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Effects of a cochlear implant simulation on immediate memory in normal-hearing adults

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Abstract

This study assessed the effects of stimulus misidentification and memory processing errors on immediate memory span in 25 normal-hearing adults exposed to degraded auditory input simulating signals provided by a cochlear implant. The identification accuracy of degraded digits in isolation was measured before digit span testing. Forward and backward digit spans were shorter when digits were degraded than when they were normal. Participants' normal digit spans and their accuracy in identifying isolated digits were used to predict digit spans in the degraded speech condition. The observed digit spans in degraded conditions did not differ significantly from predicted digit spans. This suggests that the decrease in memory span is related primarily to misidentification of digits rather than memory processing errors related to cognitive load. These findings provide complementary information to earlier research on auditory memory span of listeners exposed to degraded speech either experimentally or as a consequence of a hearing-impairment.

Keywords

Acoustic simulations; Auditory memory; Cochlear implants; Deafness; Digit span

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 or masked by noise. For instance, decreased signal-to-noise ratios have been found to cause poorer recall performance in immediate memory tasks which require listeners to simply repeat back a list of items in the order they were heard (Dallett, 1964; Rabbitt, 1966, 1968; Pichora-Fuller et al, 1995). In addition, Luce et al (1983) found that memory capacity could also be reduced by using synthetic speech stimuli matched in intelligibility to natural speech. Although they differed in methods, all of these studies led to similar conclusions and interpretations by the authors. The main conclusion was that the increased perceptual difficulty involved in the tasks caused cognitive load to increase when items were encoded in memory. Increased cognitive load during encoding may lead to the depletion or reallocation of resources normally used in other memory processes. Two memory processes that could be adversely affected by increased cognitive load are subvocal verbal rehearsal and serial scanning of items in immediate memory. Subvocal verbal rehearsal is the process of mentally repeating items in memory before recall (Baddeley et al, 1975). Serial scanning

is a method used during recall in which items in immediate memory are rapidly and subvocally reviewed until the next item to be recalled is located (Sternberg, 1966).

Despite the conclusions of earlier studies that overloaded memory processing may lead to shorter auditory memory spans, there is an alternative explanation for decreases in immediate memory span under degraded auditory conditions. It is possible that they are not primarily due to inefficiencies caused by increased cognitive load, but to misidentifications of individual items during encoding. This hypothesis was explored in this study using degraded, *noise-vocoded speech* modeled after the input received by cochlear implant users.

The motivation for measuring memory span using an acoustic model of a cochlear implant is based on the findings from several previous studies that have examined the memory skills of cochlear implant users. Deaf children with cochlear implants have been found to have shorter auditory digit spans compared to their normal-hearing peers (Pisoni & Geers, 2000; Pisoni & Cleary, 2003). In addition, deaf children using cochlear implants have also been found to perform worse than their normal-hearing peers on immediate memory tasks even when the stimuli are not presented auditorily and recall does not require a verbal response (Cleary et al, 2001). Given that pediatric cochlear implant users perform poorly on both auditory and visual memory span tasks, it is important to consider the influence that both speech perception and memory processing problems may have on auditory memory performance.

Subvocal verbal rehearsal and serial scanning have been identified as two process variables that may contribute to the shorter memory spans of deaf children using cochlear implants. Evidence of slower subvocal verbal rehearsal skills in pediatric cochlear implant users has been obtained in studies examining speaking rate and digit spans (Pisoni & Cleary, 2003). Speaking rate is a widely accepted estimate of subvocal verbal rehearsal speed and is linearly related to immediate memory capacity. Numerous earlier studies in both normal-hearing adults (Baddeley et al, 1975; Schweickert et al, 1990) and children (Cowan, et al, 1998; Hulme & Tordoff, 1989; Kail & Park, 1994) and, more recently, deaf children using cochlear implants (Pisoni & Cleary, 2003) have found that subjects who speak faster have longer memory spans. This relationship occurs because, as the rate of overt speech and subvocal verbal rehearsal speed increases, individual items can be refreshed more rapidly in immediate memory (Baddeley et al, 1975). The rapid recycling of verbally encoded items is thought to facilitate recall of items in immediate memory.

Serial scanning is also an important process used during memory span tasks. According to work by Cowan (1999), interword pauses in digit span tasks reflect serial scanning, 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.

Taken together, slowed subvocal verbal rehearsal speeds and slower serial scanning processes are both likely to contribute to the shorter immediate memory spans of deaf children using cochlear implants and may contribute to the decrease of normal-hearing listeners' digit spans in degraded auditory conditions. However, speech perception scores have also been found to be related to the digit spans of deaf children using cochlear implants, suggesting that early perceptual problems at the time of initial encoding may also contribute to their shorter auditory digit spans (Dillon et al, 2004; Pisoni & Geers, 2000). Therefore, cochlear implant users or other listeners presented with degraded auditory signals

during a memory task may simply recall items that were not presented in the list. This behavior is commonly known as an item error and may reflect early perceptual problems (Conrad, 1965).

In contrast to initial auditory encoding, verbal rehearsal and serial scanning processes are assumed to play critical roles in maintaining the correct serial order of items in memory. Thus, problems associated with subvocal verbal rehearsal and serial scanning may lead to order errors or an inability to maintain the correct sequence of items in memory (Conrad, 1965; Gupta, 2003). One problem facing researchers who examine memory capacity in listeners exposed to severely degraded auditory stimuli (e.g. cochlear implant users) is delineating item errors from order errors in auditory memory span tasks.

Unfortunately, unlike earlier studies measuring memory span in normal-hearing listeners exposed to degraded stimuli, it is impossible to measure the memory spans of cochlear implant users under normal and degraded conditions. Measurements can be made only with the degraded auditory input provided by a cochlear implant. This limitation makes it difficult to determine exactly how much of an impact the degraded auditory input has on immediate memory capacity in hearing-impaired listeners. Although there is evidence for atypical subvocal verbal rehearsal and serial scanning processes in deaf children using cochlear implants, the magnitude of these differences cannot be reliably measured unless order errors are first separated from perceptually based item-encoding errors. Similarly, in normal-hearing listeners, it remains unclear what specifically underlies decreased memory performance in degraded auditory conditions if item and order errors are not teased apart from one another. In both hearing-impaired and normal-hearing listeners, it is important to make a distinction between item and order errors to more accurately determine the consequences that degraded auditory stimuli have for an important cognitive ability such as memory.

Recent advances in acoustic simulations of cochlear implants have made it 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. In the study by Eisenberg et al (2000), normal-hearing adults and children completed a digit span recall task under 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 degraded.

Although the authors found correlations between digit spans and word/sentence recognition and speech feature discrimination under degraded auditory conditions, they did not attempt to determine whether speech perception or item errors at encoding were partly responsible for decreases in digit span. 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 digits in isolation (Eisenberg et al, 2000). Thus, it was unclear in this study whether decreases in digit span were due to item or order errors, or both.

Measuring stimulus identification in isolation is necessary in order to estimate perceptual accuracy of each stimulus item in the absence of any additional cognitive load associated with the digit span task. Thus, a pretest evaluating the ability to recognize digits in their degraded form, before being used 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 Eisenberg and colleagues conducted a

pretest in which all participants repeated the degraded digits in isolation to make sure they were identifiable, they only used one presentation of each degraded digit. Such a method for measuring the intelligibility of stimuli is limited for two reasons. First, it potentially allows for identification of items through the process of elimination because the stimuli are drawn from a small closed-set. Second, by using only single presentations of the stimuli, participants' abilities to identify the digits over multiple trials of a digit span task may have been overestimated.

An important consequence of these limitations is that no accurate conclusion can be made about the contribution of item or order errors, when digit span tasks are administered in auditory conditions modeled after the input received by cochlear implant users. It is both theoretically and clinically important to examine the contribution of item and order errors on memory performance while listening to acoustic simulations of cochlear implants. Evaluating auditory memory performance using acoustic simulations of cochlear implants is a clinically important methodology, because it may help determine if cochlear implant users' poor memory span performances are primarily related to inefficient use of memory strategies, speech perception errors, or both. It is also important to uncover the primary cause of decreased memory spans in difficult listening conditions in both hearing-impaired and normal-hearing listeners in order to determine how resilient memory processes are when cognitive load is increased. Similarly, examining auditory memory span while using degraded stimuli provides a unique opportunity to evaluate how robust speech perception skills are when listeners are simultaneously required to utilize their memory processing skills.

In order to examine item and order errors in immediate memory, we utilized an extended stimulus pretest to predict the contributions of perceptual or item errors to normal-hearing adults' digit spans, while listening to an acoustic simulation of a cochlear implant. In addition, a novel method of error categorization and analysis was used to further separate item and order errors. The acoustic simulation used in this study was similar to that of Eisenberg et al (2000) with the exception of a basalward frequency shift that was also included to make the task even more difficult and the stimuli more similar to those heard by cochlear implant users. We expected that, similar to previous studies testing memory in degraded or noisy auditory conditions, memory capacity would decrease substantially under these conditions (Luce et al, 1983; Rabbitt, 1966, 1968). However, we predicted that the decrease in performance could be primarily accounted for by item errors due to the degraded nature of the auditory stimuli and that there would be a minimal contribution of serial order errors.

Method

Participants

Twenty-five undergraduate students enrolled at Indiana University participated in this study. They received partial course credit for the introductory psychology class in which they were enrolled at the time. The group of participants included eighteen females and seven 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 0.25, 0.5, 1, 2, and 4 kHz at 20–25 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 was lowpass filtered with a cutoff frequency of 12 kHz. A bank of eight filters was then used to simulate the speech processing of an 8-channel cochlear implant. The choice of eight channels is based on studies showing that adult cochlear implant users achieve asymptotic speech perception scores when the number of channels is increased to that level (Fishman et al, 1997; Friesen et al, 2001). Additionally, the best adult cochlear implant users reach word identification levels similar to those obtained by normal-hearing listeners exposed to an eight-channel acoustic simulation of a cochlear implant, when the acoustic model is implemented without any frequency shift (Dorman et al, 1998).

The output of each filter modulated noise bands of a higher frequency range than the corresponding filter. This mismatch was designed to represent a frequency misalignment that may occur between the analysis filters of a cochlear implant's speech processor and the characteristic frequency of the neurons stimulated by the corresponding electrodes. There are indications that adult cochlear implant users are subject to some amount of frequency shift (Eddington et al, 1978; Faulkner et al, 2003), although this frequency shift is less than what would be predicted using Greenwood's equation (Blamey et al, 1996; James et al, 2001). The amount of frequency mismatch used in this model was equivalent to a 6.5 mm shift within the cochlea. For a more complete discussion of the frequency shift used in the present study see Harnsberger et al (2001).

Stimuli—Five highly familiar nursery rhymes (e.g. *Twinkle, Twinkle Little Star* and *Jack and Jill*) were used to familiarize the listeners with the degraded speech. While listening to these passages, the participants were also 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 tokens of the digits 'one' through 'nine'. 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 SAP, a speech acquisition program (Dedina, 1987). The stimuli were sampled and digitized at 22.050 kHz with 16-bit resolution and then equated for amplitude using the Level16 software program (Tice & Carrell, 1998).

Procedure

Familiarization and training tasks—Prior to testing, a sound level meter (Triplett Model 370) was used to adjust the amplitude of the stimuli to 70 dB(A) SPL. In order to familiarize the participants with the degraded speech, the five nursery rhymes were played through a high-quality tabletop loudspeaker (Cyber Acoustics MMS-1) while the participants read along silently with the written text. Nursery rhymes were chosen for the familiarization phase 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 studies with normal-hearing children.

The listeners also had approximately 25–30 minutes of open- and closed-set word recognition training prior to hearing any digits. The Lexical Neighborhood Test (LNT: Kirk et al, 1999) and Word Intelligibility by Picture Identification (WIPI: Ross & Lerman, 1979) materials were used for training. During this training period, listeners were presented with

words in their degraded form, and after giving their responses, they heard the same word in its unprocessed form. Feedback was given regardless of whether or not the listener gave the correct response. Training with degraded stimuli was designed to prevent underestimation of accuracy in digit identification due to lack of sufficient experience with the degraded speech.

Stimulus pretest—Prior to obtaining any digit span measures, the identification of degraded digits in isolation was measured and feedback was provided. The digits ‘one’ through ‘nine’ were each played five times in random order which resulted in the presentation of 45 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 repeated the correct digit.

Digit spans—Following digit identification training, participants completed forward and backward digit span tasks under both normal (unprocessed) and degraded auditory conditions. In the forward digit span task, participants were simply required to repeat the digits in the exact order in which they were presented. In the backward digit span task, participants were required to repeat the digits in the reverse order of their presentation.

Each span task started with two-digit lists, and two lists were administered at each length. If at least one of the two lists was repeated correctly, testing proceeded to the next list which was one digit longer. If both lists at one length were recalled incorrectly, testing stopped. The order of the degraded and normal digit span conditions was counterbalanced over participants. Following the traditional administration procedures in the WISC manual, backward digit span was always measured after forward digit span.

Scoring Procedures

The digit span tasks were not scored according to traditional methods that are routinely used to 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 under normal (unprocessed) presentation conditions, were used to obtain two different scores described below.

Observed digit span scores—Observed digit span scores were calculated by taking the mean of the two longest lists correctly repeated. Scores were calculated separately for forward and backward digit span in both the degraded and normal conditions. These scores reflected a participant’s immediate memory capacity for unprocessed signals.

Predicted digit spans—A second score was also calculated using an algorithm that combined digit span in normal conditions and the accuracy of identifying digits in isolation when the signals were degraded. This predicted score provided an estimate of the observed digit span under the degraded speech conditions. The predicted digit span score reflects digit span recall errors that are strictly related to the inability to correctly identify digits. For example, if a participant had a digit span of three in the normal digit condition and in the pretest only identified digits correctly 60% of the time; then 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 zero. Similarly, there is only a $(.60)^3$ probability of maintaining a digit span of three, if digits are only identified correctly 40% of the time. Equation 1 illustrates the basic steps taken to calculate the predicted digit span score given the example that the digit span in the normal condition is three, and the listener misidentified digits in the pretest 40% of the time.

- a. The probability of missing the first digit of a list and having a (1) 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) and
- d. 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 zero, one, two, three, etc., the expected value of 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 three in normal conditions, but has a predicted digit span of only 1.176 in the degraded condition, due to the effect of misidentification of digits at the time of initial encoding. In the case of a listener who never misidentifies digits, the predicted digit span is equal to the digit span observed in normal conditions. The more digit misidentifications made, the greater the difference between digit span in normal conditions and the predicted digit span. In this model, it is assumed that all digits used in the pre-test are homogeneous and equally difficult to perceive.

Digit span error scoring—In order to determine whether a larger proportion of item or encoding errors in digit span recall was obtained under the degraded speech conditions, 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) (for 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 (for 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.

The digit span error analysis is most useful for quantifying the actual number of order errors compared to other types of errors. This information is desirable because order errors in immediate memory are distinctly different from other types of errors and indicate a memory processing problem that could be related to increased cognitive load. Although this analysis does include the category of item error, it is less clear what all errors assigned to this category specifically indicate. For instance, while it is probable that an error classified into the item category does in fact indicate misencoding of a digit during presentation, it is also possible that it reflects a scenario in which a digit is initially encoded correctly but is forgotten during rehearsal or serial scanning and replaced with an alternative digit. In this case, an error in the item category would actually be due to a memory processing problem or increased cognitive load rather than to a pure misidentification caused by the degraded stimuli. This is not to suggest that item errors can conceptually be order errors. Rather it only suggests that the error categorization analysis yields estimates of each category of

error. Despite the small margin of error in this analysis, it is still beneficial to systematically separate the types of errors that may occur in the digit span task.

A $2 \times 2 \times 4$ factorial design was used to determine in which stimulus condition (normal or degraded) and recall condition (forward or backward) the four types of errors were most likely to be observed. The error rate of each type of error committed by the participants was the dependent variable. Error rates were calculated by dividing the raw number of errors made by the total number of digits presented to each listener for each condition. Error rates were expressed as proportions rather than using raw scores in order to equate for the different number of digits presented in different conditions. For instance, when using the standard digit span administration procedures, more lists are administered in forward digit span recall, making it necessary to equate the conditions according to the number of digits that were presented and how many possible errors could have been made. Following this rationale, it is assumed that each possible digit could be a source of error.

Results

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

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 all the digits with 100% accuracy. Figure 2 displays a frequency distribution of the digit identification scores obtained when digits were played in isolation under degraded speech conditions. Using each participant's processed digit identification score and the normal digit spans of each participant, the predicted degraded digit spans of each participant, the predicted degraded digit spans were calculated using the procedures summarized in Equation 1.

A paired-samples *t*-test revealed no significant difference between the predicted digit spans and those observed in the degraded speech condition in either the forward or backward recall conditions. Figure 3 illustrates the mean predicted and degraded digit spans. Predicted forward digit spans ($M = 5.50$, $SD = 1.28$) were shorter than the degraded digit spans ($M = 5.78$, $SD = 1.13$). 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 degraded 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 4 shows the proportion of errors and types of errors committed by the participants in both the forward and backward recall conditions. A univariate ANOVA revealed a main effect of error type ($F(3, 416) = 8.76$, $p = .000$). Item errors occurred significantly more often than any other type of error. Table 1 displays a stimulus-response confusion matrix of the item errors that were observed when forward and backward digit spans were collected under degraded auditory conditions. The distribution of errors and confusions was not uniform. Most of the errors occurred on the digits 'four', 'nine', 'two', and 'three'.

There was also a main effect of stimulus condition ($F(1, 416) = 10.16$, $p = .002$) on the number of errors made during digit span recall. In addition, an interaction was observed between stimulus condition and error type ($F(3, 416) = 7.17$, $p = .000$). While the main

effect of recall direction approached significance ($F(1, 416) = 3.29, p = .071$), no interaction effects involving recall direction were found despite an apparent increase in order errors in the backward recall condition when the stimuli were degraded.

To assess the influence of direction of recall and stimulus condition on order errors more accurately, a separate ANOVA was run on just the order error data. This analysis revealed a significant main effect of recall direction on order errors ($F(1, 103) = 6.26, p = .014$). As shown in Figure 4, a larger proportion of order errors occurred in backward digit span recall than in forward digit span recall. However, the increase in order errors in backward digit span recall was unaffected by whether the stimuli were degraded or not ($F(1, 103) = 1.25, p = .267$).

Discussion

As expected, the results of this study demonstrate that immediate memory spans for digits decreased when the auditory stimuli are spectrally degraded and frequency-shifted using a cochlear implant simulation model. The decrease in digit span in normal-hearing participants appears to be primarily due to item errors at the time of perceptual encoding, because the observed digit spans under degraded 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 recall errors, we found that only item errors increased significantly in degraded auditory conditions.

Although the proportion of order errors increased in the backward digit span task relative to the forward digit span task, there was no significant difference between the proportion of order errors committed in degraded and normal conditions. Therefore, previous research suggesting that decreases in memory span under degraded auditory conditions are primarily due to memory processing problems caused by increased cognitive load at the time of encoding was not fully supported by the two analyses conducted in this study (Luce et al, 1983; Pichora-Fuller et al, 1995). Instead, it appears that memory performance in some types of degraded auditory conditions is most influenced by simple misidentifications at the time of encoding.

However, it should be noted that the error categorization results of this study do not exclude the possibility that some errors classified as item errors were due to problems that occur after encoding rather than during encoding. For example, participants could repeat digits that did not appear in the list simply because they did not remember what digits were heard, not because they misidentified them. However, individual data from many listeners show frequent item errors in lists much shorter than what they recalled in normal conditions, suggesting that memory load should not have been a problem. Taking this into consideration, it is likely that the true number of item errors was only slightly overestimated, if at all, in this analysis.

The item error confusions also support the conclusion that the decrease in listeners' digit spans was related to sensory-perceptual problems. Not all digits were equally confusable during digit span recall. For example, the bi-syllabic digit 'seven' was rarely confused with other digits. In contrast, confusions among the digits 'three', 'four', and 'five', which all have fricative onsets, accounted for nearly half of the item errors. Thus, these findings indicate that the perceptual confusability of digits was the largest source of error during digit span recall conducted under degraded auditory conditions modeled after the input received by cochlear implant users.

Another important finding from the error categorization analysis was that order errors did not increase when digit spans were obtained under degraded conditions. Similar to the

memory span predictions based on digit identification in isolation, this result also suggests that memory span primarily decreases in degraded auditory conditions because of errors in identifying and encoding stimuli. This is an important finding to demonstrate in a group of normal-hearing adult listeners with mature and normal memory processing skills. Examining the contribution of item and order errors in this population provides a benchmark into the role that developmental effects may have played in previous studies using pediatric cochlear implant users. In this sample of adults, fewer memory processing errors were observed than would be expected based on previous results in deaf children using cochlear implants (Burkholder & Pisoni, 2004).

Using an identical digit span error analysis on the digit span responses of pediatric cochlear implant users and normal-hearing children in clear listening conditions, Burkholder and Pisoni (2004) found that, in contrast to the adult listeners in this study, both normal-hearing children and deaf children with cochlear implants displayed a significantly greater proportion of order errors relative to other errors in both forward and backward recall. Their results provide preliminary evidence that developmental factors, in addition to factors connected to sensory deprivation and exposure to degraded auditory stimuli may be related to the problems in subvocal verbal rehearsal (Pisoni & Cleary, 2003) and serial scanning observed in deaf children using cochlear implants (Burkholder & Pisoni, 2003). Therefore, although this study replicated that of Eisenberg et al (2000) finding that overall decreases in memory span in degraded auditory conditions are not developmentally related, the present results suggest that the specific causes of these decreases (primarily item or order errors) may be developmentally related. These results also suggest that, in adult listeners exposed to degraded auditory stimuli, memory processing skills remain rather robust despite the increased cognitive load associated with manipulations of perceptual difficulty.

The ability to make the current predictions about memory span in normal-hearing adult listeners using cochlear implant simulations provides valuable insight about memory processes in deaf individuals using cochlear implants and other listeners performing memory or other cognitive tasks under degraded auditory conditions. A second benefit of utilizing acoustic simulations of cochlear implants with normal-hearing listeners is to determine how cognitive abilities such as memory can account for the large individual differences in speech perception abilities that are observed in normal-hearing listeners' exposed to this severely degraded speech. Although this question was not specifically addressed in this study, there was evidence of substantial variability in performance that would be interesting to explore further. Further investigations of individual differences in both adults' and children's abilities to perceive speech and perform cognitive tasks under severely degraded auditory conditions are important because they may have direct implications for understanding factors that influence the pediatric and adult cochlear implant users' performance with their device. Currently there are few pre-implant predictors of success with the device that are related to cognitive processes. (However, see Bergeson & Pisoni, 2004; Pisoni et al, 2000; Pisoni & Geers, 2000; Horn et al, 2004). Further investigations of cognitive influences on normal-hearing listeners' speech perception abilities under adverse auditory conditions could contribute valuable information about what factors might also be related to cochlear implant patients' abilities to learn to understand degraded speech from their device.

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Figure 1. Mean digit span scores in the degraded and normal speech conditions. Error bars represent the standard error of the mean.

Figure 2.
Frequency distribution of the digit identification scores.

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

Figure 4. Mean proportion of errors committed by participants in the digit span task under degraded speech conditions in (A) forward and (B) backward recall conditions. Error bars represent the standard error of the mean.

Stimulus-response confusion matrix for all errors classified as item errors in the digit span error analysis. The raw number of errors for each digit is shown. The total number of errors for each digit is also shown in the far-right column

Table 1

Stimulus	Response									Total errors
	1	2	3	4	5	6	7	8	9	
1	-	0	0	1	0	0	0	1	6	8
2	0	-	7	6	0	1	0	0	0	14
3	2	1	-	1	3	0	4	1	0	12
4	1	1	14	-	17	0	2	1	1	37
5	2	1	0	1	-	1	0	0	1	6
6	0	0	0	4	0	-	0	4	0	6
7	0	1	1	1	1	1	-	0	0	5
8	1	1	0	1	0	2	1	-	1	7
9	9	1	1	0	2	0	2	1	-	16