

**RESEARCH ON SPOKEN LANGUAGE PROCESSING**  
Progress Report No. 26 (2003-2004)  
*Indiana University*

**Sequence Learning as a Predictor of Audiological Outcomes in Deaf Children  
with Cochlear Implants<sup>1</sup>**

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<sup>1</sup> This work was supported by NIH-NIDCD R01 Research Grants DC00111 and DC03937 to Indiana University.

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## Sequence Learning as a Predictor of Audiological Outcomes in Deaf Children with Cochlear Implants

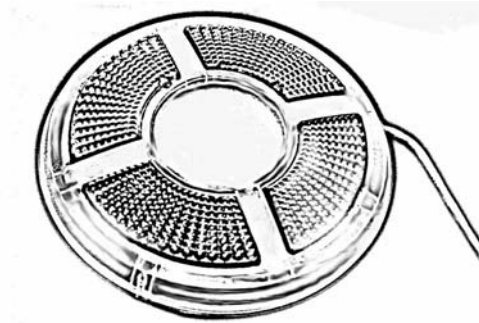
**Abstract.** The present study extends earlier research carried out by Cleary and Pisoni (2001) who found that measures of auditory sequence learning, using the Simon memory game procedure, were related to open-set spoken word recognition and language comprehension. Sequence learning scores were obtained from a new group of profoundly deaf children with cochlear implants. Two different measures of sequence learning were computed. One measure, Simon auditory redundancy gain, was used to assess the benefit of redundant auditory information on the reproduction of visual sequences of colored lights. A second measure, Simon learning improvement, was used to assess the increase in sequence learning observed over time after a period of implant use. Both learning measures were found to be correlated with traditional audiological measures of outcome and benefit. The auditory gain measure was significantly correlated with two measures of language comprehension on the Common Phrases test. Vocabulary knowledge on the PPVT was found to be correlated with the improvement in sequence learning over time. Taken together with the earlier findings reported by Cleary and Pisoni (2001), the present results suggest that differences in learning may contribute an additional source of variance to traditional measures of speech and language outcomes in this clinical population. Measures of learning and memory may therefore provide important new insights into the underlying cognitive and neurobiological factors that are responsible for the individual differences and enormous variation in a range of clinical speech and language outcome measures that are routinely obtained from deaf children who have received cochlear implants as a treatment for profound hearing loss.

### Introduction

Many of the traditional methods for measuring working memory span and the capacity of immediate memory use recall tasks that require a subject to repeat back a sequence of test items using an overt articulatory-verbal motor response (Dempster, 1981). Because deaf children with cochlear implants may also have delays and/or disorders in speech motor control and phonological development, it is possible that any differences in performance between deaf children and age-matched normal-hearing children using memory span tasks could be due to the nature of the response requirements used during retrieval and output. Differences in articulation and speech motor control could magnify other differences in encoding, storage, rehearsal or retrieval processes.

To eliminate the use of an overt articulatory-verbal response, we developed a new experimental methodology to measure immediate memory span in deaf children with cochlear implants based on Milton-Bradley's Simon, a popular memory game. Figure 1 shows a display of the apparatus which was modified so it could be controlled by a PC. In carrying out the procedure, a child is asked to simply "reproduce" a stimulus pattern by manually pressing a sequence of colored panels on the four-alternative response box. In addition to eliminating the need for a verbal response, the Simon methodology permitted us to manipulate the stimulus presentation conditions in several systematic ways while holding the response format constant. This particular property of the experimental procedure was important because it provided us with a novel way of measuring how auditory and visual stimulus dimensions are analyzed and processed alone and in combination and how these stimulus manipulations affected measures of memory span. The Simon memory game apparatus and methodology also offered us an opportunity to

study learning processes, specifically, sequence learning and the relations between memory and learning using the same identical experimental procedures and response demands.



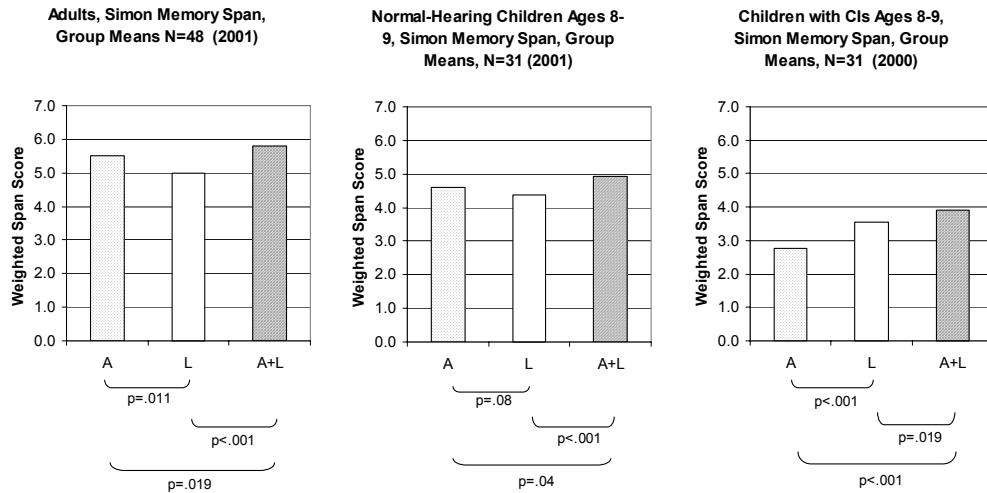
**Figure 1.** The memory game response box based on the popular Milton Bradley game “Simon.”

In our initial studies with the Simon apparatus, three different stimulus presentation formats were employed (Pisoni & Cleary, 2004). In the first condition, the target sequences to be reproduced consisted only of spoken color names (A). In the second condition, sequences of colored lights (L) were presented in the visual modality. In the third presentation condition, the spoken color names were presented simultaneously with matching colored lights (A+L).

Forty-five hearing-impaired children with cochlear implants were tested using the Simon memory game apparatus. Thirty-one of these children were able to complete all six conditions included in the testing session. They also were able to identify the recorded color-name stimuli used in this task when these items were presented alone in isolation. Thirty-one normal-hearing children who were matched in terms of age and gender with the group of children with cochlear implants were also tested. Finally, 48 normal-hearing adults were recruited to serve as an additional comparison group (see Pisoni & Cleary, 2004).

Of the six conditions tested, three measured the children’s immediate memory skills and three measured the children’s sequence learning skills. In the immediate memory task, the temporal sequences systematically increased in length as the subject progressed through successive trials in the experiment. Within each condition, the 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 was increased by one item in length. If a list was incorrectly reproduced, the next trial used a list that was one item shorter in length. This adaptive tracking procedure is similar to methods used in psychophysical testing (Levitt, 1970). Sequences used for the Simon 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. We computed a weighted memory span score for each child by finding the proportion of lists correctly reproduced at each list length and averaging these proportions across all list lengths.

A summary of the results from the Simon immediate memory task for the three groups of subjects is shown in Figure 2. The normal-hearing adults are shown in the left panel, the normal-hearing aged-matched children are shown in the middle panel and the children with cochlear implants are shown in the right panel. Within each panel, the scores for auditory-only presentation (A) are shown on the left, scores for lights-only presentation (L) are shown in the middle and scores for the combined auditory and lights presentation condition (A+L) are shown on the right.



**Figure 2.** Mean sequence memory spans in each of the three presentation conditions using the “Simon” memory game (Redrawn from Pisoni & Cleary, 2004).

Examination of the Simon memory span scores for the normal-hearing adults shown in the left-hand panel of Figure 2 reveals several findings that can serve as a benchmark for comparing and evaluating differences in performance of the two groups of children. First, we found a “modality effect” for presentation format. Auditory presentation (A) of sequences of color names produced longer immediate memory spans than visual presentation (L) of sequences of colored lights ( $p < .02$ ). Second, we found a “redundancy gain.” When information from the auditory and visual modalities was combined together and presented simultaneously (A+V), the memory spans were longer compared to presentation using only one sensory modality ( $p < .02$  for A and  $p < .001$  for L).

The modality effect and the redundancy gain demonstrate that the Simon memory game procedure is a valid and potentially useful experimental methodology for measuring immediate memory span in normal-hearing adults because it reveals subtle differences in the sensory modality used for presentation of the stimulus patterns. As in other studies of verbal short-term memory, longer Simon memory spans were found for auditory stimuli compared to visual stimuli in the normal-hearing adults, suggesting the active use of phonological coding and verbal rehearsal strategies (Penny, 1989; Watkins, Watkins & Crowder, 1974). In addition, the Simon memory spans reflected cross-modality redundancies between stimulus dimensions when the same information about a stimulus pattern was correlated and presented simultaneously to more than one sensory modality. This latter finding demonstrates that adults are not only able to combine and integrate redundant sources of stimulus information across different sensory modalities, but the consequence of this integration and redundancy gain is an increase in immediate memory capacity when the stimulus dimensions are correlated in the auditory and visual modalities.

The middle panel of Figure 2 shows the results of the three presentation conditions for the group of normal-hearing 8-and 9-year old children who were age-matched to the group of deaf children with cochlear implants. Overall, the pattern of the Simon memory span scores is similar to the findings obtained with the normal-hearing adults shown in the left-hand panel of Figure 2 although several differences were observed. First, the absolute memory spans for all three presentation conditions were lower for the normal-hearing children than the memory spans obtained from the adults. Second, while the

modality effect found with the adults was also present in these data, it was smaller in magnitude and was only marginally significant, suggesting possible developmental differences in the rate and efficiency of verbal rehearsal between adults and children in processing auditory and visual sequential patterns like those used in this task. Third, the cross-modal “redundancy gain” observed with the adults was also found with the normal-hearing children although it was also smaller in magnitude ( $p < .04$  A and  $p < .001$  for L). Again, these differences may simply be due to age, maturation and development.

The Simon memory spans for the deaf children with cochlear implants are shown in the right-hand panel of Figure 2 for the same three presentation conditions. Examination of the pattern of these memory spans reveals several striking differences from the memory spans obtained for the normal-hearing children. First, the memory spans for all three presentation conditions were consistently lower overall than the spans from the corresponding conditions obtained for the normal-hearing children. Second, the modality effect observed in both the normal-hearing adults and normal-hearing children was reversed for the deaf children with cochlear implants. The memory spans for the deaf children were longer for visual-only presentation than auditory-only presentation and this difference was highly significant ( $p < .001$ ). Third, although the cross-modal “redundancy gain” found for both the adults and normal-hearing children was also observed for the deaf children and was statistically significant for both conditions ( $p < .001$  for A and  $p < .02$  for L), the absolute size of the redundancy gain was smaller in magnitude than the gain observed with the normal-hearing children.

The results obtained for the visual-only presentation conditions are of particular theoretical interest because the deaf children with cochlear implants displayed shorter memory spans than the normal-hearing children. This finding adds additional support to the hypothesis that phonological recoding and verbal rehearsal processes in working memory play important roles in perception, learning and memory in these children (Pisoni & Cleary, 2003). Capacity limitations of working memory are closely tied to speed of processing information even for visual patterns which can be rapidly recoded and represented in memory in a phonological or articulatory code for certain kinds of sequential processing tasks. Verbal coding strategies may be mandatory in memory tasks that require immediate serial recall of temporal patterns that preserve item and order information (Gupta & MacWhinney, 1997). Thus, although the visual patterns were presented using only sequences of colored lights, both groups of children appeared to recode these sequential patterns using verbal labels and verbal coding strategies to create stable phonological representations in working memory for maintenance and rehearsal prior to response output.

The deaf children also showed much smaller redundancy gains under the multi-modal presentation conditions, which suggests that in addition to differences in working memory and verbal rehearsal, their information processing skills and abilities to perceive and encode complex multi-dimensional stimuli are atypical and compromised relative to age-matched normal-hearing children. The smaller redundancy gains observed in these deaf children may also be due to the reversal of the typical modality effects observed in studies of working memory that reflect verbal coding of the stimulus materials. The modality effect in short-term memory studies is generally thought to reflect phonological coding and verbal rehearsal strategies that actively maintain temporal order information of sequences of stimuli in immediate memory for short periods of time (Watkins et al., 1974). Taken together the present findings demonstrate important differences in both attention and memory processes in this clinical population. These basic differences in information processing skills may be responsible for the wide variation in speech and language outcomes observed in deaf children following cochlear implantation.

## Simon Learning Spans

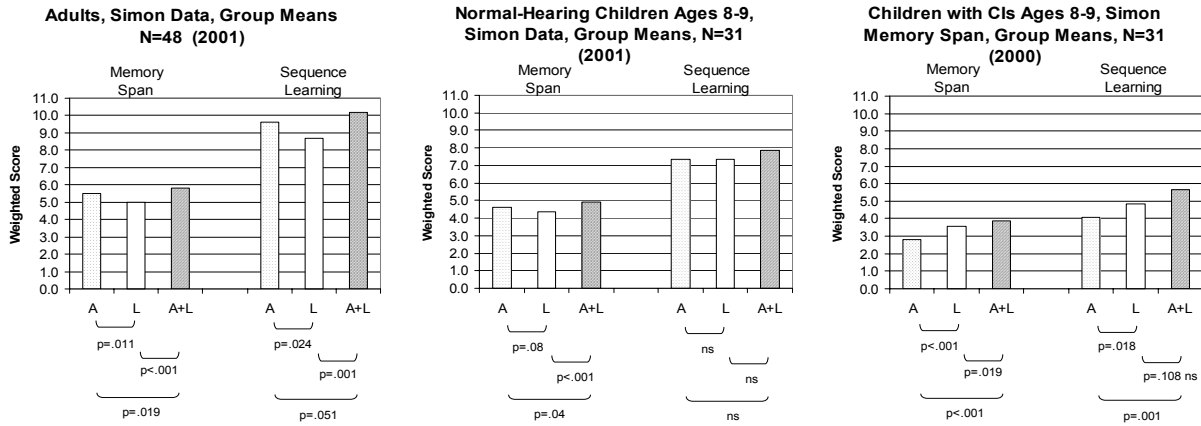
The initial version of our Simon memory game used novel sequences of color names and/or colored lights (Pisoni & Cleary, 2004). All of the sequences were generated randomly on each trial in order to prevent any learning. Our primary goal in this research was to obtain estimates of working memory capacity for temporal patterns that were not influenced by sequence repetition effects or idiosyncratic coding strategies that might increase memory capacity from trial to trial. Each test sequence was novel and was created by a random number generator so that the structure of a sequence of stimuli was always different and varied from trial to trial during the course of the experiment. If a subject correctly reproduced a pattern at a given length twice in a row, the adaptive testing algorithm in the experimental control program automatically increased the length of the sequence by one item on the next trial and then generated an entirely new temporal sequence of stimuli that was different from the sequence presented on the previous trial. This procedure was used throughout the entire experiment to obtain estimates of immediate memory capacity. Thus, there was no basis for any new learning to take place and we can use the measures of Simon memory span as estimates of capacity of immediate memory for sequences of highly familiar stimuli such as color names.

In addition to measuring immediate memory capacity, we have also used the Simon memory game procedure to study sequence learning and to investigate the effects of long-term memory on coding and rehearsal strategies in working memory (Cleary & Pisoni, 2001). To accomplish this goal and to be able to directly compare the gains in learning and the increases in working memory capacity to our earlier Simon memory span measures, we examined the effects of sequence repetition on immediate memory span by simply repeating the same pattern again if the subject correctly reproduced the sequence on a given trial. In the Simon learning condition, the same stimulus pattern was repeated on each trial for an individual subject and the sequences gradually increased in length by one item after each correct response until the subject was unable to correctly reproduce the pattern. This change in the methodology provided an opportunity to study learning based on simple repetition and to investigate how repetition of the same pattern affects the capacity of immediate memory.

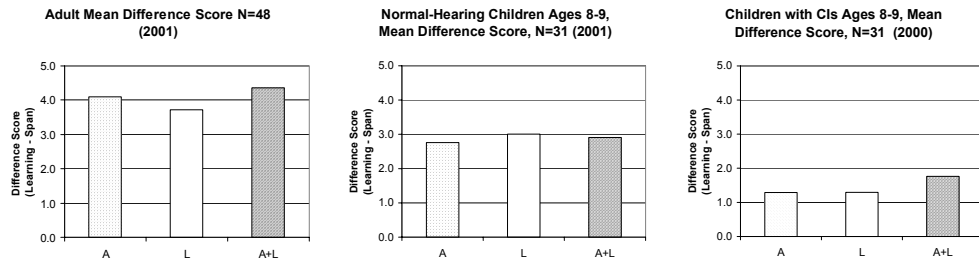
Figure 3 displays a summary of the results obtained in the Simon learning conditions that investigated the effects of sequence repetition on memory span for the same three presentation formats used in the earlier conditions, auditory-only (A), lights-only (L) and auditory+lights (A+L). The weighted memory span scores for the sequence learning conditions are shown on the right-hand side of each panel in this figure; the corresponding set of memory span scores obtained earlier under random presentation format for the same three presentation conditions are shown on the left-hand side of each panel. The data for the normal-hearing adults are shown in the left panel, the data for the normal-hearing 8- and 9-year old children are shown in the middle panel and the data for the deaf children with cochlear implants are shown in the right panel.

Examination of the two sets of memory span scores shown within each panel reveals several consistent findings. First, repetition of the same stimulus sequence produced large learning effects for all three groups of subjects. This repetition effect can be seen clearly by comparing the three scores on the right-hand side of each panel to the three scores on the left-hand side. For each of the three groups of subjects, the learning span scores on the right were higher than the memory span scores on the left. Repetition of a stimulus pattern increased immediate memory span capacity, although the magnitude of the learning effects differed systematically across the three groups of subjects. The memory spans observed for the adults in the learning condition were about twice the size of the memory spans observed when the sequences were generated randomly from trial to trial. Although a repetition effect was also obtained with the deaf children who use cochlear implants in the right panel, the size of their repetition

effect was about half the size of the repetition effect found for the normal-hearing children shown in the middle panel of Figure 3.



**Figure 3.** Mean immediate memory spans and sequence learning scores in each of the three conditions tested using the “Simon” memory game (Redrawn from Pisoni & Cleary, 2004).

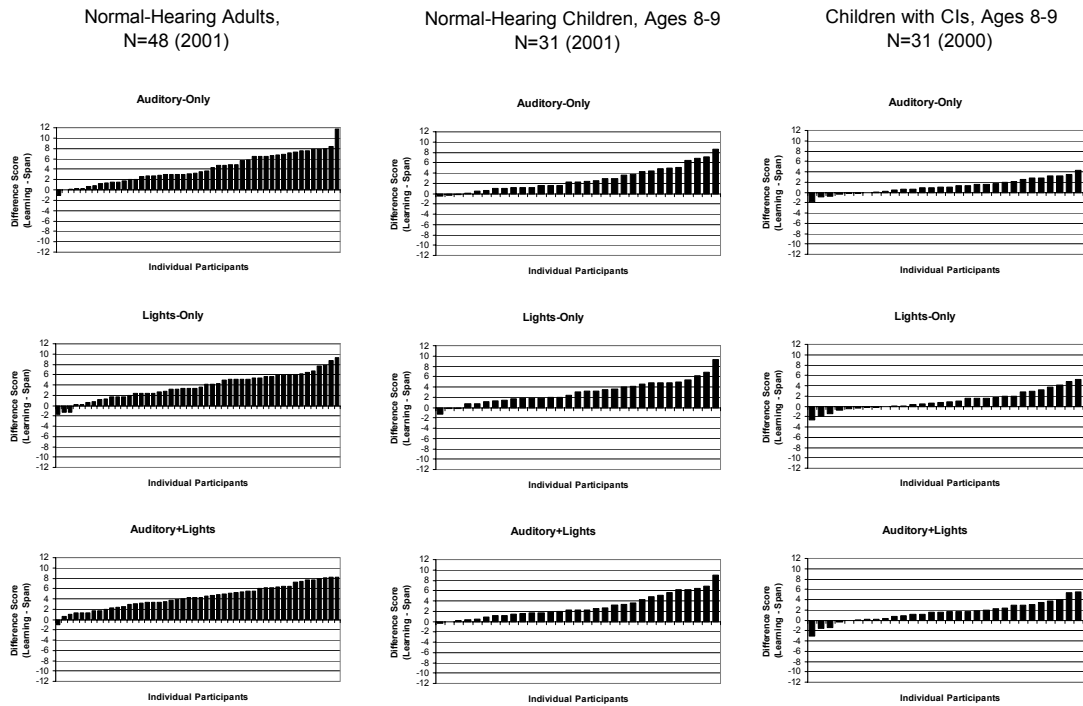


**Figure 4.** Different scores between memory and learning scores for each of the three conditions (A, L, A+L) for the three groups of participants tested using the “Simon” memory game.

Second, the rank ordering of the three presentation conditions in the sequence learning conditions was similar to the rank ordering observed in the memory span conditions for all three groups of subjects. The repetition effect was largest for the A+L conditions for all three groups. For both the normal-hearing adults and normal-hearing children, we also observed the same modality effect in learning that was found for immediate memory span. Auditory presentation was better than visual presentation. And, as before, the deaf children also showed a reversal of this modality effect for learning. Visual presentation was better than auditory presentation.

To assess the magnitude of the repetition learning effects, we computed difference scores between the learning and memory conditions by subtracting the memory span scores from the learning span scores for each subject. The average difference scores for the three groups of subjects are shown in Figure 4, while the data for individual subjects in each group for the three presentation formats are

displayed in Figure 5. Inspection of these distributions in Figure 5 reveals a wide range of performance for all three groups of subjects. While most of the subjects in each group displayed some evidence of learning in terms of showing a positive repetition effect, there were a few subjects in the tail of the distribution who either failed to show any learning at all or showed a small reversal of the predicted repetition effect. Although the number of subjects who failed to show a repetition effect was quite small in the adults and normal-hearing children, about one-third of the deaf children with cochlear implants showed no repetition learning effect at all and failed to benefit from having the same stimulus sequence repeated on each trial.



**Figure 5.** Difference scores for individual subjects showing sequence learning score minus his working memory span score. Data for the auditory-only (A) condition is shown on the top, lights-only (L) condition in the middle, and auditory-plus-lights (A+L) condition on the bottom. Data from normal-hearing adults are shown on the left, scores for normal-hearing 8- and 9-year-old children in the center, and scores for 8- and 9-year-old cochlear implant users on the right (Redrawn from Pisoni & Cleary, 2004).

To study the relations between sequence learning and speech and language development in these children, Cleary and Pisoni (2001) computed a series of correlations between the three learning scores obtained from the Simon learning task and several of the traditional audiological outcome measures of benefit that were obtained from these children as part of the larger CID project (see Geers, Nicholas & Sedey, 2003). None of the demographic variables were found to be correlated with any of the Simon sequence learning scores. However, moderate positive correlations were obtained for three measures of spoken word recognition, the WIPI, BKB sentences and the LNT ( $r = +.36$ ,  $p < .05$ ) and the auditory-only Simon learning condition. Moreover, the auditory-only Simon learning span was also found to be correlated with the TACL-R measure of receptive language ( $r = +.42$ ,  $p < .05$ ) as well as the backwards WISC digit span ( $r = +.43$ ,  $p < .05$ ). Thus, Simon learning in the auditory-only condition was positively

correlated with outcome measures that involve more complex cognitive processing activities that reflect “executive functions” and “controlled attention” (Engle, Kane & Tuholski, 1999). Performance on the TACL-R reflects the ability to comprehend subtle morphological and syntactic distinctions. Similarly, performance on the backward digit span task assesses the ability to explicitly manipulate the serial order of items actively maintained in working memory. Both of these measures, along with measures of open-set word recognition on the LNT, assess the storage and maintenance of verbal items in short-term memory and the subsequent processing operations of working memory and controlled attention.

In the current study, we assessed the relations between measures of sequence learning in children with cochlear implants and several speech and language outcome measures with a different group of deaf children who use cochlear implants. The initial studies on sequence learning by Cleary and Pisoni (2001) were carried out with 8- and 9-year old deaf children as part of the large scale CID project directed by Ann Geers (see Geers et al., 2003). The present study used deaf children from the IU School of Medicine. These children spanned a wider age range than the children used in the earlier study. We also examined two new measures of sequence learning.

## Methods

### Participants

Participants in the present study were 21 children who experienced a profound hearing loss before the age of 36 months and who received a cochlear implant before 9 years of age. Children were tested once every six months to a year for five years on a battery of clinical tests that are used to assess speech and language benefit after implantation. A summary of the demographics is provided in Table 1.

Communication Mode	Age at Implantation	Age of Onset of Deafness	Pure Tone Average (unaided)	Pure Tone Average (cochlear implant)
17 OC	39.42 (14.1)	6.19 (9.6)	111.9 (5.9)	35.9 (6.2)
9 TC				

**Table 1.** Demographic characteristics of the participants. Standard deviations are shown in parenthesis.

### Procedures

To measure sequence learning in this group of children, we used the same Simon memory game methodology that was employed in our earlier studies (Cleary & Pisoni, 2001; Cleary, Pisoni & Geers, 2001; Cleary, Pisoni & Kirk, 2002; Pisoni & Cleary, 2004). This methodology used a customized response box to investigate the effects of different presentation formats on immediate recall. Participants were presented with sequences of color names or colored lights under two conditions, visual-alone (V) and auditory+visual (AV). The child was asked to reproduce the stimulus pattern by pressing a sequence of colored response panels on the four-alternative response box using a manual response. The dependent measure of performance was the child’s immediate memory span, defined as the longest length sequence he/she could correctly reproduce.

In the sequence learning condition, the stimuli on the Simon were arranged in temporal patterns that systematically increased in length using an adaptive staircase procedure as the subject successfully progressed through a block of trials. If the participant reproduced a pattern correctly, the same pattern was

repeated again, but was increased in length by one item. If the child made an error, the same pattern was repeated again, but the sequence was reduced in length by one item. The Simon learning procedure spans in this study were obtained from all children under two presentation conditions: auditory+visual (AV) and visual-alone (V). All the children were tested at the Indiana University School of Medicine by a speech language pathologist or audiologist who was trained in testing deaf children with cochlear implants.

### **Dependent Measures**

Two measures of learning were examined in this study. The first measure, Simon redundancy gain, was computed by subtracting the V weighted span from the AV weighted span on the Simon learning task in the first interval the child was tested. The difference in performance between the AV and V conditions can be thought of as a measure of how much gain the child received from the addition of redundant auditory information to the visual pattern. Because of the way we selected children for this analysis, length of cochlear implant use and chronological age were confounded. However, to control for these difference, length of cochlear implant use and chronological age were treated as covariates in the statistical analyses.

A second measure of learning, Simon learning improvement, was computed by subtracting the Simon learning weighted span from the first interval the child was tested (for both V and AV conditions) from the span obtained in the last interval the child was tested, and dividing by the total number of years between the scores. This measure was designed to assess changes in sequence learning over time with a cochlear implant, while eliminating any baseline differences. Unlike the first measure, which was used to assess the contribution of redundant auditory information on visual sequence learning, the second measure allowed us to examine the changes in memory and learning over time after a period of cochlear implant use.

### **Outcome Measures**

To examine the relationship between these two measures of learning and the children's speech and language outcomes with their implant, we first performed a series of simple bivariate correlations with several traditional speech and language outcome measures. We looked at open-set word recognition (PBK words), sentence comprehension (Common Phrases A, V and AV), vocabulary knowledge (PPVT), language development (RDLS and CELF), and speech intelligibility (BIT). In each of these analyses, the outcome measures were from the first interval the child was tested using the Simon learning procedure.

## **Results**

### **Simon Redundancy Gain**

Pearson correlations were used to assess the relations between redundancy gain and the clinical outcome measures. A summary of these correlations is provided in Table 2. A moderate correlation was found with the Common Phrases auditory alone scores ( $r = +0.62$ ,  $p = .02$ ). After controlling for age and length of use using partial correlations, the relationship between auditory redundancy gain and auditory comprehension as measured by the Common Phrases A-alone test was still reliable, indicating that this finding is not attributable to the age or device use of the children.

Clinical Outcome Measures	Correlations with Simon Learning Redundancy Gain Scores
CPA (n=13)	0.62 ( $p=0.02$ )
CPAV (n=12)	0.56 ( $p=0.06$ )
CPV (n=16)	0.17 (ns)
PBK words (n=19)	0.23 (ns)
PBK phonemes (n=19)	0.33 (ns)
PPVT AE (n=20)	-0.40 (ns)

**Table 2.** Correlations between Simon redundancy gain scores and outcome measures.

### Simon Learning Improvement

Correlational analyses also revealed that the learning improvement measure was related to the vocabulary knowledge of the child at the time of first testing using the Simon memory game, although the relationship was in different directions for the AV and V conditions (see Table 3). The amount of auditory+visual improvement in learning over time was positively related to the child's initial vocabulary knowledge ( $r = +0.55, p = 0.04$ ), while the amount of longitudinal visual-only gain was negatively related ( $r = -0.64, p = 0.01$ ). The learning effect also remained reliable after performing partial correlations controlling for age and device use. This pattern suggests that greater vocabulary knowledge is associated with better sequence learning skills. Higher PPVT vocabulary scores were associated with increases in AV span and decreases in V span scores.

Clinical Outcome Measures	Correlations with Simon Learning Improvement Measure (AV)	Correlations with Simon Learning Improvement Measure (V)
CPA (n=11)	0.09 (ns)	-0.42 (ns)
CPAV (n=10)	-0.02 (ns)	-0.09 (ns)
CPV (n=14)	-0.23 (ns)	0.16 (ns)
PBK words (n=14)	0.07 (ns)	-0.16 (ns)
PBK phonemes (n=14)	0.17	-0.25 (ns)
PPVT AE (n=15)	0.55 ( $p=0.04$ )	-0.64 ( $p=0.01$ )

**Table 3.** Correlations between Simon learning improvement scores and outcome measures.

### Intercorrelations Between Measures of Learning

These two measures of learning were also strongly correlated with each other (see Table 4). The correlations remained strong even after partial correlations were performed controlling for age and device use. These two different measures of learning may share a common source of variance related to learning temporal sequences.

	Simon Learning Redundancy Gain (N=16)
Simon Learning Improvement Measure (AV)	+0.62 ( $p=.01$ )
Simon Learning Improvement Measure (V)	-0.63 ( $p=.01$ )

**Table 4.** Intercorrelations between the two measures of Simon learning.

## Discussion

The results of the present study reveal that simple measures of sequence learning in deaf children with cochlear implants are associated with changes in several traditional audiological outcome measures of speech and language. Our findings are of interest both clinically and theoretically because they suggest that the individual differences in outcome of children who receive cochlear implants may be due to fundamental learning processes that affect the encoding and retention of information in both short-term and long-term memory. Large improvements in immediate reproductive memory span for sequences of colored lights were obtained by simple repetition of a familiar sequence. Differences in the susceptibility to repetition effects such as these are associated with several outcome measures of speech and language. These initial findings on learning and memory suggest that differences in the development and operation of basic learning mechanisms in this clinical population may contribute an additional unique source of variance to the overall variation observed in a wide range of outcome measures following cochlear implantation. Additional studies of learning and memory in deaf children with cochlear implants are clearly warranted by the finding of this study and the earlier results on sequence learning first reported by Cleary and Pisoni (2001).

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