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Working Memory in Children with Cochlear Implants: Problems are in Storage, not Processing

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Abstract

Background—There is growing consensus that hearing loss and consequent amplification likely interact with cognitive systems. A phenomenon often examined in regards to these potential interactions is working memory, modeled as consisting of one component responsible for storage of information and another component responsible for processing of that information. Signal degradation associated with cochlear implants should selectively inhibit storage without affecting processing. This study examined two hypotheses: (1) A single task can be used to measure storage and processing in working memory, with recall accuracy indexing storage and rate of recall indexing processing; (2) Storage is negatively impacted for children with CIs, but not processing.

Method—Two experiments were conducted. Experiment 1 included adults and children, 8 and 6 years of age, with NH. Procedures tested the prediction that accuracy of recall could index storage and rate of recall could index processing. Both measures were obtained during a serial-recall task using word lists designed to manipulate storage and processing demands independently: non-rhyming nouns were the standard condition; rhyming nouns were predicted to diminish storage capacity; and non-rhyming adjectives were predicted to increase processing load. Experiment 2 included 98 8-year-olds, 48 with NH and 50 with CIs, in the same serial-recall task using the non-rhyming and rhyming nouns.

Results—Experiment 1 showed that recall accuracy was poorest for the rhyming nouns and rate of recall was slowest for the non-rhyming adjectives, demonstrating that storage and processing can be indexed separately within a single task. In Experiment 2, children with CIs showed less accurate recall of serial order than children with NH, but rate of recall did not differ. Recall accuracy and rate of recall were not correlated in either experiment, reflecting independence of these mechanisms.

Conclusions—It is possible to measure the operations of storage and processing mechanisms in working memory in a single task, and only storage is impaired for children with CIs. These findings suggest that research and clinical efforts should focus on enhancing the saliency of representation for children with CIs. Direct instruction of syntax and semantics could facilitate storage in real-world working memory tasks.

Keywords

Hearing; cognition; working memory; development; cochlear implants; children

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1. Introduction

Congenital hearing loss has historically had the power to impose a heavy toll on a child's ability to develop spoken language, but two recent technological advances have improved that prognosis. First, novel methods of screening newborns and accurately measuring thresholds have reduced the age at which treatment can commence. Whereas hearing loss was often not even suspected until children were 3 or 4 years old, the standard of care is now for infants to be diagnosed with hearing loss and fit with high-powered hearing aids within the first couple months of life. The second technological advance improving prognosis for deaf children is the cochlear implant. This device is able to bypass the damaged transduction cells of the cochlea, and stimulate the auditory nerve directly with electrical signals. These signals are, however, extremely impoverished in frequency structure compared to what the normally functioning cochlea provides. Consequently, their ability to support refined phonological representations is highly constrained.

Precisely because cochlear implants (CIs) are such rudimentary alternatives for natural hearing, it was not clear from the outset that they would be effective in treating hearing loss in children. Therefore, early research efforts involving implants and children were focused on device efficacy, investigating whether or not CIs provide adequate support for the development of spoken language [1-3], and what demographic factors account for any variability in outcomes [4,5]. More recently, however, it has become clear that research is also needed to examine the interactions that likely exist between the sorts of signals provided by these devices and cognitive functions. Although children with CIs have made remarkable strides in their abilities to learn spoken language, their average performance across measures remains roughly one standard deviation below the means of their peers with normal hearing [6,7], and variability is large. In addition, the more complex the language skill, the greater the discrepancy between scores of children with CIs and those with normal hearing [8]. Similarly, the more a cognitive task relies especially on phonological codes, the greater the difference in scores between children with normal hearing and those with hearing loss [9]. These findings suggest there may be an interaction between the quality of the signal and cognitive functioning for these children. That suggestion finds support from studies with elderly subjects, where it has been shown that the common view that cognitive functioning declines with age is actually explained by age-related declines in access to sensory information [10]. The current study was designed to improve our collective understanding of how signal processing in CIs and cognitive functioning interact for deaf children.

1.1. Working memory

One cognitive facility of particular focus when it comes to children with CIs is working memory. This construct refers to a short-term memory mechanism that stores and processes information in the service of completing mental operations [11]. Models of working memory can be divided into two broad categories based on whether they assume a single component used for both temporary storage and on-line processing, or assume that multiple and quasi-independent subsystems communicate to handle these operations. Examples of single-component systems are described by Daneman and Carpenter [12], Daneman and Merikle [13], and Just and Carpenter [14]. These models of working memory propose that one component is shared between storage and processing such that the more resources get allocated to one of these functions, the more the other one shows diminishment in efficiency.

Multiple-component accounts of working memory are most notably represented by the model proposed by Baddeley [15-17]. This model has several well-defined subsystems. One subsystem, termed the phonological loop, is responsible for the recovery of phonological structure from speech signals, which is used for storage. This stored information can then be processed by a separate component, known as the central executive. Although a subsystem itself, the central executive is also responsible for directing the operations of all other subsystems, including the phonological loop. According to these models, an individual's performance involving one subsystem would not severely impact operations of another subsystem because they are independent, except for the supervisory role performed by the central executive.

1.2. Storage

Evidence for the role of phonological structure in temporary storage is provided by studies of short-term recall for lists of words that either rhyme or do not rhyme. These studies have consistently demonstrated that recall is more accurate for lists of phonologically distinct words, such as those that do not rhyme, than for phonologically similar words, such as those that rhyme [18-21]. The interpretation of those results has been that phonologically distinct words permit a more robust representation to be used in storage than do phonologically similar words.

Further evidence for the importance of recovering a robust phonological representation is provided by studies of short-term recall by children with dyslexia. Several studies have reported that these children show a diminished advantage for phonologically dissimilar over similar words in their short-term recall, compared to their peers who read typically [22-24]. Those outcomes are interpreted as reflecting the fact that poor readers are impaired in their abilities to recover phonological structure from the speech signal, so all verbal material is processed as if it were phonologically similar. That interpretation is supported by still other studies that, although not explicitly comparing recall of phonologically similar and dissimilar words, have nonetheless demonstrated deficits in recall of word or syllable strings by individuals with dyslexia, compared to individuals without dyslexia (e.g., [22-27]).Taken together, this collection of results is viewed as reflecting poor recovery of robust phonological representations on the part of children with dyslexia, which hinders the operations of working memory. This situation highlights the importance of being able to recover a salient representation, something that children with CIs likely are not able to do, either.

1.3. Processing

There are effects on processing that arise from the difficulty of the operations to be performed, and are generally referred to as the processing load or demand. Examples of processing demands come from studies of syntactic parsing. In general, response times to complex sentences are longer than those to syntactically simpler sentences, even when sentences are matched on length. It requires greater time to read sentences with complex syntax than it does to read sentences of the same length with the same words, but simpler syntax (e.g., [28]). Furthermore, reading of individual words requires more time at points in the sentence of particular complexity than at other points, where syntax is simpler [29-31]. These outcomes specifically for syntactic parsing match more general results demonstrating that response time can be a sensitive indicator of processing [32-35]. In particular, the suggestion has been made that time reflects cognitive load because it indicates how long attention must be directed towards a particular function [36,37].

1.4. Assessing interactions of storage and processing

Gauging the strength of interaction between storage and processing provides a way to evaluate whether single- or multiple-component models of working memory best fit the data. Single-component models predict strong interactions; multiple-component models predict only weak interactions. To test for potential interactions between storage and processing, research participants have usually been asked to perform separate operations simultaneously. A study by Duff and Logie [38] provides a good example of this paradigm. In that study, adults were presented with increasingly longer printed lists of sentences during 10-s trials. In one task they were asked to judge the plausibility of each sentence (e.g., *The days are longer in summer* and *The tabletop makes dinner*). *Verification span* was the term given to the longest list for which participants could correctly judge plausibility for all sentences. In the other task participants had to recall the last word of each sentence in the list, and *word span* was the term given to the longest list for which participants could correctly recall all sentence-ending words. In a third condition, participants needed to perform the verification and word recall tasks concurrently. Decrements in performance for the combined task compared to separate tasks were used to gauge the interaction of storage and processing. Mean decrements for both verification and word span were 30 percent, with some adults showing no decrement in performance at all. It was concluded that this level of interaction was too weak to support single-component models of working memory. Rather, it seemed the outcomes were best explained by a multiple-component model such as that of Baddeley in which separate subsystems handled storage and processing. The small decrements observed could be explained by the idea that a central executive primarily responsible for processing has the additional duty of coordinating performance across subsystems.

1.5. Implications for research and clinical practice with children with cochlear implants

Deaf children who get cochlear implants (CIs) show wide variability in how well they learn spoken language, and Pisoni has consistently argued that the sources of that variability will not be understood until interactions between spoken language and cognitive functions can be taken into account [39-41]. In support of that assertion, Pisoni and Geers [42] reported correlation coefficients in the range of .52 to .71 between digit span and numerous measures of spoken language ability, such as word recognition, speech intelligibility and auditory comprehension for children with CIs. Thus, there are reasonably strong relations between working memory and spoken language, at least for children with CIs. Consequently, it is important that the nature of working memory be well-defined, especially as it operates for children with CIs. For example, if processing deficits accounted for these moderate correlations, then training explicitly to improve processing would be warranted. Tools exist for training the processing capacity of working memory specifically, and have even been used with deaf children [43]. A problem with this aspect of working memory might arise as a result of prolonged periods of auditory deprivation: If natural opportunities for developing auditory working memory do not exist, young children may be impaired in these abilities.

On the other hand, if decrements in working memory capacity for children with CIs rest entirely on their abilities to recover salient phonological representations from the acoustic speech signal and use those representations for storage, then research efforts should be focused on finding ways to provide more detailed signal structure to children with CIs. At the same time, clinical efforts would best be focused on providing phonological training [44]. The possibility that this situation may better explain conditions for children with hearing loss arises from work with adults with progressive hearing loss showing that even as phonological representations deteriorate with advancing loss, processing capacity within working memory remains unchanged [45].

1.6. The Current Study

This study was conducted to test two related hypotheses, in two separate experiments. The first hypothesis was that storage and processing within working memory could be assessed separately within a single task. Certainly these two operations have been measured separately in research with adults (e.g., [14,38,46], but the aim in the current study was to do so within a single task. Earlier experiments seeking to quantify the operations of each of these aspects of working memory typically used printed materials, and often involved syntactic comprehension. Because the objective of the first experiment in the current study was to develop methods with normal-hearing listeners that could be used in a second experiment with deaf children, any procedure requiring reading or syntactic comprehension would be a poor choice. Children with hearing loss would be expected to perform more poorly on tasks involving either or both of those skills than children with normal hearing. Instead, serial recall for closed sets of words was chosen as the task in the current experiments, a method also used in past experiments to evaluate working memory (e.g., [18-21,47,48]). Specific procedures in the current study involved participants hearing lists of consonant-vowel-consonant words, and recalling the order by reordering pictures representing those words. Using word lists eliminates potential effects of differences in syntactic abilities; using closed sets eliminates potential effects of vocabulary knowledge. The use of closed sets of words also permitted confirmation prior to conducting the serial recall task that each word was accurately recognized by these children with hearing loss. Thus, outcomes were not tainted by recognition abilities.

Another consideration in this study prompted the use of tapping on pictures instead of verbal recall as a response format in order to eliminate the need for motor programming of verbal responses. The eventual goal for these procedures was to establish them as appropriate measures to use with children with CIs. For those children, motor programming for speech is likely more effortful than for children with normal hearing, so that factor would influence outcomes if verbal responses were required. The procedure of picture pointing or tapping has been used before, and intra-subject reliability demonstrated [20]. Accuracy of recall was evaluated in the current study as a measure of storage, and was presumed to depend strongly on participants' abilities to recover phonological structure. Rate of recall was used as an index of processing difficulty.

The second hypothesis tested in this study was that children with CIs would demonstrate deficits in storage, but not in processing. Sensori-neural hearing loss involves a dearth of the cells in the cochlea responsible for transduction of mechanical signals into electrical signals. That impairment, as well as subsequent cochlear implantation, could reasonably be expected to constrain a child's access to phonological structure (including explicitly phonemic structure) in the acoustic speech signal. Indeed, several studies have revealed problems in recovering phonological structure on the part of children with hearing loss [9,49-51]. However, given the peripheral nature of the deficit, there is no reason to suspect that hearing loss (and implantation) would induce a concomitant cognitive impairment. Thus, the claim made here is that processing in working memory should remain largely intact in children who use cochlear implants. The significance of finding evidence to support or refute this hypothesis is that outcomes should help direct future research and clinical priorities.

2. Experiment 1

This first experiment tested the hypothesis that storage and processing in working memory can be measured separately using a single task. This goal was accomplished by asking participants to listen to three closed sets of words, and having them rearrange pictures representing those words on a computer monitor to indicate the order recalled. Using closed sets of words diminished concern that storage or processing would be influenced by word familiarity or frequency of occurrence within the ambient language. Informing participants of the words to be used meant that all words in the set became equal in probability of occurrence. Evidence of this effect has been available for decades, largely owing to work showing that word-frequency effects for speech recognition in noise are eliminated when closed sets are used [52]. Difficulty in storage was manipulated by varying the phonological similarity of the words: storage is less effective for phonologically similar than dissimilar words. Processing difficulty was manipulated by varying word class: nouns versus adjectives. Nouns can be represented transparently with pictures, adjectives can not. With nouns (*dog*, *house*, *rake*) pictures of the actual items can be shown. With adjectives (*hot*, *deep*, *sad*), the trait described by the word must be inferred from the picture: for example, a cup with steam rising from it is *hot*. Thus, there was a greater processing load imposed by the adjectives than by the nouns because the amount of time that attention needed to be directed to the items was longer.

Two dependent measures were collected from the data in this study: accuracy of recall and rate of recall. One prediction was that accuracy should be poorer for the rhyming words, compared to the non-rhyming words, because rhyming words are phonologically similar so it is hard to recover salient representations of these items. Accuracy was not predicted to be any poorer for the non-rhyming adjectives than for the non-rhyming nouns because both sets of words are phonologically dissimilar. The second prediction regarding outcomes was that rate of responding would be slower for adjectives than for nouns because of the additional load imposed by the adjectives: With each response, the listener needs to recreate how the lexical item relates to the associated picture. However, response rates were not predicted to be any slower for rhyming than non-rhyming nouns.

Adults and children of two ages (6 and 8 years) served as listeners in the present experiment. A principal reason for including these age groups was that the aim of this experiment was to develop methods for indexing storage and processing in working memory for children with CIs. In the second experiment, 8-year-old children with and without hearing loss (and so CIs) were tested. Therefore, 8-year-olds were recruited for this first experiment, along with younger children, to provide benchmarks against which to compare performance of children in the next experiment. Because this experiment was conducted prior to the one with the children with CIs, there was no way to match those children with younger children on a relevant language variable. It seemed reasonable to include a younger group nonetheless. Adults were included to see if results were consistent across the lifespan. In particular, if evidence were found to support a claim of a single- or multiple-component model of working memory in children, does that model hold for adults or is there a developmental change waiting for these young children? The answer to that question could affect the way that outcomes for children with CIs are interpreted.

2.1. Method

2.1.1. Listeners

Twenty-four adults between the ages of 18 and 40 years, 25 8-year-olds, and 25 6-year-olds participated. Other studies reported Cohen's *d*s for recall accuracy comparing scores of adults and 8-year-olds of roughly 1.00 (e.g., [20]). Based on those reports, these sample sizes were adequate for obtaining statistically significant age effects, if they exist. The 8-year-olds in this study ranged in age from 7 years, 11 months to 8 years, 5 months (Mean = 8 years, 2 months) and the 6-year-olds ranged in age from 5 years, 11 months to 6 years, 5 months (Mean = 6 years, 2 months). All adults and the parents of children who participated signed consent forms beforehand.

None of the listeners, or their parents in the case of children, reported any history of hearing, speech or language disorder, and parents reported that their children were free from significant histories of otitis media, defined as six or more episodes during the first three years of life. Nonetheless, screenings were conducted as an extra assurance that no participants had any undiagnosed problems. First, all listeners needed to pass hearing screenings consisting of the pure tones .5, 1, 2, 4, and 6 kHz presented at 25 dB HL to each ear separately. In addition, adults were given the reading subtest of the Wide Range Achievement Test 4 (WRAT; [53]) and had to demonstrate better than a 12th-grade reading level. Requiring that adults had literacy skills at this level was considered an adequate method of ensuring that they also had mature phonological processing abilities. Children were not given the Wide Range Achievement Test 4, but were given the Goldman Fristoe 2 Test of Articulation [54]. They were required to score at or better than the 30th percentile for their age in order to participate. The 8-year-olds were all error free. The 6-year-olds ranged from zero to four errors. These numbers indicate that the mean score for 6-year-olds was at the 62nd percentile (SD = 9), and the lowest-scoring child was at the 42nd percentile.

Children were also given the Peabody Picture Vocabulary Test–4th Edition (PPVT; [55]) as a check on their general language abilities. They needed to achieve a standard score of at least 92 (30th percentile) for their age to remain in the study. The average PPVT standard score across 8-year-olds was 114 (SD = 9), which corresponds to the 82nd percentile. The average PPVT standard score across 6-year-olds was 116 (SD = 10), which corresponds to the 86th percentile. These scores indicate that these children had receptive vocabularies roughly 1 SD above the mean of the normative sample used by the test authors.

Socio-economic status (SES) was indexed for the children, but not for the adults. Most of the adults were full-time university students, and SES can be artificially low for students. For children, SES is positively correlated with language skills in general (e.g., [56]), and with phonological processing abilities in particular [57,58]. To index SES, a metric reported by Nittrouer et al. [51] was used. It incorporates occupational status and educational level to compute an overall SES score ranging from 1 to 64. Mean SES scores (and SDs) were 36 (13) and 35 (13) for 8- and 6-year-olds, respectively. This difference was not statistically significant. Scores in this range suggest that these children predominantly came from middle-class households.

2.1.2. Equipment—All testing took place in a soundproof booth, with the computer that controlled stimulus presentation in an adjacent room. Hearing was screened with a Welch Allyn TM262 audiometer using TDH-39 headphones. Stimuli were stored on a computer and presented through a Creative Labs Soundblaster card, a Samson headphone amplifier, and AKG-K141 headphones. This system has a flat frequency response and low noise. Custom-written software controlled the audio and visual presentation of the stimuli. Order of items in a list was randomized by the software before each presentation. Computer graphics (presented at 200 × 200 pixels) were used to represent each word, letter, and number. Responses were collected by having the listener touch the pictures, shown on the computer monitor, in the order recalled. A 21-in. widescreen, touchscreen monitor (HP Compaq L2105TM) was used for this purpose.

2.1.3. Stimuli—Three sets of eight stimuli each were constructed: non-rhyming nouns, non-rhyming adjectives, and rhyming nouns. All stimuli had sampling rates of 22.05 kHz with 10-kHz low-pass filtering and 16-bit digitization. Word samples were spoken by a man, who recorded five samples of each word in random order. The non-rhyming (NON) nouns were *ball, coat, dog, ham, pack, rake, seed,* and *teen*. The rhyming (RHY) nouns were *bat, cat, hat, mat, gnat, Pat* (represented by a picture of a woman), *rat,* and *vat.* The adjectives (ADJ) were *big* (represented by a picture of a big dog next to a small dog), *deep* (a deep swimming pool), *full* (a full glass of water), *hot* (a steaming cup of coffee), *neat* (a neat desk), *sad* (a crying child), *thin* (a very thin man), and *wet* (a wet cat). Specific tokens of the words to be used were selected from the larger pool so that words would match each other closely in duration, fundamental frequency, and intonation. All were roughly 500 ms in length, had a fundamental frequency of 110, and had flat/falling intonation contours.

All words were selected to be nouns or adjectives that could be represented with a picture. They were all consonant-vowel-consonant in structure. Although words could not be equated on frequency of occurrence because of the restrictions on list construction, listeners were familiarized with the words to be used before testing. In this way *a priori* probabilities of occurrence were equated. And even though it was not used in list construction, mean frequency of occurrence per one million words was calculated, using counts of Brysbaert and New [59]. These means were 51 for NON, 26 for RHY, and 156 for ADJ.

Samples of eight non-rhyming letters (*F, H, K, L, Q, R, S, Y*) were used in practice. These were produced by the same speaker who produced the word samples. The numerals *1* through *8* were also used for practice, but these were not presented auditorily, so digitized audio samples were not needed.

Lists of different lengths were used for adults and children in order to equate the processing load introduced by list length. List length was derived by adding two items to the mean forward digit spans of adults and children between 6- and 8-years-old [60,61]. That meant that 8-item lists were appropriate for adults, but children could more appropriately handle lists of only six items. Items removed from children's lists were those with the lowest frequency of occurrence. The words *teen* and *seed* were removed from the set of NON stimuli, *vat* and *gnat* were removed from RHY, and *neat* and *thin* were removed from ADJ. The letters *K* and *L* and numerals *7* and *8* were removed from the practice lists.

2.1.4. Procedures—All testing took place in single sessions of 45 minutes to an hour, and all procedures were approved by the local Institutional Review Board.

2.1.4.1. Screenings: The hearing screening and Goldman-Fristoe or WRAT were always administered first, followed by the serial recall task. After the serial recall task, the PPVT was administered to children. Items in the serial recall task were presented via headphones at a peak intensity of 68 dB SPL. The experimenter always sat on the listener's left. The monitor was positioned directly in front of the listener, 6 in. from the edge of the table. Pictures representing the letters (training) or words (testing) appeared across the top of the monitor before the stimuli were played. After the list items were heard, listeners touched pictures in the order recalled. As each image was touched, it dropped to the vertical middle of the monitor, into the next position going from left to right. The order of pictures could not subsequently be changed. Listeners had to keep their hands on the table in front of the monitor during audio presentation. There could be no articulatory movement of any kind (voiced or silent) between hearing the items and touching all the images. Software recorded both the order of presentation and the listener's responses, and calculated how much time elapsed between the end of the final word and the touch of the final image. Testing with each stimulus type consisted of ten lists, and the software generated a new order for each list.

2.1.4.2. Baseline response rates: The first task during testing was designed to collect a baseline of response time. Colored squares with the numerals *1* through *8* (or in the case of 6-and 8-year-olds, *1* through *6*) were displayed in a row in random order across the top of the monitor. The listener was instructed to touch the numerals in order from left to right across the screen. The experimenter demonstrated one time, and then the listener performed the task four times as practice. Listeners were instructed to touch the numbers as fast as they comfortably could. They were told to keep their hands flat on the table until the numbers appeared on the screen, and not to talk or whisper until they were done with the task. After this practice, the listener performed the task five times. From those five trials, a mean time was computed and used as the baseline for calculating ‘corrected’ response times during testing.

Next the listener was instructed to touch the numbers in numerical order, as fast as they comfortably could. This was also performed five times, and was done to provide practice touching images in an order other than left to right.

2.1.4.3. Training and pre-test: The next task was practice with the test procedures using the letter strings. The images of the letters appeared in random order across the top of the monitor, and then a list of letters was presented over headphones in an order different from the one shown, at a rate of one per second. The experimenter demonstrated how to touch each image in the order heard as quickly as possible. The listener was then provided with five practice trials. Feedback regarding accuracy of recall was not provided, but listeners were reminded, if need be, to keep their hands on the table during stimulus presentation and to refrain from any articulatory movements until after the reordering task was completed.

The experimenter then moved to the first stimulus type to be used in testing, and made sure the listener recognized each item. To do this, all images were displayed on the screen, and the words were played one at a time over the headphones. After each word was played, the experimenter touched the correct image. The software then displayed the images in a different order, and again played each word one at a time. After each presentation the listener needed to touch the correct image. Feedback was provided if an error was made on the first round. On a second round of presentation, listeners were required to select all images without error. No feedback was provided this time. If a listener made an error on any item, that listener was dismissed. This pre-test was designed to make sure listeners recognized each item, and was given just prior to testing with each of the three stimulus sets.

2.1.4.4. Testing and post-test: Testing with each set of items took place immediately after the pre-test with those items. Testing consisted of ten lists, and stimuli were presented at a rate of one per second. After testing with each stimulus type, a post-test identical to the pre-test was given to ensure that listeners had maintained correct associations between images and words through testing. If a listener was unable to match even one word to the corresponding image, that individual's data were not included in the analyses.

2.1.4.5. Scoring: After testing, the software automatically compared the words recalled in each position for each list to the word orders actually presented. A word was considered wrong if it was recalled in the wrong list position. The total number of errors across list positions (out of 80 or 60, depending on whether adults or children were tested) was computed. Total error scores were next transformed into percent correct scores by multiplying the proportion of correct responses by 100. That value was used to index accuracy. The software also recorded the time required for responding to each list, and computed the mean time across the 10 lists within the condition. A corrected response time for each condition was obtained for each speaker by subtracting the baseline response time from the mean response time (across the 10 trials) for testing in each condition. From both the uncorrected and corrected response times, rate of responding per item was derived by dividing time by the number of list items. Effects of list position on responding were not examined in this experiment because other work with children had shown that they demonstrate the advantages for early and late list positions common in adults' responding [20,62]. Moreover, it is difficult to compare position effects when listeners of different ages hear lists of different lengths.

2.2. Results

One eight-year-old failed the pre-test naming task for the RHY condition, and one six-year-old failed the post-test naming task for the ADJ condition, so their data were not included. Thus, data from 24 8-year-olds and 24 6-year-olds were included in the data analysis.

Data were screened to check for homogeneity of variance across groups, and normality. Both conditions were satisfied with these data. In the reporting to follow, precise statistical outcomes are reported when $p < .10$; elsewise, outcomes are reported as *not significant*. Bonferroni adjustments for multiple comparisons were applied to all post hoc *t* tests.

2.2.1. Accuracy of recall—It had been hypothesized that this measure would index storage capacity, and that storage would be poorest for the RHY condition because the words are phonologically similar. Accordingly, predictions were: (1) Accuracy of recall for NON and ADJ words would be similar because words in both these sets are phonologically dissimilar. (2) Recall should be poorer for RHY than for NON and ADJ because RHY words are phonologically similar.

Table 1 shows condition means for percent correct recall of words across list positions, for each group separately. A two-way, repeated-measures analysis of variance (ANOVA) was performed on these accuracy measures, with age as the between-subjects factor and condition as the within-subjects factor. The main effect of age was significant, $F(2,69) = 22.06$, $p < .001$, $\eta^2 = .390$. Post hoc *t* tests revealed that overall accuracy of recall was poorer for 6-year-olds than for 8-year-olds or adults ($p < .001$ for both), but overall accuracy was not significantly different for 8-year-olds and adults. The main effect of condition was also significant, $F(2,138) = 17.08$, $p < .001$, $\eta^2 = .198$. The Age × Condition interaction was not significant. From these results, it can be concluded that 8-year-olds and adults were similar overall in their abilities to recall presentation order for strings of items presented auditorily, but 6-year-olds were poorer at recall, and there was an overall difference across conditions. However, further analyses were needed to understand the nature of those effects.

In order to understand condition effects better and really test the predictions made for these data, two *t* tests were done for each age group separately. First, scores for the NON and ADJ conditions were compared. Lack of statistical significance for these comparisons would support the first prediction, that listeners would show similar storage capacities for these words because storage depends on phonological dissimilarity and listeners' abilities to use phonological structure for storage in working memory. For 6- and 8-year-olds, this prediction was met: *t* tests comparing scores for the NON and ADJ conditions were not significant. For adults, however, a significant difference was observed, $t(23) = 2.13$, $p = .044$, indicating that recall was more accurate for the NON than for the ADJ condition. Thus, the prediction was not entirely met.

To test the second prediction, that accuracy should be poorer for the RHY condition than for the NON and ADJ conditions, *t* tests were performed for each age group separately, comparing scores for RHY and individual means across the NON and ADJ conditions. Significant effects were observed for this comparison for all three age groups: 6-year-olds, $t(23) = 2.32$, $p = .030$; 8-year-olds, $t(23) = 4.85$, $p < .001$; and adults, $t(23) = 2.56$, $p = .017$. Thus, this prediction was met for all groups.

2.2.2. Rate of responding—First, rates for the baseline condition were examined to get an indication of overall response rates for adults and children. When simply touching numbers from left to right, adults responded at a rate of 249 ms/item (SD = 39 ms); 8-year-olds responded at a rate of 310 ms/item (SD = 67 ms); and 6-year-olds responded at a rate of 413 ms/item (SD = 115 ms). Thus, there was a developmental increase in speed of responding, a trend supported by a significant effect of age in a one-way ANOVA, $F(2,69) = 25.79$, $p < .001$. Furthermore, all post-hoc *t* tests comparing groups were significant, with $p = .032$ for adults *v*. 8-year-olds, and $p < .001$ for all other comparisons.

Even though that developmental trend was observed, it remained unclear whether baseline rates needed to be used in calculations. Table 2 shows mean uncorrected rates for each age group, across all three word conditions, as well as mean rates when corrected for the baseline condition. Although adults were somewhat faster than children, particularly 6-year-olds, for uncorrected rates, an over-correction appears to result from using baseline rates to try to control for age-related differences in simple response times. As a result, the decision was made to use uncorrected rates in further statistical analyses.

Table 3 shows means for each condition for uncorrected rates (henceforth, simply *rates*). A two-way, repeated-measures ANOVA showed no significant age effect, which further supported the decision to use these uncorrected rates in statistical analyses. There was, however, a significant effect of condition, $F(2,138) = 20.44$, $p < .001$, $\eta^2 = .229$. The Age × Condition interaction was not significant. Differences in response rates across conditions were examined next, for each age group separately.

It had been hypothesized that response time could be used to index processing difficulty, and two specific predictions stemmed from that hypothesis: (1) There should be no difference in response rates for NON and RHY words because even though RHY words do not provide as salient of a representation as NON, they impose no greater processing demands. (2) However, response rates should be slower for ADJ than for either of the sets of nouns because these stimuli placed a greater load on processing. In order to test these predictions, two *t* tests were done for each age group separately. First, response rates were compared for NON and RHY words. No significant differences were found. Second, response rates were compared for ADJ and individual means across NON and RHY words. Here, significant differences were found for all age groups: 6-year-olds, $t(23) = 2.79$, $p = .010$; 8-year-olds, $t(23) = 2.67$, $p = .014$; and adults, $t(23) = 5.86$, $p < .001$. Thus, response rates across conditions varied, as they had been predicted to vary based on list design. Consequently it seems fair to conclude that response rates serve as reliable metrics of processing difficulty.

2.2.3. Recall accuracy and response rate: Is there a relationship?—An important question to be answered by the current study concerned whether or not recall accuracy and rate of responding were related, because the claim that storage and processing were independent hinged on there being a lack of significant relationship between these two measures. To test for this potential relationship, Pearson product-moment correlation coefficients were computed for each age group separately, for each condition. Only one of the nine coefficients was significant: that of NON words for 8-year-olds, $r(24) = -.564$, $p = .004$. This correlation indicates that slower responding was associated with less accurate recall.

Correlation coefficients were also computed for each condition, across age groups. The only condition to show a significant effect was NON, $r(72) = -.362$, $p = .002$, but it indicated only a mild relationship between the two measures. That significant correlation across groups likely arose from the strong relationship found for 8-year-olds alone.

Finally, it is possible for condition means of any two measures to be correlated, even when scores within conditions are not. When that combination of outcomes is observed, it suggests that there is a relationship between the measures, but within-condition variability is too great to allow it to be observed at the individual condition level. If that were found with these data, it would mean that storage and processing develop in a related manner, even though it is hard to find evidence to that effect within each condition. To test for that possibility, condition means for recall accuracy and response rate for each group were used to compute a Pearson product-moment correlation coefficient. It was not significant, so it is fair to conclude that these two measures were not related. That outcome provides support for the suggestion that storage and processing within working memory develop in a largely independent manner.

2.2.4. Vocabulary knowledge: Is it related to working memory capacity?—One final correlation analysis was conducted. It was just for children, and involved their PPVT scores. Closed sets of words were used as stimuli in this experiment to minimize the influence of vocabulary knowledge on recall. Nonetheless, it seemed worthwhile to examine if the desired goal was achieved. Accordingly, Pearson product-moment correlation coefficients were computed between PPVT scores and accuracy scores for each condition separately, and between PPVT scores and response rates for each condition separately. None of these correlation coefficients was significant. Thus, for this task in which order recall was examined for closed sets of words, no relationship was found between vocabulary knowledge and working memory. Had open sets of words been used, this outcome may well have been different.

2.3. Discussion

The purpose of this first experiment was to test whether separate measures obtained from a single task could be used to index storage and processing in working memory. The central focus of this work was on how working memory is affected by the constraints imposed by the sorts of signals available to children with CIs. The fact that cochlear implants are able to provide only impoverished signals to the auditory system makes it highly unlikely that phonological structure can be recovered optimally, so storage is predicted to be hindered for children with CIs. If working memory is best modeled as a single-component system, poor storage capacity would have deleterious consequences for processing, as well. If working memory is more appropriately modeled as a multi-component system, poor storage capacity should not hinder the processing capabilities of children with CIs.

The results of this first experiment generally supported the hypotheses offered for what would be found if working memory were best modeled as a multiple-component system, and if, accordingly, storage and processing could be evaluated separately. First, across most listeners, recall accuracy was similar for the non-rhyming nouns and adjectives, but poorer for the rhyming nouns. And second, response rates were slowest for adjectives, which had been selected expressly to impose the greatest processing load during recall. Significant correlation coefficients between recall accuracy and response rates were observed for only one of the three word sets, and for only one age group when computed separately. These outcomes indicate that considerable independence exists between storage and processing capacity, suggesting that these two functions of working memory can be assessed separately within a single task.

Although not entirely unanticipated, some interesting age effects were observed, as well. Adults showed especially well-honed sensitivity to phonological structure. Adults and 8-year-olds showed similar accuracy for the recall of adjectives, but adults performed significantly better with the non-rhyming nouns than they did with the adjectives. Eight-year-olds' recall accuracy was similar for both sets of these non-rhyming words, and similar to adults' performance with adjectives. The finding for adults suggests that storage and processing might not be entirely separate, at least not for mature and highly skilled language users: When processing demands were high (as was the case for adjectives), adults' superior abilities to recover phonological structure were slightly hindered compared to what those abilities were when processing demands were lower (as was the case for non-rhyming nouns). Nonetheless, no correlations between recall accuracy and response rates reached statistical significance for adults, for any condition. Thus, evidence of a slight interaction between storage and processing for adults mirrors results of others, such as Duff and Logie

[38]. Those investigators concluded that the small interactions between storage and processing found for adults reflected the additional supervisory role played by the central executive. For children, the population with which this study was most concerned, evidence of separate components handling storage and processing was clearly found.

An attempt was made to minimize the potential of word frequency influencing outcomes in this experiment by equating *a priori* probabilities of occurrence within lists through the use of closed sets, and it appears the approach worked. If word frequency influenced responding in spite of the suggestion that using closed sets should prohibit the effect, then it could reasonably be expected that processing would be most strongly influenced. In that case the list with the highest mean frequency of occurrence should have had the fastest response rates. In fact, the opposite was true: response rates were slowest for the ADJ condition. It is clear that having the highest frequency of occurrence provided no advantage for recall accuracy, either. In fact, adults, who should be more sensitive to frequency of occurrence effects than children, showed a small decrement in recall accuracy for the ADJ condition, compared to NON. Thus, using closed sets of words seemed to have the desired consequence of equating eliminating word frequency effects.

In conclusion, this study sought to test the plausibility of separately assessing storage and processing in working memory. Recall accuracy was used to measure storage and response rates were used to measure processing. Two hypotheses were posed about what would be found, if indeed these measures gauged operations of these two components separately. All predictions related to those hypotheses were generally met. These outcomes should enhance our abilities to explore relationships between hearing and cognition.

3. Experiment 2

This second experiment was conducted to evaluate storage and processing of information in working memory for children with CIs. Methods from the first experiment were used, but additional measures were collected in order to examine possible sources of variance in storage and processing found for these children, especially those with CIs. A complete account of the sources of variance in working memory for children with CIs should help set future directions for research and intervention by indicating what explains their abilities to store and process information in working memory.

The primary hypothesis explored in this experiment was that storage should be negatively impacted by hearing loss and subsequent cochlear implantation, but processing should be largely unaffected. Of course, this hypothesis hinges on which model of working memory best describes the phenomenon: a single- or a multiple-component model. In single-component models, degradation in storage would necessarily interfere with processing, as well. So if single-component models best represent working memory, decrements in storage introduced by the degraded signal quality available through CIs would affect processing. In multiple-component models, on the other hand, that sort of interaction would not be present. Evidence from Experiment 1 favored multiple-component models of working memory, so only storage was predicted to be impaired for children with CIs.

3.1. Method

3.1.1. Listeners—Ninety-eight children participated in this second experiment: 48 with normal hearing (NH) and 50 with severe-to-profound hearing loss who wore CIs. Roughly twice as many participants were included in each group in this experiment, compared to the first, because it was anticipated that variability would be greater due to the inclusion of a group of children with hearing loss. In addition, larger sample sizes would strengthen planned correlation and regression analyses.

All children were close to 8 years of age at the time of testing. Means (and SDs) were 8 years, 5 months (4 months) for children with NH and 8 years, 7 months (5 months) for children with CIs. Twenty-six children in each group were girls. The same metric as that used in Experiment 1 was used to index SES. Mean SES scores (and SDs) were 35 (14) and 33 (11) for children with NH and CIs, respectively. This difference was not statistically significant, and these values were similar to those of children in Experiment 1.

Of the children with CIs, 80 percent were identified with hearing loss before 12 months of age. The remaining 20 percent were identified before 24 months of age. All were presumed to have had hearing loss since birth. The mean age for receiving a first implant was 22 months of age, but age of first implantation was highly skewed. In fact, 80 percent of these children had their first implant before their second birthday. Mean length of CI experience was 81 months (SD = 17 months). Thirty-two of the 50 children with CIs had a second implant, and the mean age of receiving that CI was 46 months of age (SD = 21 months). All children used spoken language exclusively, and had been in mainstream educational environments since kindergarten. Therefore, the children with CIs were receiving similar reading instruction to the children with NH.

3.1.2. Equipment—Mostly the same equipment as that used in Experiment 1 was used in this experiment. However, instead of headphones, stimuli were presented through a Roland MA-12C powered speaker. Stimuli for the phonological awareness task were audio-visual, and a monitor separate from the touchscreen used for the serial recall task was used for presentation.

3.1.3. Stimuli—The NON and RHY words used with children in Experiment 1 were used in this second experiment. The ADJ words were not included because the goal of this experiment was to see if processing speech signals through a CI diminishes storage or processing capabilities within working memory. Those effects would present themselves as poorer accuracy or slower response rates for children with CIs compared to children with NH, and those effects should be measurable for lists on which children with NH perform well.

In addition to the serial recall tasks with these word lists, four other measures were collected to be used as predictor variables in correlation and regression analyses in order to try to uncover the sources of variance in storage and processing for children with CIs. First, a measure of vocabulary knowledge was obtained, but in this experiment, expressive vocabulary was assessed. This change from assessing receptive to expressive vocabulary was made because the latter is more frequently measured for children with hearing loss (e.g., [51]) or with reading disabilities [63] because it explains more variance in early language skills. Expressive vocabulary was measured with the Expressive One-Word Picture Vocabulary Test (EOWPVT; [64]).

Another skill assessed in this second experiment was phonological awareness. This was done using a test of awareness of initial consonants, known as the Initial Consonant Choice (ICC) task. There were 48 items in this task, and they are shown in Appendix A.

The third additional measure in this experiment was one of naming speed. With this task, a measure involving both processing speed and verbal rehearsal was obtained, without the additional demand of storage. For this measure, the Rapid Serial Naming (RSN) subtest for objects of the Comprehensive Test of Phonological Processing [65] was chosen.

Finally, a measure of non-verbal cognitive functioning was obtained using the Leiter International Performance Scale – Revised [66]. Four subtests were administered to participants: Figure Ground, Form Completion, Sequential Order, and Repeated Patterns. From these four subtests an estimate of nonverbal intelligence is computed, known as the Brief IQ.

3.1.4. Procedures—

Children were tested over a two-day period, and were given breaks between tasks. Procedures for the working memory portion of testing were identical to those of Experiment 1.

For the EOWPVT task, children label items shown on separate pages of a test book. Standard scores from this task were used as dependent measures.

In the ICC task, audiovisual stimuli consisting of a man speaking were played over the speaker and shown on a computer monitor. In this task, children hear a target word and must repeat it. Only after they repeat it correctly do they move to the choice part of the test. Children were given three opportunities to repeat the target. Then children were presented with three word choices and had to report which one started with the same sound as the target. Percent correct scores were used as dependent measures.

For the RSN task, children had to name pictures of common objects as quickly as possible. There are two pages of material for this task, each consisting of 36 items. The time it took to name the 36 objects on each page was measured separately for each page, and summed across the two pages and used as dependent measures.

The Brief IQ was obtained using standard instructions for the Leiter Scale. This is a completely nonverbal measure. Instructions are pantomimed, and responses are provided without speaking. Standard scores were used.

3.2. Results

One child with NH and fourteen of those with CIs failed either the pre- or post-test naming task for the RHY condition. For children with CIs, *t* tests were performed on scores for recall accuracy and response rate for the NON condition, and for the four additional measures, to see if there were differences between children who could and could not qualify to have their data included in analyses with the RHY words. No significant differences in any of those other scores were found based on whether children could consistently recognize the RHY words, so it was concluded that it was appropriate to use all children in each condition who met criteria for participation.

A *t* test was performed comparing response rate to the baseline condition of tapping on numbers from left to right. No difference between children with NH and those with CIs was found, so uncorrected rates were used in analyses.

3.2.1. Recall accuracy and response rates—

Table 4 shows mean accuracy scores and uncorrected response rates for both groups of children, for both conditions. These are the same measures used in analyses in Experiment 1. A two-way, repeated measures ANOVA performed on accuracy scores showed significant effects of condition, $F(1,81) = 19.88$, $p < .001$, $\eta^2 = .197$, and group, $F(1,81) = 10.09$, $p = .002$, $\eta^2 = .111$, but no significant Condition × Group interaction. An ANOVA performed on response rates showed no significant main effects, even though the group effect was close, $F(1,81) = 2.90$, $p = .093$, $\eta^2 = .035$. The Condition × Group interaction was not significant.

In Experiment 1, effects of list position were not examined because earlier work already demonstrated that children show similar position effects as adults and listeners heard lists of different length, depending on age. However, position effects in serial recall have not previously been examined for children with CIs, so they were in this experiment. Figure 1 shows accuracy scores across list positions. Patterns appear similar for both groups of children, except that children with CIs were less accurate overall and the effect of phonological similarity was diminished. Two-way, repeated-measures ANOVAs performed on outcomes for each condition separately showed significant effects of position, for NON, $F(5,480) = 95.00$, $p < .001$, $\eta^2 = .497$, and RHY, $F(5,405) = 68.40$, $p < .001$, $\eta^2 = .458$. Group differences were also significant, for NON, $F(1,96) = 15.57$, $p < .001$, $\eta^2 = .140$, and RHY, $F(1,81) = 7.69$, $p = .007$, $\eta^2 = .087$. The Position × Group interaction was not significant for either condition. Consequently, it is fair to conclude that the pattern of responding across list positions was similar for children with NH and those with CIs.

3.2.2. Comparisons with Experiment 1—Two age groups of children were included in the first experiment to provide benchmarks against which to compare scores from children in this second experiment, so children's results were compared across experiments. First, *t* tests were done to compare scores for recall accuracy and response rates in both the NON and RHY conditions for 8-year-olds in the first experiment and 8-year-olds with NH in the second experiment. No significant differences were found, which provided some evidence of reliability. Next, the same comparisons were made between the 6-year-olds in the first experiment and the 8-year-olds with CIs in this experiment. Only one test had outcomes that were close to significant: recall accuracy for the RHY condition, $t(58) = 1.87$, $p = .067$, and suggests that 8-year-olds with CIs recalled order for these words slightly better than 6-year-olds with NH. Otherwise, these latter two groups of children performed similarly. From these comparisons it seems appropriate to view the diminishment in storage capacity measured for children with CIs in this experiment compared to children with NH as a delay in development.

3.2.3. Explaining variance

3.2.3. Recall accuracy and response rate: The first set of correlation analyses conducted was done to see if there was a relationship between recall accuracy and response rate, for either the NON or RHY conditions, for either children with NH or those with CIs. Four Pearson product-moment correlation coefficients were computed: one for each condition, for each group of children. None of these correlation coefficients was significant, so it can be concluded that there was no relationship between accuracy and rate of recall.

3.2.3. Treatment variables for children with CIs: The next set of correlations was done to see if factors related to treatment influenced outcomes for children with CIs. Accordingly, age of identification of hearing loss, age of first implant, and age of second implant were correlated with recall accuracy and rate of responding for data from children with CIs. None of these correlations was significant. Of course, all these children were identified early, and received a first implant at a young age. Outcomes may have been different if there was greater variability in these treatment variables. Nonetheless, this lack of statistical significance suggests that small differences in the age of treatment initiation do not influence a child's ability to store and process acoustic materials in working memory.

3.2.3. Predictor variables: Next, regression analyses were conducted using accuracy scores as the dependent variables. Scores on each of the four additional measures (EOWPVT, ICC, RSN, and the brief IQ) were used as predictor variables in separate linear regressions. Response rate was not included in these analyses because no group differences were observed on that measure, and rate did not correlate with accuracy. Thus, the only difference in responding in the working memory task observed for children with NH and those with CIs was on recall accuracy, so they were the only scores examined for potential sources of variance. Besides, it had been predicted that children with CIs would show deficits in storage, which is indexed by accuracy, so it made sense to examine the sources of variance just for this function.

Before performing the regression analyses, however, potential group differences in the predictor variables were examined. Table 5 shows means (and SDs) for the four predictor variables. A series of *t* tests conducted on these measures revealed significant group differences for EOWPVT, $t(97) = 4.70$, $p < .001$, and ICC, $t(96) = 5.55$, $p < .001$. (One child with CIs was not able to complete any of the items on the ICC task, so data were not included from that child.) No significant differences between groups were observed for RSN or the Brief IQ.

Table 6 shows the standardized β coefficients for each regression analysis with recall accuracy as the dependent variable. Looking first at outcomes for the NON words, it can be seen that the only predictor variable to explain significant proportions of variance for both groups of children was ICC, the measure of phonological awareness. For children with CIs, expressive vocabulary (EOWPVT scores) explained significant proportions of variance, as well. Looking next at outcomes for the RHY words, different patterns can be seen. In particular, the brief IQ explained significant proportions of variance for both groups. For children with NH, no other variable explained any significant amount of variance in scores, but both ICC and EOWPVT scores explained significant amounts of variance for the children with CIs.

It is of some interest that RSN was not related to recall accuracy for either NON or RHY words. RSN at least partially indexes the rate of articulation, and that value was found to have no relationship to recall accuracy. Of course, it might be expected to be more likely that RSN would be related to response rates because both measures have to do with speed of responding. Thus, even though no group effect was found for rate, Pearson product-moment correlation coefficients were computed for RSN and response rates. For the NON condition, those correlations were not significant. However, for the RHY condition, significant relationships were observed, both for children with NH, $r(47) = .520$, $p < .001$, as well as those with CIs, $r(36) = .627$, $p < .001$. So, RSN was related to response rates for RHY words.

Returning to recall accuracy, stepwise regression was conducted for each condition and group of children separately in order to check for the effects of intercorrelations among predictor variables. For the NON words, EOWPVT and ICC scores were the only predictor variables included in the analyses because these were the only ones found to explain significant proportions of variance for either group. For children with NH, only ICC was retained by the regression model, as would be expected because it was the only variable with a significant β coefficient. For children with CIs, however, it was also found that ICC was the only predictor variable to be retained by the model. EOWPVT scores did not explain any significant proportion of additional variance in recall accuracy for NON words once the variance explained by ICC scores was removed. Thus, recall accuracy for both groups of children for the NON words was largely explained by sensitivity to phonological (i.e., phonemic) structure.

For the RHY words, EOWPVT and ICC scores were used in the analyses, as well as the Brief IQ. For children with NH, scores on both the Brief IQ and ICC tasks were retained in the stepwise regression model, with standardized β coefficients of .39 and .33, respectively. For children with CIs, scores on the EOWPVT and ICC tasks were retained in the model, with standardized β coefficients of .38 and .37, respectively. The Brief IQ did not explain any significant proportion of additional variance. Thus, different models emerged to explain recall accuracy for RHY words for children with NH and those with CIs. For both groups, substantial amounts of variance were explained by their phonological awareness abilities, as had been the case for the NON words. Additional variance was explained by IQ for children with NH, and by vocabulary knowledge for children with CIs.

3.3. Discussion

The goal of this experiment was to examine storage and processing in working memory by children with CIs, and compare outcomes to those of typical children with NH. Based on shorter digit spans, it has been suggested that children with CIs have atypical development of working memory capacities, which in turn negatively impacts development of spoken language more generally (e.g., [40]). In the current experiment, the hypothesis was tested that only storage would be diminished for children with CIs, and the effect would be due to poor access to phonological structure, a consequence of the degraded signals received through CIs.

All outcomes of the current experiment supported the hypothesis. Recall of list order was significantly poorer for the children with CIs, compared to those with NH, and phonological awareness abilities largely accounted for this effect. All other aspects of serial recall (position effects, response rates) failed to show significant differences for children with NH and those with CIs. Consequently, these outcomes do not support the conclusion that children with CIs have atypical development of working memory capacities. A more fitting appraisal of the evidence leads to the conclusion that children with CIs have poorer storage capacity within an otherwise normally functioning working memory system. This suggestion matches that of Lyxell et al. [45] for adults with acquired hearing loss, based on numerous studies they conducted.

4. General Discussion

There is considerable interest in examining the relationship between auditory and cognitive capacities of deaf children who use CIs. Where adults are concerned, evidence exists to support the broad conclusion that any appearance of decrements in cognitive functioning accumulating as hearing loss progresses arises due to the impoverishment of sensory information that is available to those cognitive systems [10,45]. However, adults in these studies had developed typical cognitive functions prior to the onset of hearing loss. Consequently, it was reasonable to ask whether or not children who were born with hearing loss would show a similar specificity of effect. In particular, the current study examined whether working memory problems in children with CIs could be traced to storage capacities only, or if evidence of processing deficits would be found, as well.

The goal of this study was really two fold. A first experiment was designed to test the hypothesis that storage and processing within a working memory system can be assessed separately. A second experiment tested the hypothesis that only the storage function of working memory is affected in children who use CIs. All predictions across experiments were largely supported.

In the first experiment, a serial recall task was used to examine storage and processing. Recall accuracy was used to assess storage capacity, and rate of recall was used to assess processing. Three sets of words were designed to manipulate independently phonological similarity, which was predicted to affect storage, and processing demands. Results showed that order recall was less accurate for the words that were phonologically similar, and recall was slowest for the words that presented the greatest processing demands. However, scores for these two measures were largely unrelated, indicating that diminished storage capacity did not affect processing difficulty for the most part, or visa versa. This latter finding is evidence that storage and processing are generally independent, so it provides support for multiple-component models of working memory.

The question of whether human working memory is best modeled as a single- or multiple-component system has important implications for understanding the effects that deafness and subsequent cochlear implantation would be expected to have on the operations of that system. For children, a serious consequence of implantation is that the development of sensitivity to phonological (especially phonemic) structure is tremendously hampered due to the impoverished nature of the available signal. Most models of working memory suggest that linguistic material is stored primarily with a phonemic code. Consequently, any deficit in sensitivity to phonemic structure should diminish storage capacity within the working memory system. In single-component models of working memory, this diminishment in storage capacity would significantly impact processing, as well, because storage and processing must share resources. In multiple-component models, only slight decrements in processing would be expected. These small decrements in processing capacity are predicted to arise because the central executive of Baddeley's model (e.g., [16]) is where processing is purported to occur, and that component is also responsible for directing other components of the system. Thus, some slight deficit in processing might be expected as the central executive is impacted in its role as director.

The second experiment in the current study offered further support for multiple-component models of human working memory, and provided evidence to support the hypothesis that children with CIs have diminished storage capacity, but working memory is otherwise intact. Accuracy of order recall was significantly poorer for children with CIs than for their peers with NH, and sensitivity to phonological structure explained the lion's share of variance in children's abilities to recall order of presentation. These results bolster the claim that storage is most affected by wearing CIs, and the reason is that CIs poorly support the recovery of phonemic structure, the very kind of structure required for storage. Similarity in rates of recall for children with NH and those with CIs supported the suggestion that processing is not affected by the use of a CI. Patterns of recall across list positions further support this conclusion.

In sum, there is no evidence that working memory is developing atypically for children with CIs. Instead it seems more accurate to describe the problem facing children with CIs as one that affects storage only. That distinction should have tremendous implications for research and clinical efforts in the future. Where research is concerned, efforts should focus on improving the quality of the sensory information available to children with CIs. Presumably, the more details about the signal that can be delivered, the more refined their phonological representations will be. These efforts could focus on improving the amount of temporal fine structure that is available through CIs (e.g., [67]), or combining amplification with a CI and hearing aid to provide at least some acoustic hearing (e.g., [68]). Even with enhanced sensory information, however, children with CIs might benefit from explicit phonological training to help direct their attention to this level of structure in the speech signal.

Of course, the task used in these experiments – recalling the serial order of unrelated words – does not resemble listening in natural situations. Typically, words are combined into sentences according to syntactic rules, incorporating semantic relationships. For adults who lose their hearing after they have acquired language that means that these kinds of linguistic devices can actually facilitate recognition, even though sensory input is diminished. For children, the situation is trickier because they need to be able to store sequences of words in a memory buffer with some reliability if they are to discover syntactic rules and semantic relationships in the usual developmental fashion. The findings of the current experiment suggest that it might be advantageous to provide some direct instruction of these linguistic devices for children with CIs. If syntax and semantics are taught to deaf children explicitly, those structures could subsequently be applied to aid storage in working memory in a top-down manner. That kind of direct instruction is typically not provided in mainstream educational environments, precisely because children with normal hearing discover syntactic rules and semantic relationships through casual exchanges. Thus, additional educational options are needed for deaf children. Although the idea of educating these children along side their peers with normal hearing provides some benefits, additional support may be desirable.

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Appendix A

Initial Consonant Choice Task of Experiment 2

Practice Examples							
1. pet	fire	pack	night	4. ball	book	seed	mouth
2. blue	bag	fox	egg	5. face	pig	fur	top
3. cake	sheep	note	kite	6. seal	can	dog	sun

****Discontinue after 6 consecutive errors.**

Test Trials				Test Trials			
1. milk	date	moon	bag	25. clean	spoon	free	cry
2. pear	pen	tile	mask	26. lamb	lick	juice	cage
3. stick	slide	drum	flag	27. dog	dart	fall	girl
4. bone	meat	lace	bud	28. rake	pig	root	bike
5. soap	king	dime	salt	29. meat	mice	new	doll
6. claw	prize	crib	stair	30. boot	cat	bus	push
7. leg	pin	lock	boat	31. nail	lay	nut	bye
8. duck	door	soup	light	32. stop	skirt	train	crawl
9. plum	tree	star	price	33. top	two	gum	big
10. key	fist	cap	sap	34. hen	save	down	have
11. zip	zoo	web	man	35. keep	rock	bark	kiss
12. gate	sun	bin	gum	36. clap	crab	tree	slip
13. rug	can	rag	pit	37. queen	wheel	gift	quit
14. sky	sleep	crumb	drip	38. hot	hill	fence	base
15. fun	dark	pet	fan	39. jog	jar	dig	cow
16. peel	wash	pat	vine	40. zap	game	zoom	bed
17. grape	class	glue	swing	41. dot	pink	fish	dime
18. leap	lip	note	wheel	42. bat	song	barn	fun
19. house	rain	heel	kid	43. fly	truck	fruit	skip
20. toes	bit	girl	tip	44. need	nose	hop	draw
21. win	well	foot	pan	45. wall	deer	leaf	web
22. met	map	day	box	46. van	vase	part	like

Practice Examples							
23. sled	frog	brush	<u>stick</u>	47. town	dip	<u>tick</u>	king
24. jeep	lock	pail	<u>jug</u>	48. glow	fry	drop	<u>grass</u>

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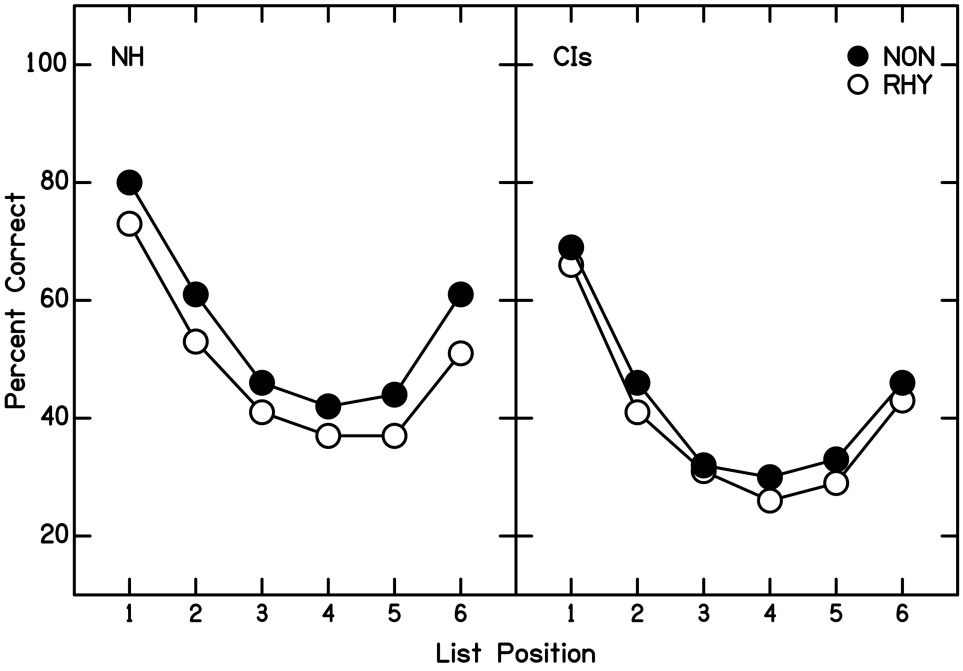

Figure 1.

Recall accuracy according to position for NON and RHY conditions of Experiment 2. Results for children with NH are shown on the left. Results for children with CIs are shown on the right.

Table 1

Mean accuracy scores (percent correct responses) across all list positions for adults, 8-year-olds, and 6-year-olds for each condition in Experiment 1. Standard deviations are in parentheses.

	NON M (SD)	**ADJ M (SD)**	**RHY M (SD)**
Adults	60.5 (12.1)	56.1 (13.8)	51.6 (12.9)
8-year-olds	54.2 (14.9)	54.4 (16.0)	43.0 (14.7)
6-year-olds	38.3 (9.4)	37.2 (11.6)	33.3 (9.8)
TOTAL	51.0 (15.4)	49.2 (16.2)	42.6 (14.6)

Table 2

Mean uncorrected and corrected rates (in ms per item) for adults, 8-year-olds and 6-year-olds, across conditions in Experiment 1. Standard deviations are in parentheses.

	Uncorrected M (SD)	Corrected M (SD)
Adults	830 (139)	581 (134)
8-year-olds	848 (179)	538 (184)
6-year-olds	925 (175)	511 (186)

Table 3

Mean rates (in ms per item) for adults, 8-year-olds and 6-year-olds for each condition in Experiment 1. Standard deviations are in parentheses.

	NON M (SD)	**ADJ M (SD)**	**RHY M (SD)**
Adults	795 (148)	925 (175)	772 (153)
8-year-olds	837 (199)	902 (230)	805 (159)
6-year-olds	880 (177)	991 (226)	904 (228)
TOTAL	837 (177)	939 (212)	827 (189)

Table 4

Mean scores for recall accuracy (percent correct) across all list positions and mean response rates (in ms) for children with NH and with CIs, for both conditions in Experiment 2. Standard deviations are in parentheses.

	Accuracy		**Response Rate**	
	NON M (SD)	**RHY M (SD)**	**NON M (SD)**	**RHY M (SD)**
NH	55.6 (16.4)	48.4 (15.1)	838 (208)	812 (171)
CIs	42.7 (15.7)	39.4 (14.0)	891 (222)	916 (255)

Table 5

Mean scores on predictor variables used in Experiment 2. Standard deviations are in parentheses.

	EOWPVT M (SD)	ICC M (SD)	RSN M (SD)	Brief IQ M (SD)
NH	110 (14)	87 (13)	83 (21)	103 (21)
CIs	94 (19)	63 (25)	90 (27)	99 (18)

Given here are standard scores for expressive vocabulary (EOWPVT); percent correct responses for phonological awareness (ICC); time (s) for naming objects on both pages for rapid serial naming (RSN); and standard scores for the Brief IQ.

Table 6

Standardized β coefficients for recall accuracy scores for both the NON and the RHY conditions, and each predictor variable in Experiment 2. Values are given for children with NH and those with CIs separately.

	NON		RHY	
	NH	**CIs**	**NH**	**CIs**
EOWPVT	.19	.47**	.08	.63**
ICC	.35*	.56**	.34*	.63**
RSN	-.15	-.22	.07	-.07
Brief IQ	.19	.18	.40**	.34*

*$p < .05$;

**$p < .01$