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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.

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

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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 that a single component is 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 toward 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