

RESEARCH ON SPOKEN LANGUAGE PROCESSING
Progress Report No. 24 (2000)
Indiana University

**Working Memory Spans as Predictors of Spoken Word Recognition and
Receptive Vocabulary in Children with Cochlear Implants¹**

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¹ This work was supported by NIH-NIDCD Research Grant DC00111 and NIH-NIDCD Training Grant DC00012 to Indiana University and by NIH Research Grant DC00064 to the Indiana University School of Medicine.

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Abstract. The present study investigated whether individual differences in working memory could account for a significant proportion of the variance in prelingually-deafened pediatric cochlear implant users' open-set word recognition and receptive vocabulary skills, after the contribution of known predictors was taken into account. The contributions of four different measures of working memory were examined separately for Oral (N=32) and TC (N=29) children. WISC digit-spans, requiring immediate recall of auditory-only lists in both forwards and backwards (reversed order) directions were collected. Two versions of a novel "memory span game" were also administered: one required memory for sequences of colored lights, the other assessed memory for colored lights presented in conjunction with auditory color-names. The contribution of working memory differed depending on the particular memory span task and dependent measure being considered. Forward digit-span accounted for a significant amount of additional variance in open set word recognition scores for both the Oral and TC groups. Backwards digit-span accounted for additional variance in word recognition scores only for the TC group. In the case of receptive vocabulary as measured using the PPVT administered in the child's preferred communication mode, forward digit-span accounted for 27% in additional variance in the vocabulary scores of the Oral group, but very little additional variance in the vocabulary scores of the TC group. Backwards digit-span showed a small contribution to the receptive vocabulary scores of both groups. Scores in the "lights-plus-sound" version of the memory game accounted for 5% in additional variance in PBK word recognition and 5% in receptive vocabulary, but only for the Oral group. The "lights-only" condition accounted for no additional variance in either word recognition or vocabulary scores. The pattern of results suggests that the observed relationships between working memory and outcome measures are specific to the auditory modality, partially linked to communication mode, and not related to individual differences in a general-purpose component of working memory.

Introduction

Children who have lost their hearing at an early age and who have learned spoken language while using a cochlear implant show a great deal of variability in the speech and language skills they eventually attain. Some children benefit a great deal from use of their implant, developing excellent auditory-only listening skills and highly intelligible speech. Other children with similar medical histories do not show such progress. The factors that contribute to this wide variability in outcome are not yet fully understood. Although approximately 37-64% of the existing variance in outcome measures can be accounted for in terms of known demographic variables such as duration of deafness, length of device use, and age at implantation, there is still a large proportion of unexplained variability that remains (Blamey et al., 2001; Dowell, Blamey, & Clark, 1995; Miyamoto et al., 1994; Sarant, Blamey, Dowell, Clark, & Gibson, 2001; Snik, Vermeulen, Geelen, Brokx, & van den Broek, 1997).

Recent studies have begun to investigate the hypothesis that individual differences in working memory may contribute to the wide variability in outcome (e.g., Pisoni, 2000; Pisoni, Cleary, Geers, & Tobey, 2000; Pisoni & Geers, 2000). In particular, this line of research has targeted a potential role of auditory working memory—a short-term storage/maintenance mechanism for auditory verbal information. Pisoni and colleagues have argued that children with cochlear implants are an important

population to study in order to learn more about the role of early sensory experience on the development of working memory and its theorized component subsystems used to process input from different modalities.

The present study was motivated by the hypothesis that the role played by working memory may differ in fundamental ways depending on whether the implanted child develops language in an Oral versus a Total Communication environment. Children designated as “oral” are typically immersed in environments in which spoken language is used without the addition of manual sign language (Archibold, 2000). In contrast, children who use “total communication” utilize a combination of spoken language and manual sign language in their everyday communication (Archibold, 2000). The manual signs used in total communication are primarily supplements to spoken language and thus are not American Sign Language proper, but rather a form of Signed English which uses supplemental signs to facilitate communication of certain aspects of spoken English that are especially difficult for hearing-impaired persons to perceive. Given this background, we hypothesized that children who primarily use oral communication may rely more heavily on auditory memory processes than children who use total communication. In the analyses reported below, we examined whether the method of communication used by the child affects the degree to which the working memory measures were able to account for the remaining unexplained variance in language outcome measures.

Several different working memory measures were obtained in this study in order to determine if the proposed contribution of working memory is specific to auditory working memory, and not, for example, related simply to some “general purpose” modality-independent component of the working memory system (Baddeley, 1992; 1998). The four different memory span tasks used in this study differed in the degree to which they incorporated an auditory processing component. The four tasks included auditory-only digit-span requiring recall of items in the forward direction, auditory-only digit-span requiring recall of items in reversed order, memory span for visual sequences of colored lights, and memory span for sequences of colored lights presented in conjunction with auditory color-names matched to the light sequence. If the contribution of working memory were only observed for the memory tasks that require auditory processing, and not for the “lights-only” visual sequences, this finding would suggest that the effects are due to phonological processing components of working memory and not some general purpose, modality-independent attentional or control component.

The inclusion of working memory measures for both visual sequences of colored lights, and sequences of colored lights presented in conjunction with auditory color-names matched to the light sequence was motivated by previous research from our lab showing that children with cochlear implants benefit less in a “memory game task” from the presentation of the informationally redundant auditory color-names than do normal-hearing children of the same age (see Cleary, Pisoni, & Geers, in press). Even pediatric CI users who were able to accurately identify the recorded color-name stimulus tokens used in this task when these tokens were presented in isolation, demonstrated a smaller “redundancy gain” between the uni-modal “lights-only” condition and the multi-modal “color-names plus lights” condition than did an age- and gender-matched group of normal-hearing eight- and nine-year old children. In the present study, we sought to replicate this result in a new sample of children from a different testing center and to examine whether the child’s communication mode affects the size of the observed redundancy gain. This aspect of the study, however, was secondary to the primary goal of using linear regression models to determine the degree to which measures of working memory accounted for variance in language outcome measures not already explained by “traditional” demographic predictors such as age at implantation, duration of use of the implant, and unaided PTA threshold prior to use.

Although there are numerous different outcome measures we might have selected, we chose auditory-only word recognition and receptive vocabulary administered via the child’s preferred

communication mode as our two principal measures. The spoken word recognition and receptive vocabulary measures examined in this report may appear similar in that both are based on the processing of single lexical items, however, the two tasks differed in several potentially important ways. The word recognition tasks used in this study required the children to repeat isolated words presented to them using an auditory-only presentation format. To complete the word recognition tasks, it was necessary that the child both perceives the item and reproduces it accurately enough for the examiner to recognize it as an attempted version of the target. The ability of the child to produce an accurate imitation did not necessarily indicate, however, that the child knew the meaning of the test item since both normal-hearing and some hearing-impaired children have been shown to be able to do this same repetition task with unfamiliar nonsense words that obey the phonotactic characteristics of the child's language (Dillon & Cleary, this volume). By comparison, the receptive vocabulary task used in this study minimized the role of articulatory production by requiring the child to demonstrate knowledge of word meaning by pointing to an appropriately matched picture from a closed set of response alternatives. Since all vocabulary target items were presented via each child's preferred communication mode (oral language or total communication), this measure essentially reflects linguistic knowledge irrespective of the sensory modality by which it was acquired.

Two different word recognition tests were included in this study in order to investigate whether key differences in test administration might impact on the results of the regression analysis. The PBK word identification task (Haskins, 1949) was administered in this study using a clinician's live-voice presentation of each word. The version of the Lexical Neighborhood Test (Kirk, Pisoni, & Osberger, 1995) used in this study employed recorded tokens of each target word. These tokens were spoken by several different talkers, such that the child heard the voices of five different talkers over the course of each set of words. In order to do well on this test, a child must be able to cope with the cross-talker variability present in the speech signal. We were interested in what impact, if any, the use of the live-voice PBK versus the recorded multi-talker LNT would have on our assessment of the role of working memory in the two groups of children.

Method

Data Selection

All data included in this report were collected as part of a larger longitudinal study currently being conducted at the Indiana University School of Medicine in Indianapolis. Data using the new memory game span task were collected in total of 85 test sessions. Five visits involving hearing aid users, thirteen visits involving postlingually deafened children (onset of hearing loss after age three years), and two visits involving data collected before the child had begun to use his/her implant were eliminated from the data set. Two more visits were eliminated due to lack of memory scores in at least one condition along with missing recorded LNT scores. A further two visits were eliminated for missing both PBK and recorded LNT scores. Data from three children (one Oral, and two TC) who only lacked recorded LNT scores were retained in the analysis. Thus, data from 61 visits remained for our final analysis.

Forty-five of the sixty-one visits involved data gathered from a child completing the memory game task for the first time. Twelve of the remaining sixteen visits yielded data collected from children who had been tested once before on the memory game task and whose first set of data from this task was already included in the data set. The remaining four data points came from children who were being tested for the second time on the memory game task, but whose first data set was eliminated from consideration for one of the reasons already listed above. There were therefore 49 different children examined in this sample.

In our initial set of statistical analyses we decided to treat all sixty-one visits as independent cases. In actuality, since 12 of the visits were repeated visits from children already represented in the sample, this inclusion violates an assumption that the cases are independently sampled. However, discarding this data was not an attractive option either since it would reduce the power of the study. An argument for retaining the twelve repeated cases is that an interval of one year separated the two visits and because of this, the associated values of “device use” and “age of child” are necessarily different between the two visits, as are also, in most cases, the level of performance on the three dependent measures. Thus, including a particular child “twice” is not simply counting the “same” case twice in the analysis. We have conducted the multiple linear regression analyses both with and without discarding the 12 visits that were repeated measures from children already represented in the sample and obtained almost identical results, thus assuring us that the violation of independence assumption had little if any impact on the final results. Thus, in the rest of this report, the values for “N” refer to the “visit” sample size, unless otherwise indicated.

Participant and Device Characteristics

A summary of participant characteristics is shown in Table 1. Of the 49 children who were included in the study, 27 primarily used oral communication. These children contributed a total of 32 visits to the analysis. Twenty-two of the children used total communication and a total of 29 visits resulted from their participation. The children ranged in age from 5.2 years to 16.5 years at time of testing. The mean age at testing over the 61 visits was 9.16 years. Mean age at time of testing did not differ significantly between the Oral and TC groups.

PARTICIPANT CHARACTERISTICS	Group Mean (SD)		Min		Max		Group Means Significantly different by independent samples t-test?
	Oral (N=32)	TC (N=29)	Oral	TC	Oral	TC	
Age at Testing in Years	9.16 (2.48)	9.16 (2.74)	5.2	5.9	15.6	16.5	ns
Age at Onset of Deafness in Years	.33 (.74)	.44 (.86)	0	0	2.4	3.0	ns
Duration of Deafness in Years	4.35 (2.27)	3.61 (1.72)	0.5	0.8	9.6	8.9	ns
Age at Implantation in Years	4.69 (1.95)	4.06 (1.59)	1.4	2.2	10	8.9	ns
Duration of Implant Use in Years	4.47 (1.70)	5.10 (2.39)	0.1	1.6	9.0	11.6	ns
PTA Threshold Pre-Implantation	109.12 (6.03)	113.21 (5.23)	96.7	103.3	118.4	120.1	$t(59) = 2.81, p = .007$

Table 1. Descriptive statistics for demographic variables in the Oral and TC groups. The participant characteristics in boldface were included as predictor variables in the regression analyses reported below.

In 25 of the 32 cases in the Oral group, and 21 of 29 TC cases, the child was reported as congenitally deaf. Three cases in each of the Oral and TC groups were from children with an onset of deafness in the first year of life. Children deafened after age 1 year, but prior to age 3 years comprised four cases in the TC group and five cases in the Oral group. The two groups are clearly also comparable with respect to this variable. Although we initially considered using age at onset of severe to profound

deafness as a covariate in our analyses, because these data were severely skewed and limited in range, we decided not to do so.

The children in both groups had been deaf for an average of about four years prior to implantation. Age at implantation was approximately four years of age, on average, in both groups. The Oral group had used an implant for a mean duration of about four and a half years at time of testing, while the TC group averaged a little over five years of implant use. Statistical tests indicated that the groups did not differ significantly in terms of duration of deafness, age at implantation, or duration of implant use. The two groups did, however, differ significantly on their unaided pure tone average (PTA) threshold averaged over responses at 500, 1000, and 2000 Hz, measured prior to implantation. Although all children had a profound hearing loss, the TC group in the present study had somewhat poorer thresholds than the Oral group. This difference supported inclusion of PTA thresholds as one of the predictor variables in our analyses.

The etiology of hearing loss in 35 of the 49 individual children was unknown. Known etiologies consisted of 7 meningitis cases, 4 genetically related cases, 2 cytomegalovirus cases, and 1 case of Mondini deformation. Table 2 provides information regarding the children's devices, speech processors, and coding strategies for both the Oral and TC groups. Examination of Table 2 reveals that the two groups were quite comparable on characteristics related to the implant itself. Establishing the comparable nature of the Oral and TC groups was important to our selection of analyses and their interpretation.

DEVICE CHARACTERISTICS	Oral (N=32)	TC (N=29)
Device Type	# of cases	# of cases
Nucleus 22	26	29
Nucleus 24	1	0
Clarion	5	0
Speech Processor Type	# of cases	# of cases
SPECTRA - Cochlear	26	25
MSP - Cochlear	0	4
Sprint - Cochlear N24	1	0
1.2 - Clarion	4	0
S - Clarion	1	0
Coding Strategy	# of cases	# of cases
SPEAK	26	25
CIS	4	0
MPEAK	0	4
SAS	1	0
ACE (CIS+SPEAK)	1	0

Table 2. Device characteristics for the Oral and TC groups.

Stimuli and Procedures

All measures were gathered by experienced speech-language pathologists or audiologists during each child's annual follow-up visit to the clinic at Riley Hospital, or in a testing room at the child's school (e.g., St. Joseph's Institute for the Deaf in Missouri), over the course of several years. At the end of this period, all children for whom memory measures were available were selected from a larger database of children according to criteria outlined earlier.

Dependent Measures

Open-set Word Recognition. Each child was administered two open-set tests of word recognition, the PBK and the LNT. Both tests require the child to repeat an auditorily-presented monosyllabic word back to the testing clinician. Scoring was done on-line as the child was tested and slight distortions in the reproduction of single phonemes within each test word were scored as correct. Although both word recognition tests were designed for use with children, caregivers of children with cochlear implants rate the words on the PBK as less familiar to their young children (ages 3-8 years) than the words used in the LNT (Kirk, Sehgal, & Hay-McCutcheon, 2000).

The Phonetically Balanced Kindergarten (PBK) test is an open-set test of word recognition using monosyllabic words presented in isolation (Haskins, 1949). Although there are four available word lists, only three of these lists are typically used (see Meyer & Pisoni, 1999). Each child was tested using one of these three lists. Presentation of the target items was carried out using auditory-only live-voice presentation with the face of the clinician concealed behind a mesh screen. In the interest of time, clinicians had the option of only administering 25 items in each 50-word list. Children who made no responses in the first 10 items were given a score of zero. Although both percent phonemes-correct and percent words-correct are usually tabulated, we chose the percent words-correct score for the present analyses.

The Lexical Neighborhood Test (Kirk, Pisoni, & Osberger, 1995) consists of one hundred monosyllabic words divided into four lists of twenty-five words each. Two of the lists contain words that are “lexically easy” (i.e., are phonetically similar to very few other words) and two of the lists contain words that are “lexically hard” (i.e., are phonetically confusable with many other words). A digitally recorded version of this test using multiple talkers has been devised (Kirk, 1998; Kirk, Hay-McCutcheon, Sehgal, & Miyamoto, 2000). In this form of the test, a child is tested on one “easy” word list and one “hard” word list, where the voice of the talker uttering the words may vary between five different talkers, three female and two male. Separate scores between 0-100% are typically generated for the “easy” list versus the “hard” word list. Because we wished to obtain a roughly normal, continuously distributed set of scores, and were not planning to look for differences based on lexical discriminability, we averaged the percent words-correct on both twenty-five-word tests for a composite LNT score.

Receptive Vocabulary. The Peabody Picture Vocabulary Test-Third Edition (PPVT) (Dunn & Dunn, 1997) was administered to each child using his/her preferred communication mode. The PPVT is a receptive measure of vocabulary development that requires the child to correctly point to one of four line drawings, in this case, after hearing a word spoken, or both spoken and signed, by the examiner.

Predictor/Independent Variables

Age at implantation, duration of implant use, PTA threshold, and communication mode were determined by consulting the medical charts for each child on file at the Indiana University Medical Center.

Memory Span Measures. WISC digit-span was administered using auditory-only live-voice presentation with the face of the clinician hidden behind a mesh screen. Administration and scoring followed the procedures provided for this particular subtest in the testing manual for the Wechsler Intelligence Scale for Children, Third Edition (WISC-III) (Wechsler, 1991). In the “digits-forward” section of the digit-span task, the child is required to simply repeat back the list of digits as heard. In the “digits-backwards” section of the task, the child is told to “say the list backward.” In both parts of the

WISC task, testing begins with lists of two items. If at least one of the two lists provided at each list length is successfully repeated, the next list length is increased by one digit until the child gets both lists incorrect at a given length, at which point testing stops. Points are awarded for each list correctly repeated with no partial credit.

An extensive description of the memory game procedure used in this study can be found in Cleary, Pisoni, and Geers (in press). The memory game task is used to obtain a measure of working memory for sequences of either visual-spatial cues or visual-spatial cues paired with auditory signals. The auditory stimuli used in the memory game task were created by recording a male speaker of American English saying the words “red,” “blue,” “green,” and “yellow” at a moderate to slow rate of speech. Each word was spoken in isolation. The durations of the stimuli were not artificially equated, but were retained in their original form. The color-names ranged between 360 ms to 400 ms in length. The recordings were digitally sampled on-line at 22.05 kHz with 16-bit amplitude quantization and the average RMS amplitudes of the individually edited speech files were approximately equated using a digital leveling procedure.

Before the memory game was administered, each child was asked to identify all four recorded tokens by pointing to the colored button matching the color-name. The stimulus tokens were presented one at a time through the same loudspeaker as was used for the memory game (Advent AV570). The presentation level was approximately 70 dB SPL as determined via a hand-held sound level meter held at the level of the child’s head. If a child correctly identified all four items in a set on the first attempt, no further identification testing was administered. If one or more errors were made, the identification task was repeated up to three times, or until zero mistakes were made on a given set of stimuli, whichever occurred first.

Presentation of the test sequences was controlled by a computer program specially created for this purpose, running on a PC computer. The response box used to collect the child’s button presses consisted of a large round disk-like plastic case housing four wide plastic buttons on its surface that are easily depressed by a child. Each button was made of a different color plastic and could be illuminated by a light located beneath its surface. The colors of the buttons matched the color-names that were recorded as stimuli. The button response box was interfaced to the PC computer so that the control program could illuminate the lights when the sound stimuli were played, and turn off the lights once the stimuli ceased outputting. In the lights-only presentation condition, the control program illuminated each light for the same stimulus duration as used in the color-name presentation condition. The computer recorded all button presses and automatically tracked the subject’s performance using an adaptive testing procedure described below.

Participants were shown how the buttons on the response box could be pressed and were told that they would be hearing sounds through the loudspeaker and seeing the buttons light up. They were then instructed to “pay attention and copy exactly what the computer does by pressing on the buttons.” The stimulus sequences used for the memory game task were generated pseudo-randomly by a computer program, with the stipulation that no single item would be repeated consecutively in a given list. A very brief inter-stimulus interval of 200 ms was used between sequence items. However, since the individual stimuli had been recorded at a relatively slow speech rate, the rate of presentation was actually about 1.67 items per second. Each child started with a list length of one item. If two lists in a row at a given length were correctly reproduced, the next list presented was increased by one item in length. If on any trial the list was incorrectly reproduced by the child, the next trial used a list that was one item shorter in length. Each child was presented with twenty lists to reproduce under each condition. After completing the twenty lists in a given condition, the child was assigned a span score calculated by summing the proportion of lists correctly reproduced at each list length tested.

Although the experimenter provided no explicit feedback regarding the accuracy of the child's responses, whenever the child pressed a button during the response period the button was illuminated and the appropriately mapped sound was played out. The color-name plus lights condition was always administered first, followed by the lights-only condition. Each presentation condition of the memory game task took approximately four minutes to complete.

Planned Analyses / Proposed Linear Regression Model

Three multiple linear regression analyses were planned. The dependent (predicted) measures were either open set word recognition measured via the PBK, open set word recognition measured via the LNT, or receptive vocabulary development as measured by the PPVT administered in the child's preferred communication mode. The independent, predictor variables were chosen based on prior research findings indicating that several demographic factors appear to play a substantial role in determining prelingually-deafened children's success with a cochlear implant. Chronological age at time of cochlear implantation, duration of implant use, and residual hearing as measured by PTA threshold prior to implantation were all included as predictor variables for this reason. Skewedness and kurtosis values for each of the three variables are shown for both groups of children in Table 3 in order to demonstrate the suitability of these measures for psychometric analysis. Given the relatively small number of observations per group, use of additional predictor variables was judged to be inadvisable.

	ORAL (N=32)	
	Skew	Kurtosis
Age at Implantation	0.55	0.17
Duration of Implant Use	0.00	1.17
PTA Threshold Pre-Implantation	-0.37	-0.58
	TC (N=29)	
	Skew	Kurtosis
Age at Implantation	1.34	1.99
Duration of Implant Use	1.13	1.15
PTA Threshold Pre-Implantation	-0.38	-0.89

Table 3. Skew and kurtosis values for each demographic predictor variable.

Results and Discussion

Colinearity Issues

Potential problems of multi-colinearity were examined by calculating simple bivariate correlations among the three demographic predictor variables. Age at implantation and duration of implant use were not significantly correlated with each other in either group (Oral: $r = -.08$, TC: $r = -.10$). For the TC group, PTA threshold pre-implant was not significantly correlated with age at implantation or with duration of implant use ($r = -.29$, $p = .13$, and $r = .23$, $p = .22$, respectively). For the Oral group, however, PTA threshold pre-implant was found to be significantly correlated with age at implantation and duration of use: the correlation of PTA and age at implantation was $r = -.40$, $p = .024$, while the correlation between PTA and duration of implant use was $r = .43$, $p = .014$. Since both of these values were moderate correlations, below the suggested r of $.50$ for exclusion or combination of predictor variables, we retained all three variables in the regression analyses for the Oral group. In general, the

pattern of obtained correlations indicates that for both groups, children who were implanted at an older age had slightly more residual hearing (lower thresholds) on average, perhaps because children with more residual hearing often undergo a longer trial period with hearing aids before resorting to cochlear implantation. These correlations also suggest that children with a longer history of CI use (who received implants earlier than their peers) tended to have less residual hearing (higher thresholds). This latter relationship makes sense given changes in candidacy requirements for pediatric CI users over the last decade.

Role of Chronological Age

Chronological age at time of testing posed its own unique problem because it varied widely in our samples. Simply including it as another predictor variable was not appropriate for several reasons. First of all, age at time of testing is completely redundant with the combined information from age at implantation and duration of CI use (age at test = age at implantation + duration of CI use). Therefore, age at testing cannot be meaningfully included as a predictor variable if age at implantation and duration of CI use are also to be used as predictors. We therefore decided that we would first determine the amount of variability in the dependent measures that was accounted for by age at implantation, duration of implant use, and PTA thresholds prior to considering the contribution of working memory, and then interpret this intermediate result as necessarily reflecting the contribution of chronological age--without specifically being able to separate its effects from those of the other demographic predictors.

As shown in Table 4, chronological age was also significantly correlated with all four measures of working memory. In addition, although raw PPVT vocabulary scores were, as might be expected, strongly correlated with age, PBK and LNT open-set word recognition scores were unrelated to age at testing. Thus, although the percent of variance in PPVT scores accounted for by age at implantation, duration of use, and PTA threshold will also reflect the contribution of chronological age, very little contribution from chronological age should be reflected in the amount of variance in word recognition scores accounted for by the three demographic predictor variables.

CORRELATIONS WITH CHRONOLOGICAL AGE AT TESTING		
	Oral (N=32)	TC (N=29)
Predictor Variables		
Age at Implantation	.73***	.50**
Duration of Implant Use	.62***	.82***
PTA Threshold	-.02	.04
Potential Predictor Variables		
Memory Span Game Lights	.56**	.54**
Memory Span Game Colors	.66***	.49**
WISC Digit-span Forward	.34	.56**
WISC Digit-span Backwards	.63***	.71***
Outcome Measures		
Word Recognition – PBK	.11	-.11
Word Recognition – LNT	.03	-.12
Vocabulary – PPVT Raw Score	.74***	.84***

*** $p < .001$, ** $p < .01$, * $p < .05$, uncorrected p-values.

Table 4. Correlations with chronological age at time of testing

Group Mean Performance on Outcome Measures

Mean scores for the word recognition and receptive vocabulary measures are shown in Table 5 for the Oral and TC groups. The spread of scores was quite similar in both groups for each of the three measures. Although the Oral children, as a group, did significantly better than the TC group on PBK open-set word recognition, the groups did not differ reliably on LNT open-set word recognition using recorded tokens from multiple talkers or on PPVT receptive vocabulary administered in the child's preferred communication mode.

DEPENDENT / OUTCOME MEASURES	Group Mean (SD)		Min Score		Max Score		Group Means Significantly different by independent samples t-test?
	Oral (N=32)	TC (N=29)	Oral	TC	Oral	TC	
PBK Word Recognition Percent Correct	45.50 (23.05)	30.62 (20.09)	8	0	88	68	$t(59) = 2.68, p = .01$
LNT Word Recognition Percent Correct	48.77 (21.81)	40.30 (21.49)	0	2	82	80	ns
PPVT Receptive Vocabulary Raw Score	88 (34)	90 (29)	20	37	172	169	ns

Table 5. Descriptive statistics for the three outcome measures, for Oral and TC groups

Variance Accounted for by Traditional Demographic Predictors

The statistical package SPSS was used to conduct the linear regression analyses. First, we assessed the contribution of the traditional demographic predictors using the forced-entry option for entering variables into the regression model. The amount of variance accounted for by the traditional predictors is shown in Table 6.

For the Oral group, the traditional predictors alone accounted for a significant portion of the variance in PBK, LNT, as well as PPVT scores (PBK: $F(3,28) = 4.15, p = .015$; LNT: $F(3,27) = 3.73, p = .023$; PPVT: $F(3,28) = 12.7, p < .001$). In contrast, for the TC group, the picture differed in several important ways. The pre-included predictors failed to account for a significant amount of the variance in the word recognition measures (PBK: $F(3,25) < 1$; LNT: $F(3,23) < 1$), but did account for a significant amount of variance in PPVT scores ($F(3,25) = 25.67, p < .001$).

This intermediate set of results indicates that with regards to open-set word recognition, the traditional predictor variables behaved much as expected for the Oral group. However, for the TC group, these variables were strikingly ineffective as predictors for word recognition performance. For the PPVT, a measure of receptive language that was administered using the child's preferred communication mode, the traditional predictor variables accounted for a very large amount of the variance in these scores for the TC group, and a slightly smaller, but still substantial amount of variance in the Oral group.

PBK	ORAL (N=32)		TC (N=29)	
	Percent of variance accounted for by demographic predictors	Additional percent of variance accounted for	Percent of variance accounted for by demographic predictors	Additional percent of variance accounted for
Digit-span Forwards	30.80%	16.80%	3.20%	44.80%
Digit-span Backwards		1.80%		17.30%
Memory Game Colors+Lights		5.40%		3.20%
Memory Game Lights-Only		0.20%		0.30%
LNT	ORAL (N=31)		TC (N=27)	
	Percent of variance accounted for by demographic predictors	Additional percent of variance accounted for	Percent of variance accounted for by demographic predictors	Additional percent of variance accounted for
Digit-span Forwards	29.30%	14.40%	3.80%	27.00%
Digit-span Backwards		0.00%		5.30%
Memory Game Colors+Lights		0.70%		0.20%
Memory Game Lights-Only		0.10%		1.10%
PPVT	ORAL (N=32)		TC (N=29)	
	Percent of variance accounted for by demographic predictors	Additional percent of variance accounted for	Percent of variance accounted for by demographic predictors	Additional percent of variance accounted for
Digit-span Forwards	57.60%	26.70%	75.50%	3.20%
Digit-span Backwards		6.20%		5.00%
Memory Game Colors+Lights		5.20%		0.40%
Memory Game Lights-Only		0.10%		0.00%

Table 6. Percent of variance in PBK, LNT, and PPVT scores accounted for by the traditional demographic predictors, and the additional variance accounted for by each of the four working memory measures.

Additional Variance Accounted for by Working Memory Measures

As the next step in our analyses, we assessed the contribution of individual differences in the four different working memory measures by retaining the traditional predictors in the model, adding one memory measure as a predictor, and then recalculating the percent of variance accounted for using the forced-entry option. This was done four times per dependent measure, once for each type of memory measure considered individually. Table 6 lists the amount of additional variance accounted for by each memory measure.

Forward digit-span accounted for an additional 17% of the total variance in the Oral group’s PBK open-set word recognition scores, and 14% in their LNT open-set word recognition scores. For the TC group, for whom the traditional predictors had proved rather ineffective, forward digit-span accounted for a surprisingly large 44.8% in additional variance in PBK scores and a similarly large 27% in additional variance in LNT scores. These results support the proposal that the forward digit-span and open-set word recognition tasks share a common processing component. Whether this commonality is at the level of

early perceptual identification, phonological rehearsal, or retrieval from phonological working memory cannot, however, be determined from the present data.

For receptive vocabulary as measured via the PPVT, the observed relationship was somewhat different. Forward digit-span accounted for a sizable 26.7% in additional variance for the Oral group, but only 3.2% in additional variance for TC group. These values are consistent with the hypothesis that forward digit-span is a strong predictor of outcome when the administration format of the outcome measure requires auditory encoding, as was the case for the Oral group, but not the TC group.

Backwards digit-span accounted for virtually no additional variance in either word recognition measure for the Oral group. This finding suggests that the comparatively sophisticated explicit sequence manipulation strategies that can be used to advantage on the backwards digit-span task bear little relation to the skills required for simple repetition of auditory stimuli. This proposal is not fully consistent, however, with the finding that for the TC group, backwards digit-span was able to account for a moderate amount of additional variance in word recognition scores, 17.3% for PBK scores and 5.3% for LNT scores. As addressed further in the General Discussion, reduced audibility of the digit-names may have contributed to this finding in the TC group.

For both groups of children, Oral and TC, backwards digit-span accounted for about 5-6% of additional variance in receptive vocabulary scores. These results are similar to values we have previously obtained using the same two tasks with eight- and nine-year-old normal-hearing children. In normal-hearing children, backwards digit-span accounts for approximately 7% of the variance in receptive vocabulary, when chronological age is partialled out. We believe this finding reflects a tendency for children who possess above-average linguistic abilities relative to their age group to also exhibit more sophisticated explicit sequence manipulation strategies.

Results obtained using the memory game task showed smaller contributions to the total variance than those observed using digit-spans. Scores for lights-plus-sound presentation condition of the memory game accounted for ~5% in additional variance in PBK word recognition scores and PPVT scores for the Oral group, and similar but somewhat smaller amounts of variance in the TC group. Scores for the lights-only presentation condition of the memory game accounted for almost no additional variance in any of the dependent measures for either group. Thus, only when the memory game included an auditory component did this measure account for any additional variance in the dependent measures.

Analysis of the memory game's contribution to LNT scores did not follow our expectations, particularly with regard to the Oral group of children. The memory game, even in the lights-plus-sound condition, failed to account for any significant additional variance in LNT scores. The LNT and PBK test administrations did, however, differ in some important ways—the LNT used recorded tokens from multiple-talkers while the PBK was administered using monitored live-voice by a clinician. Although LNT and PBK scores were highly correlated with each other $r = +.83$, it appears that the ability to deal with cross-talker variability as measured by the LNT is not well predicted by performance in the memory game presentation conditions used in the present study.

Group Mean Performance on Working Memory Tasks

Group mean performance for the forward and backwards digit-span tasks is shown in the two top panels of Figure 1. Scores for the Oral group are shown in the top left panel. Scores for the TC group are shown in the top right panel. Not surprisingly, for both groups, backwards digit-span scores were consistently lower than forward digit-span scores. Although the size of this difference was slightly larger for the Oral group than for the TC group (mean difference = 2.1 points vs. 1.7 points, respectively), the

groups did not differ reliably from each other on this measure. Similarly, although both forward and backwards digit-span scores were higher on average for the Oral group than for the TC group, the differences between the groups did not reach statistical significance.

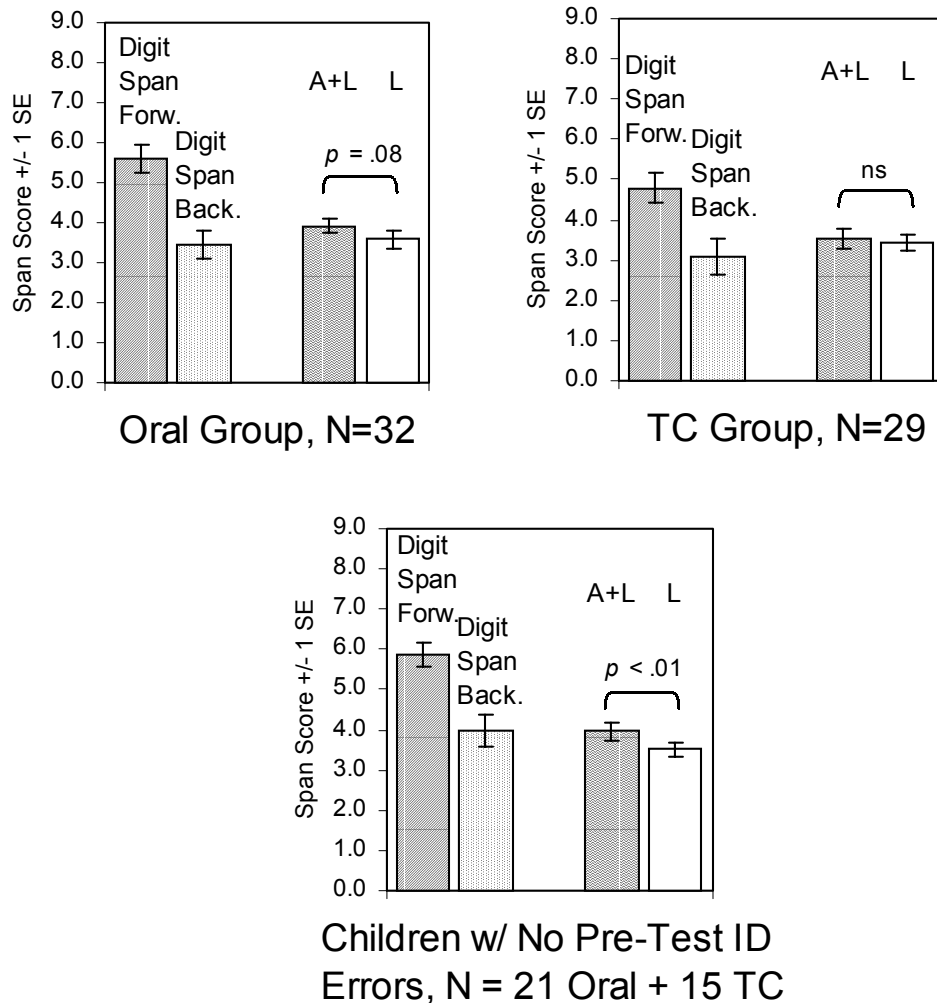


Figure 1. Mean performance in the four working memory tasks: WISC forward digit-span, WISC backwards digit-span, the memory game task in the auditory-plus-lights presentation condition (A+L), and the memory game task in the lights-only presentation condition (L).

The top two panels of Figure 1 also show the mean span scores obtained in the present study for each memory game condition (“A+L” and “L”) for both the Oral and TC groups. Comparing first across groups, we found that although both presentation condition means were somewhat higher for the Oral group than for the TC group, the within-group variability was too large for these differences to be statistically reliable. Next we examined within-group differences on the two memory game presentation conditions. As previously reported, in prior research with normal-hearing eight- and nine-year olds, we found that on average, better performance is obtained in the multi-modal “auditory-plus-lights” presentation condition of the memory game (“A+L”) than in the “lights-only” presentation condition

(“L”) (Cleary, Pisoni, & Geers, in press). This “redundancy gain” has been attributed to normal-hearing children’s ability to make use of the additional auditory information to facilitate their encoding and memory of the sequences in this task. Cleary, Pisoni, and Geers also found that prelingually-deaf eight- and nine-year old children with cochlear implants, who had at least four years experience with their device at time of testing, showed smaller redundancy gains from the addition of auditory cues to visual-spatial sequences than did age- and gender-matched normal-hearing children.

For the Oral children in the present study, although the mean span in the auditory-plus-lights condition was longer, as expected, than in the lights-only condition, this difference did not quite reach statistical significance ($t(31) = 1.83, p = .077$, mean difference = +.34 units). These results suggest, however, that the Oral group made some use of the redundant auditory stimuli. The children in the TC group displayed virtually no difference between the two conditions ($t < 1$, mean difference = +.11 units), indicating that, as a group, they were not able to benefit from the redundant auditory signals provided and relied primarily on visual-spatial encoding to carry out the sequence reproduction task in both conditions of the memory game.

In one final analysis, we analyzed only the performance of children (both Oral and TC), for whom we were able to verify that the child could correctly identify all four auditory color-names when these stimulus tokens were played in isolation during a “stimulus identification pre-test.” For 36 of the 61 available visits, no identification errors were made by the child. For twenty visits, this data was unavailable. In the remaining five visits, one or more identification errors were observed. When only the 36 visits with no identification errors were analyzed, we found evidence for a significant redundancy gain in the memory game task ($t(35) = 2.75, p = .009$, mean difference = +.43 units). This result demonstrates that for the children who were consistently able to identify the auditory stimuli when presented in isolation, the presence of the informationally redundant auditory color-names resulted, on average, in improved performance in memory span, relative to the lights-only presentation condition. Of these 36 visits, 21 were contributed by children using oral communication and 15 from children using total communication. These results are shown in the lower panel of Figure 1.

Partial Reanalysis of Regression Results

Based on the difference in memory game performance given success at the stimulus identification pretest, we recalculated all values in Table 6 omitting all cases in which the child made an error in identifying the color-name stimuli used in the memory game. For the Oral group, now with an N of 21 (as compared to 32) visits, the pattern of variance accounted for was virtually unchanged. For the TC group (now with an N of 15 as compared to 29), eliminating cases in which identification errors were made had the effect of boosting the amount of variance in word recognition scores accounted for by the traditional demographic predictor variables of age at implantation, duration of CI use, and PTA threshold to about the same level as the Oral children (i.e., 30%), but did not substantially change the amount of variance in receptive vocabulary scores accounted for by traditional predictors, or the amount of additional variance accounted for by the digit-span and memory game span measures. Finally, in order to further investigate our failure to find the expected pattern of results regarding the ability of the multi-modal “A+L” condition of the memory game to predict LNT word recognition scores in the Oral group, we again recalculated all values in Table 6 using only the subset of 36 cases for which we could verify correct identification of all color-name stimuli when presented in isolation. This change did not, however, result in any greater percentage of additional variance in LNT scores accounted for by the multi-modal memory game condition.

General Discussion

The primary goal of the present study was to investigate whether individual differences in working memory could account for a significant proportion of the variance in the open-set word recognition and receptive vocabulary skills of prelingually-deafened children with CIs, after the contribution of known demographic predictors was taken into account. In order to answer this question, we first determined the degree to which age at implantation, duration of CI use, PTA thresholds prior to implantation, and, indirectly, chronological age, were able to account for variance in the outcome measures. We found that these traditional predictors of outcome accounted for more variance in word recognition scores in the Oral group than in the TC group. The inability of the traditional predictors to account for variance in the TC group's word recognition scores was unexpected. This result suggests that if a child does not rely primarily on oral language, the child's open-set word recognition performance will not necessarily follow in a predictable fashion from his/her demographic profile. Furthermore, the results also suggest that simply having greater/earlier experience with an implant or more residual hearing cannot insure that auditory-only word recognition skills will develop proportionally, because the development of such skills is dependent not just on the presence of such advantageous circumstances but also on practice and experience with oral language (Hart & Risley, 1995).

Although the demographic factors accounted for a large amount of variance in both groups' receptive vocabulary scores, more variance was accounted for in the TC group than in the Oral group. This result may indicate that although the traditional "non-cognitive" predictors account for most of the individual differences observed in receptive vocabulary for TC children, traditional predictors account for less of the variability observed in Oral children's receptive vocabulary because additional factors, such as individual differences in working memory, also play a role in learning vocabulary via the auditory modality.

Auditory digit-span requiring recall of digit sequences in the forward direction accounted for a sizable amount of additional variance in PBK and LNT word recognition scores in both groups of children. This amount was considerably larger for the TC group than for the Oral group. The reason for this result requires further investigation. The audibility of the digits may have contributed to this difference, although the inclusion of PTA thresholds in the linear regression model should have, in theory, partially compensated for reduced audibility. It would have been helpful to have identified any children who were unable recognize the digits when spoken in isolation. Future data collection should incorporate this additional procedure.

For receptive vocabulary development, we found a partially reversed pattern of results, with forward auditory digit-spans accounting for a greater amount of additional variance in the Oral group, than in the TC group. We suggest two possible reasons for this result. For children who use oral language, individual differences in cognitive factors such as working memory may, in fact, play a key role in facilitating the development of their receptive language skills. Furthermore, if difficulty discriminating the auditory digits contributed to individual differences in digit-span performance in the TC group, then there is no reason why this variability should predict individual differences in a dependent measure that is administered using total communication.

For the Oral group, scores in the "auditory-plus-lights" presentation condition of the memory game did account for some additional variance in PBK word recognition and PPVT receptive vocabulary scores. For the TC group, the "auditory-plus-lights" presentation condition of the memory game failed to predict any additional variance in either of these dependent measures, presumably because the TC children used only visual-spatial encoding to perform the memory game task. In contrast, scores in the "lights-only" presentation condition of the memory game did not account for any additional variance in

the dependent measures in either the Oral or TC group. This suggests that the contribution of working memory is specific to auditory/verbal encoding in working memory, and not some generic, modality-independent component of the working memory system. The contribution of working memory is only observed for memory tasks that involve phonological processing of the input patterns.

Finally, we also found that children who use primarily oral communication, and children who were able to identify all the memory game auditory stimulus tokens correctly, showed a larger redundancy gain on average in the multi-modal memory game presentation condition relative to the “lights-only” presentation condition compared to children not in these groups. This result indicates that like normal-hearing children, some children with CIs engage in verbal encoding strategies and can therefore use the informational redundancy present in the auditory signal to aid them in the multi-modal presentation condition.

Children with cochlear implants are, we believe, an important clinical population to study in order to learn more about the effects of early sensory experience on cognitive processing. The present findings suggest that the contribution of working memory to the development of language skills may vary depending on whether the implanted child develops language in an Oral vs. Total Communication environment and the level of abstraction involved in the language skill under examination, i.e., the learning of phonological forms (word recognition/repetition) versus semantics (vocabulary skills). Our findings indicate that some of the currently unexplained variance in auditory word recognition and receptive language performance in pediatric CI users may be accounted for by individual differences in the underlying cognitive processes employed in auditory memory span tasks. We propose that an important cognitive processing variable related to how young children encode and manipulate the phonological representations of spoken words in working memory contributes to the development of oral/aural language skills in children with cochlear implants (see also, Pisoni, 2000).

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