

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

**Effects of a Cochlear Implant Simulation on Immediate Memory Span  
in Normal-Hearing Adults<sup>1</sup>**

**Rose A. Burkholder, David B. Pisoni, and Mario A. Svirsky<sup>2</sup>**

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

---

<sup>1</sup> This work was supported by NIH-NIDCD R01 Research Grants DC00111 and DC03937 and Training Grant T32 DC00012 as well as the American Hearing Research Foundation. We are grateful for the time and support from past and present Speech Research Laboratory members Brianna Conrey, Caitlin Dillon, Kuai Hinojosa, and Jeff Reynolds who participated in the piloting of this experiment. We also thank Shivank Sihna and Luis Hernandez for their technical assistance and expertise on this project.

<sup>2</sup> Indiana University School of Medicine and Purdue University Departments of Biomedical and Electrical Engineering.

## Effects of a Cochlear Implant Simulation on Immediate Memory Span in Normal-Hearing Adults

**Abstract.** Measures of immediate memory span were obtained from 25 normal-hearing adults who listened to an 8-channel, frequency shifted acoustic simulation of a cochlear implant. A short period of digit identification training was conducted before forward and backward digit spans were obtained under both processed and unprocessed conditions. As expected, forward and backward digit spans were significantly shorter when the stimuli were processed than when they were presented in unprocessed form. Participants' digit spans in unprocessed conditions and their accuracy in identifying digits in isolation were used to calculate predicted digit span scores in the processed speech condition. The observed digit spans in the transformed speech conditions did not differ significantly from the predicted digit spans. This result suggests that the decrease in immediate memory span is related to misidentification or misencoding of digits, due to the nature of the signal degradation, rather than to inefficient subvocal verbal rehearsal or serial scanning processes of the phonological representations in short-term memory under these unusual auditory conditions.

### Introduction

Several previous studies have found that recall performance on auditory memory span tasks is adversely affected in normal-hearing listeners when the auditory signals are degraded. For instance, decreased signal-to-noise ratios have been found to produce poorer memory performance in both working memory and short-term memory tasks (Dallett, 1964; Rabbitt, 1966, 1968; Pichora-Fuller, Schneider, & Daneman, 1995). In addition, Luce, Feustel, and Pisoni (1983) found that immediate memory capacity could also be reduced by using synthetic speech stimuli. Although they differed in methods, these studies lead to similar conclusions and interpretations by the authors. The main conclusion from these studies is that the perceptual difficulties in the tasks caused cognitive load to increase when items were encoded in memory. Increased cognitive load leads to the depletion or reallocation of resources normally used in other memory processes such as subvocal verbal rehearsal and serial scanning. Thus, as a result of reduced access to limited memory resources, processing capacity decreases under noisy or degraded auditory conditions.

Recently, working memory capacity and rehearsal processes have also been examined in individuals for whom auditory stimuli are always degraded because they use electrical stimulation provided by a cochlear implant to perceive speech and other sounds. In particular, several studies have reported that deaf children with cochlear implants have shorter forward and backward auditory digit spans compared to their normal-hearing peers (Pisoni & Geers, 2000). Deaf children with cochlear implants may have shorter memory spans simply because they have difficulty in correctly perceiving and encoding some of the test stimuli prior to recall. For instance deaf children may "recall" items that were not even presented in the list. These perceptually-driven errors are defined as item errors (Conrad, 1965).

However, deaf children using cochlear implants have also been found to perform poorly on immediate memory tasks even when the stimuli are not presented auditorily and recall does not require spoken responses. In a recent study, Cleary and colleagues (2001) demonstrated that deaf children using cochlear implants had shorter memory spans than their normal-hearing peers in a memory task that required the child to simply reproduce sequences of colored lights by manually pressing colored and illuminated response buttons. Their findings suggest that problems with memory processes other than the early encoding of auditory input may also contribute to the shorter digit spans of deaf children who use

cochlear implants. Cleary and colleagues proposed that deaf children using a cochlear implant performed poorly even on a task of visual memory span because they were inefficient at coding visual sequences verbally and were slower at verbally rehearsing phonological representations of color names in working memory.

Measures of overt speaking rates suggest that deaf children with cochlear implants perform subvocal verbal rehearsal more slowly than age-matched, normal-hearing children. Speaking rate is widely accepted as an estimate of subvocal verbal rehearsal speed based on a series of studies in normal-hearing adults (Baddeley, Thompson, & Buchanan, 1975; Schweickert, Guentert, & Hersberger, 1990) and children (Cowan, et al., 1998; Hulme & Tordoff, 1989; Kail & Park, 1994) that demonstrated that overt speaking rate is linearly related to memory capacity. People who speak faster have longer digit spans. The explanation of this result is that as the rate of overt speech and subvocal verbal rehearsal speed increases, items can be refreshed more rapidly in the short-term memory store. The rapid cycling of verbally encoded items through the short-term memory store increases and facilitates recall of items in immediate memory (Baddeley et al., 1975).

Recently, Pisoni and Cleary (2003) reported that the speaking rates of deaf children using cochlear implants were strongly correlated with their digit spans. Children with the fastest speaking rates had the longest memory spans. Deaf children with cochlear implants speak more slowly than their normal-hearing peers, which may further explain why their digit spans are shorter than the digit spans of normal-hearing children (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2003).

In addition to measuring subvocal verbal rehearsal processes in deaf children with cochlear implants, serial scanning speed has also been studied in this population. According to the recent work of Cowan (1999), interword pauses in immediate serial recall tasks reflect serial scanning, which is the process in which digits in the list are retrieved and scanned in serial order until the next item to be recalled is located (Sternberg, 1966). In a recent study, Burkholder and Pisoni (2003) measured interword pause durations during the digit span recall tasks in deaf children using cochlear implants and age-matched, normal-hearing children. They found that the interword pauses of the deaf children using cochlear implants were nearly twice as long as the interword pauses of the normal-hearing children.

The findings of Burkholder and Pisoni (2003) suggest that, in addition to having slower subvocal verbal rehearsal processes, deaf children with cochlear implants are also slower at serially scanning and retrieving verbal items (digits) in short-term memory. Taken together, the slowed subvocal verbal rehearsal speeds and slower serial scanning processes are both likely to contribute to the shorter memory spans of deaf children using cochlear implants. Thus, in addition to the initial encoding problems that lead to item errors by deaf children using cochlear implants, memory processing problems also contribute to their shorter memory spans. In contrast to initial auditory encoding, verbal rehearsal and serial scanning processes play a critical role in correctly maintaining the serial order of items in memory. Thus, problems associated with subvocal verbal rehearsal and serial scanning are likely to lead to order errors in immediate serial recall or the inability to maintain and recall the correct sequence of items in memory (Conrad, 1965; Gupta, 2003). It seems evident then that a primary problem facing researchers examining memory capacity in deaf children with cochlear implants or any other population of hearing-impaired listeners is delineating item errors from order errors in auditory memory span tasks.

However, unlike earlier studies measuring memory span in normal-hearing adults and children, it is impossible to measure the memory spans of deaf children using cochlear implants both before and after being exposed to the degraded auditory input that they receive through a cochlear implant. It is also difficult to determine exactly how much of an impact the degraded auditory input or item errors have on memory capacity. Although there is evidence for subvocal verbal rehearsal and serial scanning problems

in deaf children using cochlear implants, the magnitude of these problems cannot be reliably measured unless order errors are first separable from pure encoding errors.

However, it is possible to observe directly how memory span is affected in normal-hearing listeners who are exposed to auditory stimuli modeled after a cochlear implant's unique auditory input. To measure how memory capacity in normal-hearing listeners is influenced by listening to stimuli similar to a cochlear implant, Eisenberg and her colleagues (2000) used an acoustic simulation of a cochlear implant. Normal-hearing adults and children completed a digit span recall task in clear auditory conditions and while listening to stimuli filtered into eight different frequency bands designed to simulate output from a cochlear implant. As expected, both adults and children performed significantly worse on digit span recall when the digits were processed by the simulator.

Although the authors found weak correlations between digit spans, word and sentence recognition, and speech feature discrimination under the degraded auditory conditions, they did not attempt to determine whether item errors were entirely responsible for this decrease in digit span or whether order errors may have also been induced while listening to the degraded stimuli. In other words, although standard clinical tests of spoken word recognition and speech perception abilities were administered to these normal-hearing listeners to assess their general ability to understand speech through the cochlear implant simulation, insufficient data were collected on how accurate the listeners were at identifying test stimuli in isolation (Eisenberg et al., 2000). Measuring stimulus identification in isolation is necessary in order to estimate perceptual accuracy of each stimulus item in the absence of the additional cognitive load associated with the immediate serial recall task. Thus, a pretest evaluating the ability to recognize digits in their processed form, before being embedded in a memory task, is needed to determine more precisely the magnitude of item errors in digit span recall of normal-hearing listeners exposed to an acoustic simulation of a cochlear implant. Although the authors did conduct a pretest to ensure that all participants identified the degraded digits in isolation, they only used one presentation of each degraded digit. Using such a limited number of stimuli to test identification in isolation may have resulted in an overestimation of how accurate participants really were at the task.

In the present study, we utilized a stimulus pretest to predict and determine the contributions of perceptual errors to normal-hearing adults' digit spans while listening to an acoustic simulation of a cochlear implant. The acoustic simulation used in this study was similar to Eisenberg et al.'s (2000) with the exception that a basalward frequency shift was also included to make the task even more difficult by increasing the frequency or pitch of the stimuli. We expected that, similar to previous studies testing memory in degraded or noisy auditory conditions, memory capacity would decrease substantially (Luce et al., 1983; Rabbitt, 1966, 1968). In addition, we predicted that the nature of this decrease will primarily be accounted for by item errors due to the degraded nature of the auditory stimuli. However, we also expected that the perceptual difficulty of this task would lead to an increase in serial order errors in normal-hearing adults despite their intact memory processing abilities.

## **Method**

### **Participants**

Twenty-five undergraduate students enrolled at Indiana University participated in this study. They received partial course credit for the introductory Psychology class. The group of participants included 18 females and 7 males. A brief hearing screening was administered by the first author to determine whether the participants' hearing was within normal limits. Using a standard, portable pure-tone audiometer (Maico Hearing Instruments, MA27) and headphones (TDH-39P), each participant was tested at 250, 500, 1000, 2000, and 4000 Hz at 20 dB first in the right ear and then in the left ear. None of

the participants showed any evidence of a hearing loss. All participants also reported that they were monolingual native speakers of American English and had no prior history of speech, language, hearing, or attentional disorders at the time of testing.

### Stimuli and Materials

**Simulation Strategy.** All auditory stimuli were processed offline using a personal computer equipped with DirectX 8.0 and a Sound Blaster Audigy Platinum sound card. The signal processing procedure used for the cochlear implant simulation was adapted from real-time signal processing methods designed by Kaiser and Svirsky (2000). The signal processing strategy used bandpass filtering with a cutoff frequency of 1200 Hz. Eight filters were then used to simulate the speech processing capabilities of an 8-channel cochlear implant. The output of each filter modulated noise bands of a higher frequency range than the initial analysis filters. This mismatch was designed to model the natural frequency mismatch that occurs when the electrodes of a cochlear implant are shifted more basalward in the cochlea. The basalward shift used in this model was equivalent to a 0.5 mm shift within the cochlea.

**Stimuli.** Several familiar nursery rhymes (i.e. *Twinkle, Twinkle Little Star*; *Jack and Jill*) were used to familiarize the listeners with the processed speech. The nursery rhymes included in the familiarization phase are included in the Appendix. While listening to these passages, the participants were provided with the written text of the nursery rhymes so they could read along with them. The stimuli used for pretest digit identification included isolated utterances of the digits 1 through 9. The digit span lists were taken from the Wechsler Intelligence Scale for Children (WISC; Wechsler, 1991) and Wechsler Adult Intelligence Scale (WAIS; Wechsler, 1997). All stimuli used for familiarization and the digit span training task were recorded digitally in a sound attenuated booth by the first author using an individualized version of a speech acquisition program (Dedina, 1987; Hernandez, 1995). The stimuli were sampled and digitized at 22,050 Hz with 16-bit resolution and then equated for amplitude using the Level16 software program (Tice & Carrell, 1998).

### General Procedures

**Familiarization Task.** Prior to testing, a sound level meter (Triplett Model 370) was used to adjust the amplitude of the stimuli to 70 dB SPL. In order to familiarize the participants with the processed speech, the five nursery rhymes were played through a high-quality tabletop loudspeaker (Cyber Acoustics MMS-1) while the participants read along with the written text. Nursery rhymes were chosen for familiarization, because they are well known to most listeners and they have a distinctive prosody and rhythm that may assist in recognizing the degraded stimuli as real speech. In addition, these stimulus materials were chosen because the experimental procedure was specifically designed for future use with normal-hearing children. Thus, the utilization of these tasks in adults served as a pilot study for a companion project that will be carried out with normal-hearing children.

**Stimulus Pretest.** Prior to obtaining any digit span measures, the identification of processed digits in isolation was measured and feedback was provided. The digits 1 through 9 were each played five times in random order which resulted in the presentation of 40 digits. Participants indicated verbally what digit they thought they heard on each trial. If the response was correct, the experimenter simply affirmed that the correct answer had been given. However, if the response was incorrect, the experimenter played the correct response.

**Digit Spans.** Following digit identification training, participants completed several digit span tasks under both normal and processed auditory conditions. The order of presentation of the processed and unprocessed conditions was counterbalanced over participants. However, following the traditional

digit span administration procedures in the WISC manual, backward digit span was always administered after forward digit span.

### Scoring Procedures

**Observed Digit Span Scores.** The digit span tasks were not scored according to traditional methods that quantify digit span in terms of how many lists of digits are correctly repeated. Rather, the results from both the forward and backward digit span tasks, conducted in unprocessed conditions, were used to obtain two different scores. The first score derived from the digit span tasks was a measure of the average length of the two longest lists of digits that each participant could repeat correctly in both the unprocessed or processed conditions. This score reflected a participant's memory capacity.

**Predicted Digit Spans.** A second score was also calculated using an algorithm that combined memory capacity in unprocessed conditions and the accuracy of identifying digits in isolation when they were processed. This score provided an estimate of the predicted digit span in the transformed speech condition. For example, if a participant had a digit span of 3 in the unprocessed digit condition and in the pretest only identified digits correctly 60% of the time, for each digit, there would be a 40% chance that it will be misheard and recalled incorrectly. Thus, there is a 40% chance of missing the first digit of the first list and having a digit span of 0. This "predicted" digit span score is meant to reflect the degree of digit span recall problems strictly related to the inability to correctly identify digits. These errors will have a negative effect on the digit span measured in processed speech conditions. The size of the effect of perceptual errors on the digit span can be estimated mathematically. Equation 1 illustrates the basic steps taken to calculate the predicted digit span score given the example that the digit span in unprocessed conditions is 3 and digits were incorrectly identified in the pretest 40% of the time. The calculation of predicted digit span through this method was achieved using a MatLab script.

- a) the probability of missing the first digit of a list and having a digit span of 0 is expressed as:
  - i.  $.40$
- b) the probability of correctly recalling the first digit but misidentifying the second digit is expressed as:
  - i.  $(.60)(.40)$
- c) the probability of repeating the first two digits correctly and incorrectly recalling the third is:
  - i.  $(.60)(.60)(.40)$
- d) and the probability of correctly recalling all digits is:
  - i.  $(.60)(.60)(.60)$
- e) therefore, taking into account all the probabilities of having a digit span of 0, 1, 2, 3, etc., the predicted digit span is:
  - i.  $.4(0) + (.6)(.4)(1) + ((.6)^2(.4)(2) + (.6)^3(3)) = 1.176$

Thus, in this example, the listener has an observed digit span of 3 in unprocessed conditions but has a predicted digit span of only 1.176 in the processed condition due to the effect of misidentification of digits at the time of initial encoding.

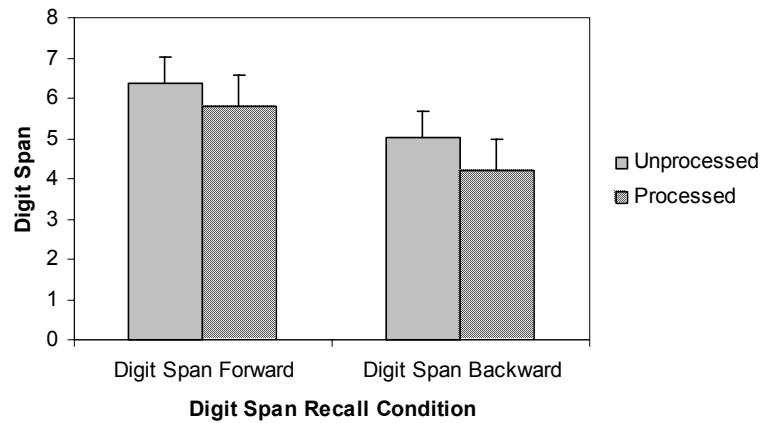
**Digit Span Error Scoring.** In order to determine whether item or encoding errors were more numerous in digit span recall conducted in the processed speech condition, the participants' digit span errors in all incorrectly recalled lists were classified according to error type. In addition to classifying the item and order errors, omission and combination errors were also recorded. An item error was recorded if a digit(s) that did not appear in the original list was recalled in the place of an intended digit(s) (Example: 6, 1, 5, 8 repeated as "6, 9, 4, 8"). Order errors included responses in which all the correct digits of a list were repeated but in an incorrect order or in a combination of incorrect orders (Example: 6, 1, 5, 8 repeated as "5, 6, 1, 8"). An error of omission was scored when one or more numbers were omitted from the list. Errors in digit span recall that consisted of several different types of errors were considered to be combination errors.

A 2 x 2 x 4 factorial design was used to determine in which processing of the conditions the four types of errors were most likely to be committed by the participants (unprocessed or processed and recall forward or backward). The error rate of each type of error committed by the participants was the dependent variable. The error rate was calculated by dividing the raw number of errors made by the total number of possible errors for each recall condition. The total number of errors possible was determined by the number of lists completed and the number of digits administered in each list. According to this method, it is assumed that each possible digit could be a source of error.

Error rates were expressed as proportions rather than using raw scores in order to equate for the different number of possible errors in the two conditions. For instance, when using the standard digit span administration procedures, a greater number of errors are possible in forward digit span recall, making it necessary to equate the conditions according to how many lists were administered and how many possible errors could have been made. More lists were administered in the forward digit span condition, and typically participants progress through more lists, resulting in more opportunities for the participants to commit errors. In addition, participants were generally able to complete more lists in the unprocessed condition, resulting in a greater number of errors possible during recall under these conditions.

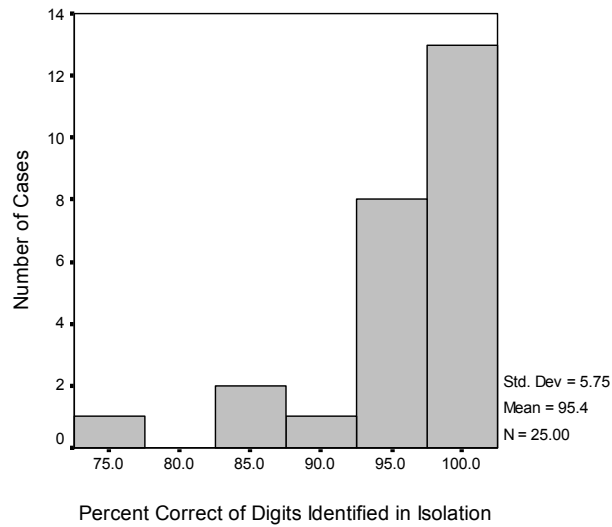
## Results

As expected, both forward and backward digit span recall were significantly worse under the processed speech conditions. Figure 1 illustrates the digit spans obtained in the processed and unprocessed speech conditions. The mean forward digit span obtained under the processed speech conditions ( $M = 5.78$ ,  $SD = 1.13$ ) was nearly one digit shorter ( $t(24) = 2.62$ ,  $p = .015$ ) than the mean forward digit span observed in the unprocessed conditions ( $M = 6.36$ ,  $SD = .97$ ). Similarly, backward digit spans were nearly one digit shorter ( $t(24) = 3.41$ ,  $p = .002$ ) under processed conditions ( $M = 4.22$ ,  $SD = 1.49$ ) than in unprocessed conditions ( $M = 5.02$ ,  $SD = 1.42$ ).



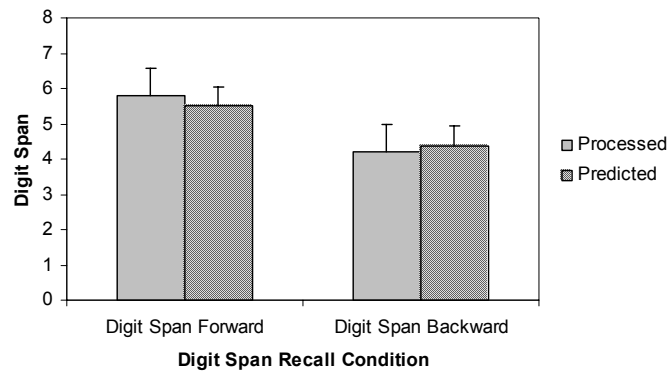
**Figure 1.** Mean digit span scores in the processed and unprocessed speech condition. Error bars represent the standard error of the mean.

Prior to calculating the predicted digit spans, the data obtained from the digit pretest were analyzed. Scores on the isolated digit pretest ranged from 76%-100% with nearly half of the participants capable of identifying the digits with 100% accuracy. Figure 2 displays a frequency distribution of the digit identification scores obtained when digits were played in isolation under processed speech conditions. Using each participant's processed digit identification accuracy and the unprocessed digit spans of each participant, predicted processed digit spans were calculated using the procedures summarized above.



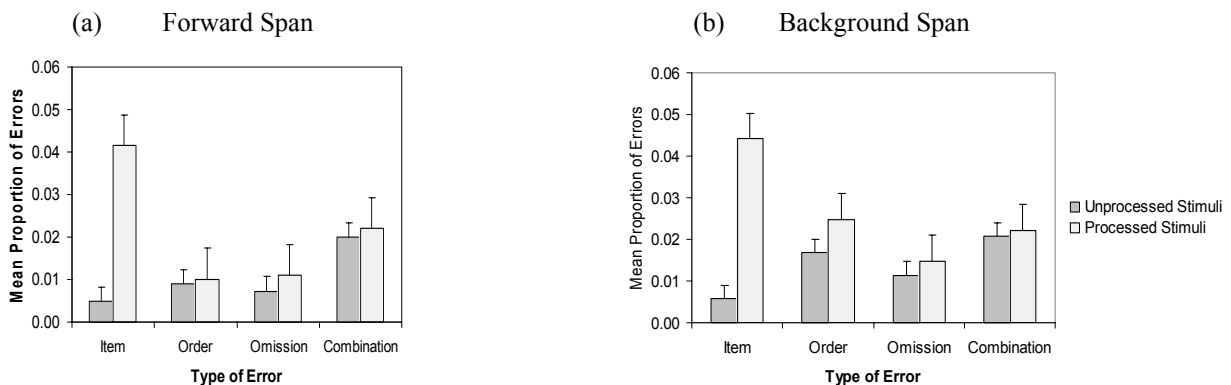
**Figure 2.** Frequency distribution of the digit identification scores.

A paired-samples *t*-test revealed no significant difference between the forward and backward predicted digit spans and the observed digit spans in processed speech conditions. Figure 3 illustrates the mean predicted and processed digit spans. Predicted forward digit spans ( $M = 5.50$ ,  $SD = 1.28$ ) were lower than the observed digit spans ( $M = 5.78$ ,  $SD = 1.28$ ), however this difference did not reach significance ( $t(24) = .703$ ,  $p = .489$ ). Predicted backward digit spans ( $M = 4.38$ ,  $SD = 1.42$ ) were slightly higher than the observed backward digit spans ( $M = 4.22$ ,  $SD = 1.49$ ) but this difference also did not reach significance either ( $t(24) = 1.19$ ,  $p = .246$ ).



**Figure 3.** Mean predicted digit span scores and observed digit spans in the processed speech condition. Error bars represent the standard error of the mean.

Figure 4 shows a graph of the proportion of errors and type of digit span errors committed by the participants in both the forward and backward recall conditions. A univariate ANOVA revealed a main effect of error type ( $F(3, 416) = 8.76$ ,  $p = .000$ ) and processing condition ( $F(1, 416) = 10.16$ ,  $p = .002$ ). In addition, there was an interaction effect between the processing condition and error type ( $F(3, 416) = 7.17$ ,  $p = .000$ ). The main effect of recall direction approached significance ( $F(1, 416) = 3.29$ ,  $p = .071$ ) and no interaction effects involving recall condition were found despite the finding that processing errors did increase more in the backward recall condition when the auditory stimuli were processed.



**Figure 4.** Mean proportion of errors committed by participants in the digit span task under processed speech condition in (a) forward and (b) backward recall conditions. Error bars represent the standard error of the mean.

## Discussion

As expected, the results demonstrate that immediate memory span for digits declined when the auditory stimuli were processed by a simulator that was designed to model the signal transmitted to cochlear implant users. The decline in digit span in these normal-hearing participants appears to be primarily due to item errors at the time of encoding, because the observed digit spans under processed speech conditions were no worse than would be expected after accounting for accuracy in identifying digits in isolation. In addition, using a classification system to identify the digit span recall errors, we found that item errors increased the most under the simulator. Although the proportion and number of order errors increased in the backward digit span task while remaining unaffected in forward digit span recall, this difference was not significant. Previous research suggesting that memory resources may be recruited to assist in auditory processing during memory tasks presented in noise and contribute to decreased memory span performance was not supported by the results obtained in this study (Luce et al., 1983; Pichora-Fuller et al., 1995).

However, the memory task used in the present study differed in several ways from the previous studies. One difference that may have contributed to the lack of a primary influence of order errors in this task was that it involved the recall of a small set of digits rather than recall of words. In addition, the words to be recalled in previous studies were embedded within sentences in which the listeners were tested for comprehension, making it a more traditional working memory task rather than a serial recall task (Daneman & Carpenter, 1980). The additional processing demands required in these tasks and the less limited range from which auditory stimuli could be selected makes them more challenging than the serial digit recall task used in the present study. However, backward digit span recall is considered to be a more complex cognitive task requiring additional executive planning, controlled attention, verbal rehearsal, and recall strategies than forward span (Li & Lewandowsky, 1995; Thomas, Milner, & Haberlandt, 2003). Therefore, increasing difficulty of the task through a cochlear implant simulation utilizing a frequency shift was expected to cause more processing difficulties as well. Order errors occurred more often in the backward recall condition, but these differences were not significant.

Any evidence of more order errors due to the degradation of the auditory stimuli is noteworthy, because the normal-hearing adults used in the present study undoubtedly had typical working memory processing skills. However, research suggests that deaf children using cochlear implants may also have poorer memory processing skills because of their slower subvocal verbal rehearsal speeds and serial scanning rates (Burkholder & Pisoni, 2003; Cleary et al., 2001). It seems then that testing deaf children with cochlear implants in an auditory digit span task would certainly contribute further to the incidence of order errors and not only elicit item errors that reflect their hearing impairment and speech and word recognition skills. However, because of the substantial and dominant role that item errors played in the decreased digit span performance of these normal-hearing adults, it should still be assumed that pure perceptual errors may also underlie some of the difficulties that deaf children with cochlear implants have in digit span recall.

Unfortunately, however, we cannot determine what the memory spans of deaf children with cochlear implants would be had they not had a hearing impairment or can we derive what their predicted memory span would be when first exposed to the degraded auditory input. However, the ability to make these predictions about memory span in normal-hearing listeners, exposed to a cochlear implant simulation, could be a useful benchmark for further interpretations that can be made about memory processes in deaf individuals using cochlear implants. In addition, with further analyses of the verbal digit span responses of the deaf children with cochlear implants, an error categorization process similar to the one used in this study could be used to determine the proportion of item and order errors that contribute to their shorter memory spans (Burkholder & Pisoni, 2004).

Although the present study on memory span with normal-hearing adults was motivated by earlier research on immediate memory span in deaf children using cochlear implants, it is necessary to acknowledge several limitations that may be associated with these kinds of comparisons. For example, although the acoustic simulation of a cochlear implant used in this study does accurately represent how speech is processed by a cochlear implant, it is currently unknown what differences may occur in the way the auditory stimuli are processed and perceived at peripheral and cortical levels in normal-hearing and deaf populations. Neuroplasticity associated with a period of prolonged deafness followed by cochlear implantation has been documented extensively in both animals and humans (e.g., Leake, Hradek, & Snyder, 1999; Moore, Vollmer, Leake, Snyder, & Rebscher, 2002; Ponton, 2001) and may be a substantial source of the limitations involved in studies utilizing acoustic simulations of cochlear implants.

Additionally, it may not be appropriate to examine the effects of a simulation on memory by making comparisons between adults and children. Developmental differences related to the speed of subvocal verbal rehearsal and serial scanning processes could potentially confound the interpretation of results obtained by making comparisons between adults and children (Cowan, 1999; Cowan et al., 1998). However, other memory mechanisms and processes and their relationship to other cognitive tasks have been found to be similar between adults and children, making an examination of these relationships interesting in normal-hearing adults and deaf children using cochlear implants (Gupta, 2003). A final drawback in making comparisons between normal-hearing individuals' performance on tasks using an acoustic simulation of a cochlear implant and the performances of actual cochlear implant users is related to the large differences in the amount of exposure that each group of listeners has had with the auditory input. However, the lack of experience with such a degraded auditory input by normal-hearing listeners provides an ideal situation in which to further examine the time course of perceptual learning, adaptation, and cognitive performance while listening to the unusual stimuli for only a short period of time.

## References

- Baddeley, A.D., Thompson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Behavior*, *14*, 575-589.
- Burkholder, R.A., & Pisoni, D.B. (2003). Speech timing and working memory in profoundly deaf children after cochlear implantation. *Journal of Experimental Child Psychology*, *85*, 63-88.
- Burkholder, R.A., & Pisoni, D.B. (2004). *Analysis of Digit Span Recall Error in Paediatric Cochlear Implant Users and Normal-Hearing Children*. Poster session presented at the European Symposium of Paediatric Cochlear Implantation, Geneva, Switzerland.
- Cleary, M., Pisoni, D.B., & Geers, A. (2001). Some measures of verbal and spatial working memory in eight- and nine-year-old hearing-impaired children with cochlear implants. *Ear and Hearing*, *22*, 395-411.
- Cleary, M., Dillon, C., & Pisoni, D. (2002). Imitation of nonwords by deaf children following cochlear implantation. *Annals of Otolaryngology, Rhinology, and Laryngology*, *111*, 91-96.
- Conrad, R. (1965). Order error in immediate recall of sequences. *Journal of Verbal Learning & Verbal Behavior*, *4*, 161-169.
- Cowan, N. (1999). The differential maturation of two processing rates related to digit span. *Journal of Experimental Child Psychology*, *72*, 193-209.
- Cowan, N., Wood, N., Wood, P., Keller, T., Nugent, L., & Keller, C. (1998). Two separate verbal processing rates contributing to short-term memory span. *Journal of Experimental Psychology*, *127*, 141-160.
- Dallett, K.M. (1964). Intelligibility and short-term memory in the repetition of digit strings. *Journal of Speech and Hearing Research*, *7*, 362-368.

- Daneman, M., & Carpenter, P.A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*, 450-466.
- Dedina, M.J. (1987). SAP: A speech acquisition program for the SRL-VAX. In *Research on Speech Perception Progress Report No. 13* (pp. 331-337). Bloomington, IN: Speech Research Laboratory, Indiana University.
- Eisenberg, L., Shannon, R., Martinez, A., Wygonski, J., & Boothroyd, A. (2000). Speech recognition with reduced spectral cues as a function of age. *Journal of the Acoustical Society of America*, *107*, 2704-2709.
- Gupta, P. (2003). Examining the relationship between word learning, nonword repetition, and immediate serial recall in adults. *Quarterly Journal of Experimental Psychology*, *56A*, 1213-1236.
- Hernandez, L.R. (1995). Current computer facilities in the Speech Research Laboratory. In *Research on Speech Perception Progress Report No. 13* (pp. 389-393). Bloomington, IN: Speech Research Laboratory, Indiana University.
- Hulme, C., & Tordoff, V. (1989). Working memory development: The effects of speech rate, word length, and acoustic similarity on serial recall. *Journal of Experimental Child Psychology*, *47*, 72-87.
- Kail, R., & Park, Y. (1994). Processing time, articulation time, and memory span. *Journal of Experimental Child Psychology*, *57*, 281-291.
- Kaiser, A. R., & Svirsky, M.A. (2000). *Using a personal computer to perform real-time signal processing in cochlear implant research*. Paper presented at the Proceedings of the IXth IEEE-DSP Workshop., Hunt, TX.
- Leake, P.A., Hradek, G.T., & Snyder, R.L. (1999). Chronic electrical stimulation by a cochlear implant promotes survival of spiral ganglion neurons after neonatal deafness. *Journal of Comparative Neurology*, *412*, 543-562.
- Li, S.-C., & Lewandowsky, S. (1995). Forward and backward recall: Different retrieval processes. *Journal of Experimental Psychology: Learning, Memory, & Cognition* *21*, 837-847
- Luce, P.A., Feustel, T.C., & Pisoni, D.B. (1983). Capacity demands in short-term memory for synthetic and natural speech. *Human Factors*, *25*, 17-32.
- Moore, C., Vollmer, M., Leake, P., Snyder, R., & Rebscher, S. (2002). The effects of chronic intracochlear electrical stimulation on inferior colliculus spatial representation in adult deafened cats. *Hearing Research*, *164*, 82-96.
- Pichora-Fuller, M.K., Schneider, B.A., & Daneman, M. (1995). How young and old adults listen to and remember speech in noise. *Journal of the Acoustical Society of America*, *97*, 593-607.
- Pisoni, D.B., & Cleary, M. (2003). Measures of working memory span and verbal rehearsal speed in deaf children after cochlear implantation. *Ear and Hearing*, *24*, 106S-120S.
- Pisoni, D., & Geers, A. (2000). Working memory in deaf children with cochlear implants: Correlations between digit span and measures of spoken language processing. *Annals of Otology, Rhinology, and Laryngology*, *185*, 92-93.
- Ponton, C.E.J. (2001). Of kittens and kids: Altered cortical maturation following profound deafness and cochlear implantation. *Audiology & Neuro Otology*, *6*, 363-380.
- Rabbitt, P. (1966). Recognition memory for words correctly heard in noise. *Psychonomic Science*, *6*, 383-384.
- Rabbitt, P. (1968). Channel-capacity, intelligibility, and immediate memory. *Quarterly Journal of Experimental Psychology*, *20*, 241-248.
- Schweickert, R., Guentert, L., & Hersberger, L. (1990). Phonological similarity, pronunciation rate, and memory span. *Psychological Science*, *1*, 74-77.
- Sternberg, S. (1966). High-speed scanning in human memory. *Science*, *153*, 652-654.
- Thomas, J., Milner, H., & Haberlandt, K. (2003). Forward and backward recall: Different response time patterns, same retrieval order. *Psychological Science*, *14*, 169-174.
- Tice, R. & Carrell, T. (1998). Level 16, Version 2.0.3, University of Nebraska.

- Wechsler, D. (1991). *Wechsler Intelligence Scale for Children – III*. San Antonio, TX: The Psychological Corporation.
- Wechsler, D. (1997). *Wechsler Adult Intelligence Scale – III*. San Antonio, TX: The Psychological Corporation.

## Appendix

Stimulus materials used for familiarization with the acoustic model of a cochlear implant.

Hickory, Dickory, Dock

*Hickory, dickory, dock,  
The mouse ran up the clock.  
The clock struck one,  
The mouse ran down.  
Hickory, dickory, dock!*

Jack and Jill

*Jack and Jill went up the hill  
To fetch a pail of water  
Jack fell down and broke his crown,  
And Jill came tumbling after*

One, Two, Buckle My Shoe

*One, two, buckle my shoe,  
Three, four, knock at the door.  
Five, six, pick up sticks,  
Seven, eight, lay them straight.  
Nine, ten, big fat hen.*

Star Light

*Star light, star bright  
First star I see tonight  
I wish I may, I wish I might  
Have the wish I wish tonight*

Twinkle, Twinkle

*Twinkle, twinkle, little star,  
How I wonder what you are!  
Up above the world so high,  
Like a diamond in the sky.  
Twinkle, twinkle, little star,  
How I wonder what you are!*