience is working memory, specifically, the phonological loop of working memory and its two subcomponents, the phonological store and the subvocal rehearsal mechanism both of which are extremely sensitive to frequency of occurrence of events in the environment.

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