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**Memory Span and Sequence Learning Using Multimodal Stimulus  
Patterns: Preliminary Findings in Normal-Hearing Adults<sup>1</sup>**

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## Memory Span and Sequence Learning Using Multimodal Stimulus Patterns: Preliminary Findings in Normal-Hearing Adults

**Abstract.** The Simon memory game has been developed in our laboratory as a means of measuring memory span without requiring an explicit verbal response. This report presents a preliminary analysis of memory span data obtained from normal-hearing adults over two sessions using this new methodology. Traditional memory span measures were obtained from two standard tasks, digit span and word span, as well as six versions of the memory game. The memory game required subjects to reproduce sequences of colors by pressing response buttons on a four-alternative response box. In addition to a “memory span” task, in which color sequences of increasing length were generated randomly, a “sequence learning” task was administered using the memory game, in which identical sequences of increasing length were repeated, plus or minus one item, in order to measure longer-term information processing abilities. Color stimuli in each memory game task were presented either visually (a visual-spatial sequence of colored lights), auditorily (a sequence of spoken color words), or audiovisually (a visual-spatial sequence of colored lights and the same sequence of spoken color words presented simultaneously). Results showed that subjects reproduced far longer sequences in the sequence learning task compared to the memory span task, and subjects reproduced longer sequences in the audiovisual condition than in the visual or auditory conditions. Overall, performance was best in conditions where subjects could benefit from sequence repetition and multimodal information redundancy. The results of this study serve as normative, benchmark data for future studies using the memory game with several clinical populations.

Working memory, the system within the human cognitive system responsible for the temporary storage and processing of information, is useful as an explanatory device for both the limitations of high-level cognitive processes and individual differences in information processing abilities (Baddeley, 1992; Richardson, et al., 1996; Engle, Kane, & Tuholski, 1999). The working memory model has three major components: a visual-spatial short-term memory; a verbal short-term memory; and a central executive, an attentional system that controls the flow of information to and from the other components (Baddeley & Hitch, 1974; Kail & Hall, 2001). The verbal short-term memory – often called the phonological or articulatory loop – can be further divided into two subcomponents: a phonological store for verbal material, and mechanisms that enable rehearsal (Baddeley, 1986). The phonological loop has been an influential component of the working memory model, integrating a wide range of data and generating a large body of research (Gupta, 1996; see Baddeley, 1998, for a review of research on the phonological loop).

Verbal short-term memory capabilities are distinguished by two prominent features: a rapid rate of forgetting and a limited capacity. A measure of an individual’s short-term memory span is thought to be indicative of that individual’s overall information processing capabilities (Miller, 1956). Individual differences in memory span abilities are thus important in the processes of acquiring new knowledge and retrieving stored information from long-term memory (Engle, 1996). Recently, the case has been made that individual differences in short-term memory capabilities are fundamental to individual differences in language-related abilities (Gupta & MacWhinney, 1997; Gupta & Dell, 1999; Gupta, 1996). More specifically, researchers have

hypothesized that the short-term, phonological storage component within the phonological loop is the fundamental mechanism of language learning (Baddeley, Gathercole, & Papagno, 1998).

Traditional methods of measuring verbal short-term memory capacity almost always involve verbal reproduction of presented lists of items. Performance deficits on such traditional memory span measures shown by hearing-impaired individuals, or by other clinical populations who have deficits in speech production, might therefore be the result of problems associated with the hearing impairment itself, rather than a memory deficit. Thus, the verbal response requirement in traditional memory span studies is a potential confound when attempting to obtain short-term memory data from various clinical populations. Recently, the study of individual differences observed in hearing-impaired children with cochlear implants has become a topic of great interest (Pisoni, Cleary, Geers, & Tobey, 2000). It is not clear what the basis is for individual differences in performance among deaf children with cochlear implants on a variety of outcome measures that assess speech perception, language comprehension, speech intelligibility, and reading (Pisoni & Geers, 2000). However, differences in fundamental information processing capabilities may be the foundational factors responsible for individual differences in language processing in children with cochlear implants, as well as in other clinical populations (Pisoni, 2000). It would be advantageous, therefore, to have a means of obtaining memory span measures from clinical populations, especially the hearing impaired, that does not require an explicit verbal response.

The “Simon memory game” has been developed in our laboratory as a means of collecting memory span data without requiring verbal output (Cleary, Pisoni, & Geers, in press; Carlson, Cleary, & Pisoni, 1998). The memory game also allows us to use visual, auditory, and audiovisual stimulus presentation formats. In their first study with children, Cleary, Pisoni, and Geers (in press) found that in all three stimulus presentation formats, deaf children with cochlear implants had shorter memory spans than normal-hearing children. Normal-hearing children were also better than the cochlear implant children at utilizing “multimodal information redundancy” – the added benefit of receiving simultaneous auditory and visual information about the sequence. Cleary, Pisoni, and Geers (in press) concluded that performance differences on the memory game between the normal-hearing children and the cochlear implant children suggests differences in encoding or rehearsal strategies and “atypical” working memory development in deaf children with cochlear implants.

Until now, no study has looked specifically at performance by normal-hearing adults on both the “memory span” and “sequence learning” versions of the memory game. In addition, there are no data on the test-retest reliability of the memory game. Thus, the purpose of this study was to collect normative, benchmark memory span and sequence learning data from normal-hearing, native English-speaking adults using the Simon methodology. The present study involved testing adults over multiple sessions to obtain test-retest reliability measures. The data obtained in this study will be useful in conjunction with data already collected from normal hearing children, pediatric cochlear implant users, deaf children and adults, and other clinical populations (e.g., Sommers & Sawyer, 2001).

## **Method**

### **Subjects**

Forty-eight Indiana University undergraduates participated in Session One. Forty-three of the original forty-eight returned for a second session one week following their first session. Subjects ranged in age from 18 to 24 years, with the mean age of 20.5 years. Subjects were paid \$5 for participation in Session One and \$10 for participation in Session Two; each session lasted

approximately 45 minutes. All participants were native speakers of English with no speech or hearing disorders and normal or corrected-to-normal vision at the time of testing.

## Materials

For the digit span task, tokens of the 10 spoken digits (0 to 9) were obtained from the Texas Instruments 46-Word (TI46) Speaker-Dependent Isolated Word Corpus (Texas Instruments, 1991). For the word span task, tokens of 66 spoken monosyllabic words were drawn from a prerecorded digital database (see Torretta, 1995, for a detailed description). All words were classified as “easy” words: these words are higher in frequency relative to their neighbors and come from a sparsely populated lexical neighborhood (Luce & Pisoni, 1998). Stimuli used in the digit span and word span tasks were presented over high-quality headphones at approximately 75 dB SPL. Subjects made their responses by writing on prepared answer booklets at the end of each trial. After recording their responses, subjects initiated the next trial by pressing the “Enter” key on the keyboard. See Goh and Pisoni (1998) for a more detailed description of the digit span and word span tasks used in the present study.

For the Simon memory game, auditory tokens of the four color words (“red”, “yellow”, “blue”, and “green”) were recorded by a single male speaker of American English. The memory game response box was modeled after the commercial product “Simon” by Milton Bradley. It consisted of four colored, back-lit response buttons. Subjects reproduced visual, auditory, or audiovisual sequences of colors by pressing the response buttons on the memory response box. See Cleary, Pisoni, and Geers (in press) for a more detailed description of the Simon memory game.

## Procedure

Subjects were tested individually or in groups of three or fewer. All subjects completed the digit span task, then word span task, followed by six versions of the memory game.

In the digit span task, subjects were presented with a list of digits (0-9) over headphones. Once the entire list had been presented, subjects wrote down as many digits from the list as they could remember, in the order in which they were originally presented. The lists of digits began at length 4 and increased to length 10, with two lists presented at each list length for a total of 14 trials (Goh & Pisoni, 1998).

In the word span task, subjects were presented with a list of monosyllabic words, again over headphones. Once the entire list had been presented, subjects wrote down as many words from the list as they could remember, in the order in which they were originally presented. The lists of words began at length 3 and increased to length 8, with two lists presented at each list length for a total of 12 trials. The stimuli in the word span task were non-repeating and without replacement.

The memory game consisted of two different tasks: a “memory span” task and a “sequence learning” task. In the memory span task, subjects were given a sequence of colors and were asked to reproduce the sequence by pressing the response buttons. The sequences of colors were randomly generated, with the stipulation that no item was ever repeated consecutively in a given list. Sequences began at length 1, and subjects were presented with a total of 20 lists. An “adaptive testing procedure” was used to generate the stimulus sequences (Levitt, 1970): if a subject correctly reproduced two consecutive sequences at the same sequence length, the next sequence was increased in length by one item. If a subject made an error in reproducing a

sequence, the next sequence was decreased in length by one item.

In the sequence-learning task, subjects were given a sequence of colors and were asked to reproduce the sequence by pressing the response buttons. In this task, the sequences of colors were repeated. That is, subsequent sequences were exactly the same as the immediate preceding sequences, plus or minus one item. Sequences began at length 3, and subjects were presented with a total of 12 lists. A similar adaptive testing procedure was used in the sequence learning task: if a subject correctly reproduced a given sequence, then the next sequence presented was the identical sequence, increased in length by one item. If a subject made an error in reproducing a sequence, the next sequence was decreased in length by one item (see Cleary & Pisoni, 2001).

For each memory game task, three stimulus presentation formats were used. In the visual (V) condition, subjects saw a visual-spatial sequence of colored lights and heard nothing. In the auditory (A) condition, subjects heard a sequence of spoken color words and saw nothing. In the audiovisual (AV) condition, subjects saw a visual-spatial sequence of colored lights and also heard the same sequence of spoken color words simultaneously. The audiovisual presentation condition involved “multimodal information redundancy” (Cleary, Pisoni, & Geers, in press): redundant information about the sequence was presented to the subject simultaneously through both the auditory and visual modalities.

Within each task, the stimulus presentation conditions were counterbalanced, and the tasks themselves were counterbalanced in order of administration. There were 12 different orders of the memory game, and 4 subjects were assigned to each order, making a total of 48 subjects in Session One. Forty-three of the original forty-eight subjects returned for Session Two, 7-10 days following Session One. Subjects who returned for a second session completed all tasks in the same order in which they had completed them in Session One.

## Results

### Scoring

Two methods were used to score the digit span and word span tasks. The Strict Span score is the longest list length where both trials are perfectly recalled, plus 1/2 point for every subsequent trial also perfectly recalled (Daneman & Carpenter, 1980). The Absolute Span score is the sum of the total number of items in each perfectly recalled trial (LaPointe & Engle, 1990). The Strict Span is an item-based scoring method, while the Absolute Span is a list-based scoring method. Both scoring methods showed the same pattern of results.

Data from the Simon memory game were scored four different ways. The “One-time Score” is the longest sequence length correctly reproduced at least one time (on at least one trial). The “Half-time Score” is the longest sequence length correctly reproduced at least half of the time (on half of all trials). The “All-time Score” is the longest sequence length correctly reproduced one hundred percent of the time (on all trials). Finally, a weighted score was calculated, which is the sum of the proportion of correctly reproduced trials at each sequence length (Cleary, Pisoni, & Geers, in press). All four scoring methods showed the same pattern of results. A summary of all four scoring methods can be found in the Appendix.

### Digit Span and Word Span

Data from the digit span and word span tasks for both sessions are shown in Table 1. According to the Strict Span scoring method, subjects averaged a digit span of roughly 7 items and a word span of roughly 5 items. The Absolute scoring method reflects this difference between

the digit span and word span tasks. The results for Session Two were consistent with those for Session One: subjects again averaged a digit span of approximately 7 items and a word span of approximately 5 items. These findings are consistent with earlier findings using similar methods of obtaining digit span and word span scores (Goh & Pisoni, 1998).

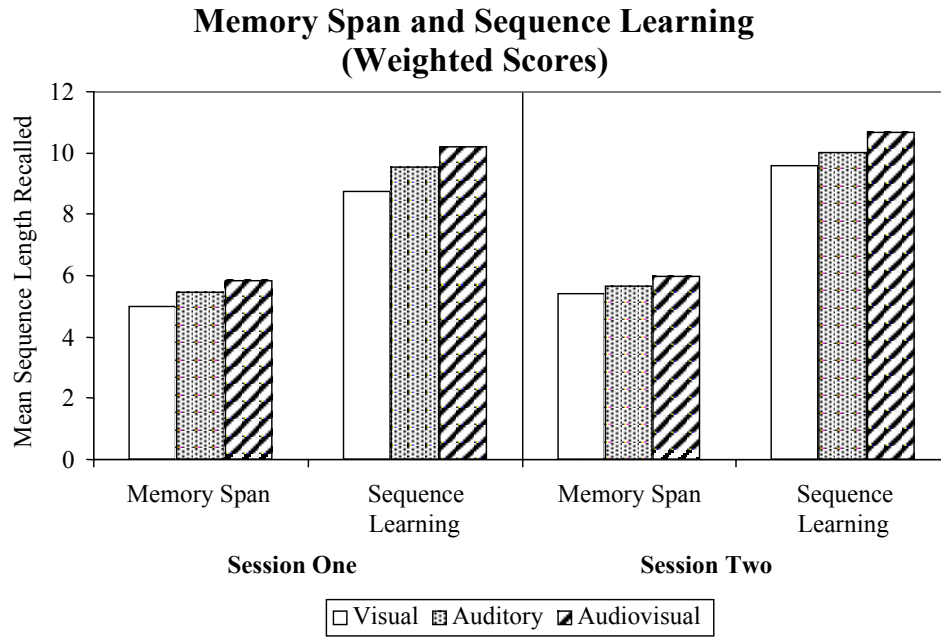
	Mean	SD	Min	Max
Session One (n = 48)				
Strict Score				
Digit Span	7.05	1.09	4.5	10
Word Span	5.31	0.70	3.5	7
Absolute Score				
Digit Span	46.85	16.49	13	98
Word Span	28.67	8.27	10	51
Session Two (n = 43)				
Strict Score				
Digit Span	7.30	1.06	4.5	10
Word Span	5.30	0.76	4	7
Absolute Score				
Digit Span	50.98	16.90	13	98
Word Span	28.77	9.10	14	51

**Table 1.** Digit span and word span scores: both sessions.

### Simon Memory Game

Figure 1 shows the weighted scores in the three conditions of the Simon memory game for each session, averaged across subjects. The left panel of Figure 1 displays scores from Session One, while the right panel of Figure 1 displays scores from Session Two. For each session, memory span scores are plotted on the left side, and sequence learning scores are plotted on the right side. The open bar represents scores in the visual only (V) condition; the dotted bar represents scores in the auditory only (A) condition; and the striped bar represents scores in the audiovisual (AV) condition. The means plotted in Figure 1 are also displayed in Table 2.

In both sessions, irrespective of scoring method, the results showed an improvement in performance in the sequence-learning task over the memory span task. For both the memory span and the sequence learning tasks, performance was best in the audiovisual condition, while performance in the auditory only condition was better than performance in the visual only condition. Additionally, the average scores increased slightly from Session One to Session Two.



**Figure 1.** Mean sequence length recalled, Sessions One and Two. Weighted scores.

	Memory Span			Sequence Learning		
	Mean	SD	Range	Mean	SD	Range
Session One						
Visual	5.0	0.89	(3.2, 7.3)	8.7	2.69	(3.9, 14)
Auditory	5.5	0.94	(2.3, 7.4)	9.6	2.88	(4.8, 14)
Audiovisual	5.8	0.78	(4.3, 8.2)	10.2	2.45	(5.6, 14)
Session Two						
Visual	5.4	0.97	(3.7, 8.5)	9.6	2.71	(5.2, 14)
Auditory	5.7	1.00	(4.1, 8.3)	10.0	2.93	(5.0, 14)
Audiovisual	6.0	0.95	(4.3, 8.2)	10.7	2.54	(6.1, 14)

**Table 2.** Memory Span and Sequence Learning tasks, Sessions One and Two. Weighted scores.

A 2 (Task) x 3 (Stimulus Presentation Format) x 2 (Session) repeated measures analysis of variance (ANOVA) on the weighted scores revealed main effects of Task,  $F(1, 42) = 232.348$ ,  $p < .001$ , of Stimulus Presentation Format,  $F(2, 84) = 15.426$ ,  $p < .001$ , and of Session,  $F(1, 42) = 5.896$ ,  $p < .05$ . No interactions were found among any of these variables.

Table 3 illustrates the main effect of Task in terms of “sequence repetition gain.” The difference between a subject’s sequence learning score and his or her memory span score can be thought of as a gain in performance due to repetition of the identical sequence. The sequence repetition effect was robust across all three stimulus presentation formats. Performance was increased by approximately four items when the sequence of colors was repeated.

	Session One			Session Two		
	Mean	Proportion	Percent	Mean	Proportion	Percent
Weighted Scores						
Visual	3.7	45/48	94%	4.2	41/43	95%
Auditory	4.1	47/48	98%	4.4	40/43	93%
Audiovisual	4.4	47/48	98%	4.7	43/43	100%

**Table 3.** Sequence repetition gain.

A post hoc analysis on the main effect of Stimulus Presentation Format, collapsed across Task and across Session, revealed that the difference between the audiovisual and visual only conditions was responsible for this main effect,  $t(362) = 3.303$ ,  $p < .001$ . Table 4 shows this main effect in terms of a “multimodal redundancy gain.” The difference between a subject’s score in the audiovisual condition and his or her score in the visual only condition can be thought of as the gain in performance due to redundant auditory information. Multimodal redundancy gain was a robust effect, appearing in a high percentage of all trials in both the memory span and sequence learning tasks.

	Session One			Session Two		
	Mean	Proportion	Percent	Mean	Proportion	Percent
Weighted Scores						
Memory Span	0.84	42/48	88%	0.58	37/43	86%
Sequence Learning	1.46	35/48	73%	1.07	35/43	81%

**Table 4.** Multimodal redundancy gain.

A second post hoc analysis on the “Stimulus Presentation Format” effect, this time with the memory span and sequence learning tasks analyzed separately, revealed further differences in Stimulus Presentation Format within the memory span task, but not within the sequence-learning task. Table 5 summarizes the findings of this post hoc analysis. Though no Task x Stimulus Presentation Format interaction was found, within the memory span task a significant difference was found between the audiovisual and auditory only conditions,  $t(180) = 2.591, p < .01$ , suggesting that redundant visual information also resulted in a multimodal redundancy gain. Furthermore, a significant difference was found between the auditory and visual conditions,  $t(180) = 2.568, p < .01$ . Thus, auditory information led to a longer memory span than visual information. This is a new finding using the Simon memory game.

Weighted Scores		
	Memory Span	Sequence Learning
Auditory x Visual	$t(180) = 2.568, p < .01$	$t(180) = 1.535, p = .126$
Audiovisual x Auditory	$t(180) = 2.591, p < .01$	$t(180) = 1.595, p = .112$
Audiovisual x Visual	$t(180) = 5.353, p < .001$	$t(180) = 3.307, p < .001$

**Table 5.** Post hoc analysis with the memory span and sequence learning tasks analyzed separately.

### Test-Retest Reliability

Test-retest reliability for the digit span, word span, Simon memory span, and Simon sequence learning tasks was also assessed in this study. Table 6 summarizes the test-retest reliability of the digit span and word span tasks. Both the list-based and item-based scoring methods show high correlations between scores in Session One and Session Two for the digit span task and the word span task.

Test-Retest Reliability		
	Digit Span	Word Span
Strict Score	$r = .73^{**}$	$r = .60^{**}$
Absolute Score	$r = .73^{**}$	$r = .59^{**}$

\*\*  $p < .01$

**Table 6.** Test-retest reliability: digit span and word span.

The test-retest reliability of the digit span and word span tasks is useful as a benchmark against which the test-retest reliability scores of the Simon memory game might be compared. The reliability coefficients of each condition of the Simon memory game are shown in Table 7. Overall, moderate positive correlations were obtained in all conditions of the Simon memory game. Notably, the highest correlation was observed in the condition where both sequence repetition and multimodal information redundancy was available ( $r = .69, p < .01$ ).

Test-Retest Reliability: Weighted Scores		
	Memory Span	Sequence Learning
Visual	$r = .40^{**}$	$r = .31^*$
Auditory	$r = .46^{**}$	$r = .56^{**}$
Audiovisual	$r = .44^{**}$	$r = .69^{**}$

\*\*  $p < .01$   
\*  $p < .05$

**Table 7.** Test-retest reliability: memory span and sequence learning tasks.

## Discussion

Three main effects were found in the present study: Task (memory span vs. sequence learning), Stimulus Presentation Format (Visual vs. Auditory vs. Audiovisual), and Testing Session (One vs. Two). No interactions were found among the three main effects. Subjects were able to reproduce far longer sequences in the sequence-learning task compared with the memory span task. On average, repeating the pattern allowed subjects to reproduce sequences approximately four items longer than patterns presented in the memory span task. This robust effect occurred in all three stimulus presentation conditions. Subjects also reproduced longer sequences in conditions where multimodal information redundancy was available. In particular, redundant auditory information, in addition to the visual-spatial sequence of colors, led to the reproduction of longer sequences in both the memory span and sequence learning tasks. Although no Task x Stimulus Format interaction was evident, the memory span task was more sensitive than the sequence-learning task to the differences between auditory and visual stimulus presentation formats.

Moderate positive test-retest reliability coefficients were found across all stimulus presentation conditions in both the memory span and sequence learning tasks. Equivalent forms of the memory game were administered one week apart, and comparable results were obtained in both sessions. Main effects for Task and Stimulus Presentation Format were found in both Session One and Session Two. The difference in mean scores between the two sessions is probably due to familiarity or practice effects, which could certainly be controlled for in future studies by increasing the duration between testing sessions or allowing a practice session before the testing session.

The present study demonstrates the contribution of sequence repetition and multimodal information redundancy to human memory in a group of young, healthy adults. In normal-hearing adults, using the Simon memory game, sequence repetition and multimodal information redundancy allow subjects to overcome the basic capacity limitations of short-term memory. In certain clinical populations, however, this may not always be the case (Cleary, Pisoni, & Geers, in press; Pisoni, Cleary, Geers, & Tobey, 2000). Individual differences in working memory suggest possible differences in the basic underlying information processing abilities of some clinical populations. It is these differences in central cognitive abilities that appear to be driving individual differences in the ability to acquire and process spoken language (Gupta & MacWhinney, 1997; Pisoni, 2000). The present study of the information processing capabilities

of normal hearing adults, specifically with respect to their ability to use sequence repetition and multimodal information redundancy to overcome short-term memory capacity limitations, provides benchmark data against which other studies of information processing in clinical populations can be compared. Data from our laboratory have already been reported on pediatric cochlear implant users (Cleary, Pisoni, & Geers, in press; Pisoni et al., 2000; Cleary et al., 2000). Other studies of post-lingually deafened adults are underway.

In future studies using the Simon memory game, we intend to investigate the effects of presentation rate on memory span and sequence learning when multimodal information redundancy is present. The rate at which stimuli are recognized and processed has been shown to reveal important sources of individual differences in memory span (Dempster, 1981). Increasing the rate of presentation in the memory game should increase the demands on short-term memory capacity, forcing subjects to rely more heavily on highly automatic processes and thus on redundant multimodal information. We are also currently developing a methodology in our laboratory for presenting “spatially neutral” sequences of colors, in order to block the spatial coding of the visual sequence and force subjects to rely exclusively on verbal coding. Finally, we intend to use the memory game response box format to present multimodal stimuli in implicit learning paradigms, specifically using serial reaction time and artificial grammar tasks (e.g., Nissen & Bullemer, 1987; Reber, 1993).

## References

- Baddeley, A.D. (1986). *Working memory*. New York: Oxford University Press.
- Baddeley, A.D. (1992). Working memory. *Science*, 255, 556-559.
- Baddeley, A.D. (1998). *Human memory: Theory and practice*. Boston: Allyn & Bacon.
- Baddeley, A.D., Gathercole, S.E., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review*, 105, 158-173.
- Baddeley, A.D., & Hitch, G. (1974). Working memory. In G.H. Bower (Ed.), *Recent advances in the psychology of learning and motivation* (Vol. VII, pp. 47-89). New York: Academic Press.
- Carlson, J.L., Cleary, M., & Pisoni, D.B. (1998). Performance of normal-hearing children on a new working memory span task. In *Research on Spoken Language Processing Progress Report No. 22* (pp. 251-275). Bloomington, IN: Speech Research Laboratory, Indiana University.
- Cleary, M., & Pisoni, D.B. (2001). Sequence learning as a function of presentation modality in children with cochlear implants. Poster presented at *CID New Frontiers Conference*. St. Louis, MO.
- Cleary, M., Pisoni, D.B., & Geers, A.E. (in press). Some measures of verbal and spatial working memory in eight- and nine-year-old hearing-impaired children with cochlear implants. *Ear & Hearing*.
- Cleary, M., Pisoni, D.B., Kirk, K.I., Geers, A.E., & Tobey, E. A. (2000). Working memory and language development in children with cochlear implants. Poster presented at *CI2000: The 6<sup>th</sup> International Cochlear Implant Conference*. Miami, FL.
- Daneman, M., & Carpenter, P.A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, 19, 450-466.
- Dempster, F.N. (1981). Memory span: Sources of individual and developmental differences. *Psychological Bulletin*, 89, 63-100.
- Engle, R.W. (1996). Working memory and retrieval: An inhibition-resource approach. In J.T.E. Richardson (Ed.), *Working memory and human cognition* (pp. 89-119). Oxford: Oxford University Press.

- Engle, R.W., Kane, M.J., & Tuholski, S.W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102-134). Cambridge, UK: Cambridge Univ. Press.
- Goh, W.D., & Pisoni, D.B. (1998). Effects of lexical neighborhoods on immediate memory span for spoken words: A first report. In *Research on Spoken Language Processing Progress Report No. 22* (pp. 195-213). Bloomington, IN: Speech Research Laboratory, Indiana University.
- Gupta, P. (1996). Immediate serial memory and language processing: Beyond the articulatory loop. *Technical Report No. CS-96-02*. Urbana: Beckman Institute, Cognitive Science Group.
- Gupta, P., & MacWhinney, B. (1997). Vocabulary acquisition and verbal short-term memory: Computational and neural bases. *Brain and Language*, *59*, 267-333.
- Gupta, P., & Dell, G.S. (1999). The emergence of language from serial order and procedural memory. In B. MacWhinney (Ed.), *The emergence of language* (pp. 447-481). Mahwah, NJ: Lawrence Erlbaum.
- Kail, R., & Hall, L.K. (2001). Distinguishing short-term memory from working memory. *Memory & Cognition*, *29*, 1-9.
- LaPointe, L.B., & Engle, R.W. (1990). Simple and complex word spans as measures of working memory capacity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*, 1118-1133.
- Levitt, H. (1970). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America*, *49*, 467-477.
- Luce, P.A., & Pisoni, D.B. (1998). Recognizing spoken words: The neighborhood activation model. *Ear & Hearing*, *19*, 1-36.
- Miller, G.A. (1956). The magical number seven plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*, 81-97.
- Nissen, M. J. & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, *19*, 1-32.
- Pisoni, D.B. (2000). Cognitive factors and cochlear implants: Some thoughts on perception, learning, and memory in speech perception. *Ear & Hearing*, *21*, 70-78.
- Pisoni, D.B., Cleary, M., Geers, A.E., & Tobey, E.A. (2000). Individual differences in effectiveness of cochlear implants in children who are prelingually deaf: New process measures of performance. *The Volta Review*, *101*, 111-164.
- Pisoni, D.B., & Geers, A.E. (2000). Working memory in deaf children with cochlear implants: Correlations between digit span and measures of spoken language. *Annals of Otology, Rhinology and Laryngology Supplement*, *185*, 92-93.
- Reber, A.S. (1993). *Implicit learning and tacit knowledge: An essay on the cognitive unconscious*. Oxford: Oxford University Press.
- Richardson, J.T.E., Engle, R.W., Hasher, L., Logie, R.H., Stoltzfus, E.R., & Zacks, R.T. (1996). *Working memory and human cognition*. Oxford: Oxford University Press.
- Sommers, M.S., & Sawyer, D. (2001). Predictors of visual enhancement and lipreading in younger and older adults. Poster presented at the meeting of the Acoustical Society of America. Chicago, IL.
- Texas Instruments. (1991). TI 46-word speaker-dependent isolated word corpus (CD-ROM). Gaithersburg: NIST.
- Torretta, G.M. (1995). The "easy-hard" word multi-talker speech database: An initial report. In *Research on Spoken Language Processing Progress Report No. 20*, (pp. 321-334). Bloomington, IN: Speech Research Laboratory, Indiana University.

**Appendix**  
**Simon memory game results scored by four methods**

**Session One (N = 48)**

	Memory Span			Sequence Learning		
	Mean	SD	Range	Mean	SD	Range
<b>One-time Scores</b>						
Visual	5.6	0.82	(4, 7)	9.3	2.46	(5, 14)
Auditory	6.0	0.91	(3, 8)	10.1	2.65	(5, 14)
Audiovisual	6.4	0.79	(5, 9)	10.5	2.28	(6, 14)
<b>Half-time Scores</b>						
Visual	5.4	0.89	(4, 7)	9.1	2.58	(4, 14)
Auditory	5.8	0.97	(3, 8)	10.0	2.76	(5, 14)
Audiovisual	6.2	0.92	(5, 9)	10.5	2.34	(6, 14)
<b>All-time Scores</b>						
Visual	4.0	1.13	(1, 6)	8.5	3.09	(3, 14)
Auditory	4.7	1.22	(3, 7)	9.4	3.21	(4, 14)
Audiovisual	4.8	1.06	(2, 7)	10.1	2.63	(5, 14)
<b>Weighted Scores</b>						
Visual	5.0	0.89	(3.2, 7.3)	8.7	2.69	(3.9, 14)
Auditory	5.5	0.94	(2.3, 7.4)	9.6	2.88	(4.8, 14)
Audiovisual	5.8	0.78	(4.3, 8.2)	10.2	2.45	(5.6, 14)

**Session Two (N = 43)**

	Memory Span			Sequence Learning		
	Mean	SD	Range	Mean	SD	Range
<b>One-time Scores</b>						
Visual	6.0	1.03	(4, 9)	10.2	2.43	(6, 14)
Auditory	6.2	1.00	(5, 9)	10.5	2.64	(6, 14)
Audiovisual	6.6	0.98	(5, 9)	11.1	2.23	(7, 14)
<b>Half-time Scores</b>						
Visual	5.8	1.07	(4, 9)	10.1	2.48	(5, 14)
Auditory	6.1	1.12	(4, 9)	10.4	2.79	(5, 14)
Audiovisual	6.5	1.06	(5, 9)	11.1	2.28	(6, 14)
<b>All-time Scores</b>						
Visual	4.6	1.37	(2, 6)	9.4	3.13	(4, 14)
Auditory	4.8	1.23	(3, 7)	9.8	3.21	(4, 14)
Audiovisual	5.2	1.19	(3, 7)	10.7	2.66	(5, 14)
<b>Weighted Scores</b>						
Visual	5.4	0.97	(3.7, 8.5)	9.6	2.71	(5.2, 14)
Auditory	5.7	1.00	(4.1, 8.3)	10.0	2.93	(5.0, 14)
Audiovisual	6.0	0.95	(4.3, 8.2)	10.7	2.54	(6.1, 14)