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The Cognition and Behaviour of Eight- and Nine-Year-Old Hearing-Impaired Children with Cochlear Implants

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Abstract

Objective: The purpose of this study was to examine working memory for sequences of auditory and visual stimuli in prelingually deafened pediatric cochlear implant users with at least 4 yr of device experience.

Design: Two groups of 8- and 9-yr-old children, 45 normal-hearing and 45 hearing-impaired users of cochlear implants, completed a novel working memory task requiring memory for sequences of either visual-spatial cues or visual-spatial cues paired with auditory signals. In each sequence, colored response buttons were illuminated either with or without simultaneous auditory presentation of verbal labels (color-names or digit-names). The child was required to reproduce each sequence by pressing the appropriate buttons on the response box. Sequence length was varied and a measure of memory span corresponding to the longest list length correctly reproduced under each set of presentation conditions was recorded. Additional children completed a modified task that eliminated the visual-spatial light cues but that still required reproduction of auditory color-name sequences using the same response box. Data from 37 pediatric cochlear implant users were collected using this modified task.

Results: The cochlear implant group obtained shorter span scores on average than the normal-hearing group, regardless of presentation format. The normal-hearing children also demonstrated a larger "redundancy gain" than children in the cochlear implant group—that is, the normal-hearing group displayed better memory for auditory-plus-lights sequences than for the lights-only sequences. Although the children with cochlear implants did not use the auditory signals as effectively as normal-hearing children when visual-spatial cues were also available, their performance on the modified memory task using only auditory cues showed that some of the children were capable of encoding auditory-only sequences at a level comparable with normal-hearing children.

Conclusions: The finding of smaller redundancy gains from the addition of auditory cues to visual-spatial sequences in the cochlear implant group as compared with the normal-hearing group demonstrates differences in encoding or rehearsal strategies between these two groups of children. Differences in memory span between the two groups even on a visual-spatial memory task suggests that atypical working memory development irrespective of input modality may be present in this clinical population.

INTRODUCTION

Working memory is generally characterized as a limited capacity system used for short-term maintenance of information in memory. A long-standing debate surrounds the question of the extent to which input from the different sensory modalities is channeled independently through the mechanisms of working memory (Fastenau, Conant, & Lauer, 1998; Hale, Bronik, & Fry, 1997; Swanson, 1996). Over the years the theoretical construct of working memory has been "fractionated" into modality-specific pathways in the brain's prefrontal cortex sharing a common "executive" control center (Baddeley, 1986; Smith & Jonides, 1999). Much effort has been expended in trying to understand how sensory experience contributes to these apparent divisions (Lewkowicz & Lickliter, 1994; Stein & Meredith, 1993). Although past research has tended to study developmental changes in working memory in general terms of memory capacity, processing speed, and susceptibility to interference, the modality specificity of these influences is now undergoing extensive examination (e.g., Hale et al., 1997; Kail, 1991; Swanson, 1996).

Clear effects of early sensory experience and learning have been demonstrated by showing how memory performance improves with greater familiarity with the to-be-remembered items and the acquisition of strategies for circumventing capacity limitations (Dempster, 1981; Naus & Ornstein, 1983). Several common encoding strategies, by their very nature, seem to favor use of the auditory input modality. The learned strategy of verbal rehearsal for example, although best suited for the task of remembering the phonological characteristics of spoken or read words, is thought to be a mandatory process that is automatically used by normal-hearing adults whenever verbal labels can be applied (Brandimonte, Hitch, & Bishop, 1992; Carmichael, Hogan, & Walter, 1932). This heavy reliance on verbal encoding strategies has naturally led to interest in whether access to a typical oral/aural-based language environment is necessary for the development of aspects of working memory that are assumed to be modality-independent—Baddeley's "central executive" component, for example (Baddeley, 1992).

Literature published between the 1950s and 1970s suggested that hearing-impaired children in general were less adept overall than normal-hearing children in their working memory for some types of visual (but verbally codeable) sequences because these children lacked effective verbal strategies for rehearsal (Conrad, 1972; Furth, 1966; Marschark & Mayer, 1998; Mayberry, 1992). In the 1980s and 1990s, however, the focus of research shifted to showing that manually signed equivalents to verbal strategies could be adopted to analogous benefit, although the comparable efficiency of these manual strategies, and the frequency of their use by signing individuals came under debate (Hanson, 1990; Hanson & Lichtenstein, 1990; Shand, 1982; Tomlinson-Keasey & Smith-Winberry, 1990).

The present study investigated the processing and short-term storage of auditory and visual-spatial sequences in prelingually deafened pediatric cochlear implant users—profoundly deaf children who were without auditory input during their early development, but who currently use a prosthetic device that presents an electrically coded instantiation of sound directly to their auditory nervous system. Through an intervention program that follows the implant surgery, most cochlear implant users eventually acquire at least an awareness of sound through their implant and many (the majority) go on to develop open-set speech perception skills and are able to produce intelligible speech (Geers et al., 2000; Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000; Tobey et al., 2000). The skills attained through use of a cochlear implant vary quite widely among children, and the variables and processes that contribute to this outcome are not well understood (Pisoni, 2000; Pisoni, Svirsky, Kirk, & Miyamoto, 1997).

Large individual differences in spoken word recognition skills and language development continue to be observed in pediatric users of cochlear implants (Miyamoto et al., 1994; Tyler, Fryauf-Bertschy, Kelsay, Gantz, Woodworth, & Parkinson, 1997). A sizable proportion of this variability can be accounted for in terms of physiological and hardware-related factors. Miyamoto et al. (1994) suggest that about 40% of the variance in open-set speech perception measures can be accounted for in terms of processor type, duration of deafness, communication mode, age of onset of deafness, duration of cochlear implant use, and age at implantation. Other studies, using similar sets of variables, have obtained R-squared values ranging between 37% and 64% (Dowell, Blamey, & Clark, 1995; Snik, Vermeulen, Geelen, Brokx, & van den Broek, 1997). In young children, the age at which the hearing impairment occurred, the length of auditory deprivation, and amount of experience using the implant have all been shown to play important roles in predicting outcome (Fryauf-Bertschy, Tyler, Kelsay, Gantz, & Woodworth, 1997; Miyamoto et al., 1994; Nikolopoulos, O'Donoghue, & Archbold, 1999). From recent reexamination of audiological candidacy requirements, it has also been determined that the presence of even minimal amounts of residual hearing under aided conditions before implantation can also contribute positively to success with an implant (Seghal, Kirk, Pisoni, & Miyamoto, Reference Note 2; Zwolan, Zimmerman-Phillips, Ashbaugh, Hieber, Kileny, & Telian, 1997). However, there is still a large proportion of unexplained variance in this multivariate prediction of speech perception performance (Pisoni et al., 1997).

Our current research program on individual differences in cochlear implant users is motivated by the hypothesis that some significant part of this current error variance can be accounted for by cognitive factors related to the efficiency with which representations of spoken words are stored and retrieved from memory, after identification (Pisoni, 2000). In particular, given the pediatric cochlear implant user's newly acquired access to auditory information, one of our goals has been to tease apart pos sible contributions from modality-specific versus modality-independent aspects of working memory.

Although it is common practice to administer tests of "general intelligence" before implantation (Miyamoto, Robbins, & Osberger, 1993; Tiber, 1985), the early finding that overall IQ was a poor predictor of speech perception performance seems to have discouraged more detailed investigation of whether certain subscales within the IQ batteries might show more predictive power than others (for exceptions, see Quittner & Steck, 1991; Tiber, 1985; and for general discussion of intelligence measures obtained from pediatric cochlear implant users, see Knutson, Boyd, Goldman, & Sullivan, 1997). New research, however, has begun to explore the cognitive development of children with cochlear implants in greater detail and to investigate the specific information processing skills used in spoken language processing (Pisoni, 2000).

The focus on working memory in the present study was largely motivated by recent findings reported in Pisoni and Geers (2000) on auditory digit span in hearing-impaired children with cochlear implants. Auditory digit span is a simple and widely used task that requires that the subject listen to a list of digits and then repeat back the list items in the correct order. Typically, the length of the list is increased over the course of several trials until the subject can no longer do the task correctly.

Pisoni and Geers found that in a large group of pediatric cochlear implant users (N = 43), simple forward digit span measures (administered live voice with lipreading permitted, and requiring a spoken response during immediate recall) were significantly correlated with open-set spoken word recognition scores even when the most obvious confounding variables were statistically controlled for (simple bivariate $r = +0.64$; with variance from a test of speech feature discrimination removed $r = 0.37$). Pisoni and Geers interpreted this finding as evidence for the influence of "processing variables"—that is, skills and abilities "that are used in the encoding, rehearsal, storage, retrieval, and manipulation of the phonological representations of spoken words" (Pisoni & Geers, 2000, p. 93). Their findings on auditory digit spans were replicated more recently in a new sample of cochlear implant users (one of the two groups reported on in the current paper). Reanalysis of the pooled dataset (N = 88) showed that statistically significant correlations of at least $r = +0.30$ still remained, even with statistical "partialling-out" of variability linked to slight age differences, communication mode, duration of deafness, duration of device use, age of onset of deafness, number of active electrodes, as well as a measure of auditory speech feature discrimination (Pisoni, Cleary, Geers, & Tobey, 2000). Examination of the same dataset using the closely related procedure of factor analysis has led to a similar result (Geers, Reference Note 1).

These recent findings on auditory digit span suggest that approximately 10% of the variance in open set speech perception measures may be accounted for by individual differences in the cognitive skills tapped by the forward digit span memory task, or perhaps some other co-varying but as yet unidentified variable. In making the case for the relevance of memory span measures, Pisoni et al. (2000) have therefore proposed that an important cognitive processing variable related to how young children encode and manipulate the phonological representations of spoken words is contributing to the more general development of oral/aural language skills in pediatric cochlear implant users.

Surprisingly, relatively little other research has focused directly on auditory working memory in users of cochlear implants. Lyxell, Andersson, Arlinger, Bredberg, Harder, and Ronnberg (1996) have, however, examined in adult cochlear implant users whether it might be "possible to predict the level of speech understanding (postimplant) by means of a preoperative cognitive assessment." Because Lyxell had previously obtained results suggesting that individual differences in processing speed and working memory capacity could account for a portion of the variability found in the speechreading/lipreading scores of normal-hearing adults, he hypothesized that this same relationship might also be observed in users of cochlear implants. Although Lyxell et al. reported negative results for the above study—that is, no evidence of working memory capacity being predictive of speechreading ability—they have, as yet, only examined the case of postlingually deafened adult cochlear implant users, and not prelingually deafened pediatric users of cochlear implants.

In another, more clinically oriented study of postlingually deafened cochlear implant users, Gantz, Woodworth, Abbas, Knutson, and Tyler (1993) identified six preoperative measures that accounted for approximately two-thirds of the between-subject variability in sound-only open-set word recognition scores 9 mo postimplant. The Wechsler Memory Test, a battery of learning, memory, and working memory measures, though initially included in the battery of predictor variables, failed to exhibit any sizable correlation with the word recognition scores. Gantz et al. did, however, report that "the ability to extract information from sequentially arrayed signals and rapidly process that information as measured by the signal detection score from the Visual Monitoring Task, appears to be relevant to word understanding with an implant" (Gantz et al., 1993, p. 915). The visual detection task used by Gantz et al. required participants to monitor a series of visually presented digits shown one at a time, for a specified subsequence—e.g., an odd-even-odd sequence of digits—thus requiring short-term storage of at least two items in recent memory during presentation (Knutson, Hinrichs, Tyler, Gantz, Shartz, & Woodworth, 1991). In another article by this research group on the skills of postlingually deafened adults, the scores on this same visual monitoring task were again found to correlate between +0.30 and +0.40 with auditory-only measures of phoneme discrimination (Knutson et al., 1991).

At first glance it may appear somewhat surprising that a "visual" skill that seems minimally dependent on the verbal ability associated with spoken language would show any relation to subsequent gains made in speech understanding by hearing-impaired listeners. One point that bears discussion, however, is whether hearing subjects typically approach the above visual monitoring task using non-verbal strategies (i.e., do they tend to rehearse or keep a verbal tally using the spoken names of the items immediately prior in the monitored sequence, or can the visual patterns on the screen avoid "verbal mediation" en route to being remembered?) Here it is relevant to consider recent evidence showing that the skills tapped in such "visual monitoring" tasks develop somewhat atypically in at least some pediatric cochlear implant users as compared with normal-hearing children. Quittner, Smith, Osberger, Mitchell, and Katz (1994) used a task similar to Gantz et al.'s (1993) with normal-hearing and hearing-impaired children (cochlear implant and hearing aid users) ages 6 to 13 yr. The participants were required to monitor a series of single-digit numerals on a screen and respond only when a certain specified sequence of two successive numbers was seen. No auditory stimuli were presented in this task. Both groups of hearing-impaired children did significantly worse than the hearing controls in the 6 to 8 yr age range, and although this difference was not statistically significant in the older age range of 9 to 13 yr (probably due to high within-group variability), average performance was still worse in the hearing-impaired groups. Although no word recognition or language development outcome measures were reported for these samples, the results suggest that some pediatric cochlear implant users (even those with several years experience with an implant) may encounter more difficulty than is typical for their age-matched hearing peers even when they are presented with a memory/attention task that could conceivably be performed on the basis of vision alone.

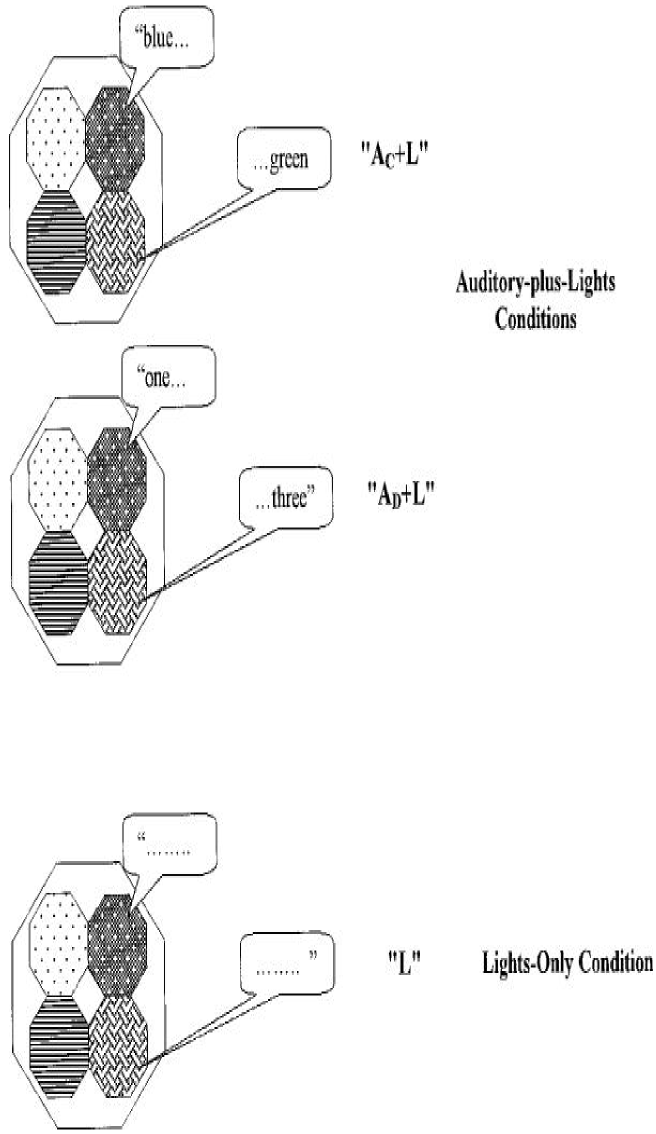

Figure 1: Diagram of memory game apparatus and experimental conditions given a list length of two items. Each shaded hexagon represents a large colored button back-lit by a light. All auditory stimuli were presented via a loudspeaker located just behind the memory game response box. The verbal labels simply illustrate the consistent mapping between a particular auditory stimulus and a given button location. "AC+L" = auditory color-names-plus-lights; "AD+L" = auditory digit-names-plus-lights; "L" = lights-only.

The motivation for using this particular methodology was to obtain a measure of memory span using a nonlinguistic manual response, rather than a spoken or signed verbal response as is used in traditional digit span tasks. A nonlinguistic manual response was adopted to avoid possible confounds involving individual differences in rate and fluency of articulation and/or manual signing (i.e., productive language skills). The choice of target stimuli was determined by our interest in assessing differences in memory span as a function of whether or not redundant auditory cues in addition to visual-spatial cues were presented as part of the target sequence. That is, we examined the effect of presenting auditory stimuli during a task that could also be performed on the basis of vision alone. We also manipulated whether or not the redundant sound stimuli were semantically congruent with the light sequence. In one condition, whenever a sound was presented, the auditory stimulus was the color-name of the currently illuminated button. In a second multi-modal condition, a spoken digit-name was arbitrarily assigned to each of the four response buttons and consistently presented whenever the matched button was illuminated. Finally, a uni-modal control condition also was included that presented sequences only of lights without any auditory stimuli (Fig. 1).

For the normal-hearing children, we expected that the presence of an informationally redundant auditory stimulus would lead to higher memory span scores compared with the uni-modal stimulus-presentation condition. In the cochlear implant group, our primary focus was on whether those cochlear implant users who could correctly identify the auditory stimuli when presented in isolation would show the same benefit from the addition of the redundant auditory signals as was expected for the normal-hearing group. Because all of the pediatric cochlear implant users in the current study had used their cochlear implants for at least 4 yr, we judged it more likely that the mechanisms of phonological working memory might have developed in some members of this sample, than if relatively inexperienced users had been selected. Although the previous research showing differences in visual monitoring performance in pediatric cochlear implant users was suggestive, the cochlear implant group was not necessarily expected to perform differently from the normal-hearing children on the visual-spatial-only version of the memory game task.

An examination of the relationship between traditional verbal digit span and each of the three different presentation conditions of the memory game task was also planned for both groups of children. Because the digit span task makes no demands on visual-spatial aspects of working memory, smaller correlations between verbal digit spans and auditory-plus-visual-spatial memory game scores were expected for those children who could be shown to be doing the memory game task by vision alone, and larger correlations were anticipated for those children who demonstrated use of the redundant auditory stimuli in this task.

General Discussion

One of the long-term goals of our current research program is to develop a practical methodology for assessing and tracking the development of verbal working memory in pediatric cochlear implant users over time. Our interest in this problem partially stems from recent debate in the area of cognitive development having to do with the role of working memory in language development and lexical acquisition (Baddeley, Gathercole, & Papagno, 1998; Gupta & Dell, 1999). The results presented in this article address some methodological and theoretical issues regarding the assessment of working memory in a special population of children for whom the auditory modality has been partially compromised since birth. We found that experienced school-age users of cochlear implants did not integrate a semantic redundancy present in a memory span task across the auditory and visual sensory modalities as effectively as age-matched normal-hearing children. This finding suggests that fundamentally different sensory encoding and/or rehearsal processes may be operating in these two populations. Although the cochlear implant is now providing the cochlear implant children with access to sound and spoken language, their atypical early sensory and perceptual experiences are still evident in how they perceive and encode sensory information even after more than 4 yr of experience with a cochlear implant.

The cochlear implant children reported on in this study performed more poorly as a group overall than the normal-hearing children even when the memory game task used only visual-spatial stimuli. When differences are, in fact observed, investigators tend to find that the visual/spatial stimuli used in the particular task lent themselves to linguistic (verbal) labeling. When verbal labeling is possible, hearing-impaired children seem to be at obustness, etc.), their performance on a memory span task using self-generated verbal labels would be expected to be reduced relative to that of normal-hearing children. It is possible that this occurred in the Quittner et al. (1994) study discussed in our introduction involving visual monitoring of a stream of orthographically presented digits.

We acknowledge this as a possible explanation for the reduced memory spans of the cochlear implant group in the lights-only condition, but if this relatively sophisticated verbal coding approach were truly being attempted, we would have expected to see a larger effect of informational redundancy in the cochlear implant group. The fact that no significant differences were found as a function of presentation condition for the cochlear implant children in Experiment 1, and that only a small advantage was observed in Experiment 3 for the multi-modal presentation condition over the lights-only presentation condition, suggests to us that these children relied primarily on visual-spatial encoding of the target sequence to perform the task. These results were obtained despite the fact that many of these cochlear implant children did well on the auditory WISC digit span task and on the auditory-only presentation condition of the memory game.

In summary, the present results suggest that even those cochlear implant children who are able to accurately identify speech signals in isolation, may not have phonological working memory mechanisms or processing strategies that are developed to a point equivalent to chronologically age-matched normal-hearing children. This outcome would not exactly be surprising, as many important milestones in the development of speech perception and memory are reached during the first 2 yr of life (Aslin, Jusczyk, & Pisoni, 1998; Jusczyk, 1997). Despite their prelingually deafened status, most of the cochlear implant users reported on in this paper received their implant at a point in time when the FDA did not permit implantation of children under 2 yr of age. Additionally, because the implantation procedure requires that candidates show a demonstrated failure to benefit from conventional hearing aids, we can be fairly certain that most of these 8- and 9-yr-old children had received only minimal auditory input for at least one quarter to one third of their lives. It should not be surprising, then, that the encoding strategies and working memory mechanisms of pediatric cochlear implant users seem to differ measurably from those of normal-hearing children.

Ongoing research in our lab is attempting to describe in more detail how these encoding/rehearsal mechanisms differ, and what kind of developmental changes can be observed or effected in these children. Increasingly, clinicians are beginning to see pediatric cochlear implant users that have reached ceiling levels of performance on the traditional standardized measures of speech perception and spoken word recognition that are typically used with this population—and yet these children are still clearly having problems with reading and other more advanced language skills that are based on listening, phonological encoding, and other metalinguistic abilities. Further investigation of how pediatric cochlear implant users engage in cognitive processing of information originating from this reintroduced sensory input modality may help us develop new assessment and treatment techniques (Pisoni, 2000). Eventually we would like to answer the question of whether individual differences in the function of particular components of working memory within the pediatric cochlear implant pop ulation might have a meaningful causal relation to the level of verbal language skill attained by individual children. The present research begins to address this important issue because it provides some of the first behavioral data on working memory in pediatric cochlear implant users involving tasks in which the potential contribution of each available sensory modality was varied.

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