RESEARCH ON SPOKEN LANGUAGE PROCESSING
Progress Report No. 23 (1999)
Indiana University

Some Measures of Verbal and Spatial Working Memory in Eight- and Nine-Year-Old Hearing-Impaired Children with Cochlear Implants[1]

Miranda Cleary, David B. Pisoni,[2] and Ann E. Geers[3]

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

---

[1] This work was supported by NIH Research Grant DC00111 and Training Grant DC00012 to Indiana University. We extend grateful appreciation to B. Staley and J. L. Carlson for their help in testing of the normal-hearing children, to the CID staff for the testing of all hearing-impaired cochlear implant users, and to K. I. Kirk and L. Gerken for helpful comments and advice on an earlier version of this study.

[2] Also DeVault Otologic Research Laboratory, Department of Otolaryngology-Head and Neck Surgery, Indiana University School of Medicine, Indianapolis, IN.

[3] Center for Applied Research on Childhood Deafness, Central Institute for the Deaf, St. Louis, MO 63110

Some Measures of Verbal and Spatial Working Memory in Eight- and Nine-Year-Old Hearing-Impaired Children with Cochlear Implants

Abstract. Two groups of 8 and 9-year-old children, 45 normal-hearing (NH) and 45 hearing-impaired users of cochlear implants (CI) completed a working memory task that presented either visual-spatial cues or visual-spatial cues paired with auditory signals. In this task colored buttons were illuminated in a sequence either with or without the synchronized auditory presentation of verbal labels for the buttons (color-names or digit-names). The child was required to reproduce each sequence by pressing the appropriate buttons. The longest list length reproduced under each set of conditions was recorded. The NH group demonstrated an advantage for the auditory plus visual-spatial task over the visual-spatial-only task when the labels matched the colors of the lights. The children in the CI group did not show this same advantage. The ability of many of the CI users to correctly identify the auditory stimuli when presented in isolation did not lead to their use of the informationally redundant auditory cues. Overall, the CI group did significantly worse than the NH children even on the visual-spatial-only sequences, suggesting important differences in encoding strategies. A modified task that eliminated the visual-spatial cues from the target sequence of auditory color-names was run with NH children and a second group of pediatric CI users. In this case, errors in stimulus identification were associated with reduced span scores. The highest scoring CI users obtained spans on this task equivalent to the scores of the bottom third of the NH group, indicating that when visual-spatial encoding was not an option, some CI users were capable of engaging in verbal encoding in a manner on par with some NH children.

Introduction

A long-standing debate surrounds the question of the extent to which information from the different sensory modalities is channeled independently through the mechanisms of short-term memory (Fastenau, Conant, & Lauer, 1998; Hale, Bronik, & Fry, 1997; Swanson, 1996). Over the years the theoretical construct of short-term/working memory[4] 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 divisions as they appear to exist in the mature individual (Lewkowicz & Lickliter, 1994; Stein & Meredith, 1993). Examining the long-term impact of various forms of sensory deprivation may help shed further light on the nature of these “divisions” in normally developed organisms.

Past research on the development of short-term memory has tended to focus on whether increases in memory capacity, processing speed, or resistance to interference are primarily responsible for age-linked changes—with the modality specificity of these effects only now undergoing careful examination (e.g., Hale, Bronik, & Fry, 1997; Kail, 1991; Swanson, 1996). Effects of early sensory experience and learning have been examined by assessing how performance improves with greater familiarity with the to-be-remembered items and acquired strategies for circumventing capacity limitations (Dempster, 1981; Naus &

---

[4] *Short-term* memory tasks using verbal materials usually require no more than a simple parroting back of presented items, or immediate labeling of a test sequence as either identical to or different from a prior sequence. *Working* memory is argued to be used when maintenance of novel information is required while other incoming information is also processed, or some manipulation or transformation of items in memory is necessary.

Ornstein, 1983). Many encoding strategies, by their very nature, appear to favor a particular 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, tends to be utilized by normal-hearing adults whenever verbal labels can be applied—even to deleterious effect in the case of encoding and remembering ambiguous shapes, for example (Brandimonte, Hitch, & Bishop, 1992; Carmichael, Hogan, & Walter, 1932). This heavy reliance on verbal encoding strategies has naturally led to much interest in whether access to a typical oral/aural based language environment is a necessary component to the normal development of aspects of working memory such as Baddeley's "central executive" which is assumed to be modality-independent (Baddeley, 1992).

Literature published in the 1950-1970's suggested that hearing-impaired children in general were less adept overall than normal-hearing children in their short-term memory for some types of visual (but verbally code-able) sequences because these children lacked effective verbal strategies for rehearsal (Conrad, 1972; Furth, 1966; see Marschark & Mayer, 1998; Mayberry, 1992 for some recent reviews). In the 1980's and 90's however, the focus 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 some debate (Hanson, 1990; Hanson & Lichtenstein, 1990; Shand, 1982).

The present study investigated the processing and short-term storage of auditory and visual-spatial sequences in prelingually-deafened pediatric cochlear implant (CI) users--profoundly deaf children that have been without auditory input for a period in their very early development, but who have then been supplied with access to sound via an electrically-coded signal presented directly to their auditory nervous system. Through an intervention program that follows the implant surgery, most pediatric CI users eventually come to gain at least an awareness of sound through their implant, and in some cases go on to develop good speech perception and production skills (Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, in press). The skills attained through cochlear implant use vary quite widely among children, and the variables and processes that contribute to this outcome are not well understood (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 et al., 1997). A sizable proportion of this variability can be accounted for in terms of physiological and hardware-related factors. Miyamoto et al. (1994) suggest for example, 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 CI use and age at implantation. Other studies, using similar sets of variables, have obtained R-squared values ranging between 37-64% (Dowell, Blamey, & Clark, 1995; Snik, Vermeulen, Geelen, Brokx, & van den Broek, 1997). In young children, the age at which the hearing-impairment occurred, the duration of the period of auditory deprivation, and amount of experience using the implant have all been shown to play an important role 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, 1997; Zwolan et al., 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 and variation in CI users is motivated by the hypothesis that some significant part of this current error variance can be accounted for in terms of already established knowledge about the distribution of specific cognitive capacities in the general population of young children. In particular, one of our goals has been to tease apart possible contributions from modality-specific versus modality-independent mechanisms of short-term and/or working memory, in light of the pediatric cochlear implant user's newly acquired access to auditory information.

Although it is common practice to administer tests of "general intelligence" prior to 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 (though see Quittner & Steck, 1991; Tiber, 1985; and for general discussion of intelligence measures obtained from pediatric CI users, 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.

The focus on short-term memory in the present study was largely motivated by recent findings reported in Pisoni and Geers (1998) involving auditory digit span. 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 a several trials until the subject can no longer do the task correctly. Pisoni and Geers showed that in a large group of pediatric CI users (N=43), simple forward digit span measures (administered live voice with lip-reading permitted, and requiring a spoken response during recall) were significantly correlated with open-set spoken word recognition scores even when the most obvious confounding variables were statistically controlled for (simple bivariate $r = +.64$; with variance from a test of speech feature discrimination removed $r = +.37$). Pisoni and Geers interpreted this finding as demonstrating the influence of "processing variables"—that is, "skills and abilities that have to do with the encoding, storage, retrieval and rehearsal of phonological representations of spoken words" (Pisoni & Geers, 1998, p. 342). Their findings on auditory digit spans were replicated more recently in a new sample of CI users (one of the two groups reported on in the current paper). Reanalysis of the pooled data set (N=88) showed that statistically significant correlations of at least +.30 still remained, even with a wholesale (albeit non-ideal) statistical "partialing-out" of the 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, 1999). Examination of the same data using the closely related procedure of factor analysis has led to a similar result (Geers, 1999). These 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 (1999) has 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 development of oral/aural language skills in pediatric cochlear implant users.

Surprisingly, relatively little other research has focused directly on short-term auditory memory in users of cochlear implants. Lyxell et al. (1996) have, however, examined whether for adult cochlear implant users it might be "possible to predict the level of speech understanding [post-implant] by means of a preoperative cognitive assessment." Since 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 speech-reading/lip-reading 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, there was no evidence of working memory capacity serving as a strong predictor of speech reading ability—they have, as yet, only examined the case of post-lingually deafened adult cochlear implant users, and not pre-lingually deafened pediatric users of CIs.

In another, more clinically-oriented study of post-lingually deafened CI users, Gantz, Woodworth, Abbas, Knutson, and Tyler (1993) identified six preoperative measures to account for approximately two-thirds of the between-subject variability in sound-only open-set word recognition scores nine months post-implant. 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 sequence 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 et al., 1991). In another paper by this research group on the skills of post-lingually deafened adults, the scores on this same visual monitoring task were again found to correlate between +.30 to +.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 evidence that the skills tapped in such typical "visual monitoring" tasks develop somewhat atypically in at least some pediatric CI users as compared to normal-hearing children. Quittner, Smith, Osberger, Mitchell, & Katz (1994) used a task similar to Gantz et al.'s with normal-hearing and hearing-impaired children (cochlear implant and hearing aid users) ages 6 to 13 years. 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 6-8 years age range, and while this difference was not statistically significant in the older age range of 9-13 years (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 the Quittner et al. sample, these 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.

EXPERIMENT 1

The task employed in this report is neither the traditional verbal auditory digit span measure used in Pisoni & Geers (1998) (although digit span measure was also gathered for comparison purposes), nor the visual monitoring task used by Quittner et al. (1994) (though it shares some characteristics with this task). Instead, the "memory game" procedure used in this study involves the presentation of a sequence of sounds in conjunction with a sequence of colored lights located behind a series of four large translucent buttons mounted on a response box modeled after the popular Milton Bradley electronic game "Simon™". (See Figure 1.) The task requires the child to immediately reproduce the target sequence by pressing on the appropriate buttons in the proper order thereby causing the synchronized sounds to be heard as the buttons are pressed. The difficulty of the task is adjusted by increasing the list length of the sequence to be reproduced when the child is doing well, and shortening it after an error is made. A computer program monitors the child's performance using an adaptive testing algorithm and records the longest list length a child is able to attain under a given set of conditions as a measure of "memory span". Further details can be found in Carlson, Cleary and Pisoni (1998) and in our Methods section below.

The motivation for using this particular response format was to obtain a measure of memory span using a non-linguistic manual response, rather than a spoken or signed verbal response as is used in traditional digit span tasks. A non-linguistic manual response was adopted to avoid 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 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 tested 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 auditory-plus-visual-spatial condition, a spoken digit-name was arbitrarily assigned to each of the four response buttons and consistently presented whenever the matched button was illuminated (see Figure 1).

From a previous study by Cleary (1997), we knew that it was possible to obtain a measure of working memory span from normal-hearing adults using our proposed manual response format. In a later study we then attempted to use a similar procedure to compare preschool-age children's memory spans in three different conditions--when a light sequence was presented in conjunction with a sequence of nonsense syllables, in conjunction with a sequence of auditory digit-names, and alone, without auditory stimuli (Carlson, Cleary, & Pisoni, 1998). Although the procedure used was very similar to that of the current study, we obtained no significant differences between the stimulus conditions. However the children in the Carlson et al. study were 45 normal-hearing three- to five-year-olds, not all of whom were able to do the required task with any reasonable amount of facility. Additionally, we had not yet at that point introduced the new color-name condition, which we are now using to examine the effect of informational redundancy across two modalities of input.

Prior to conducting the current study, we had also established that children with cochlear implants could be reasonably asked to complete the task since we had piloted the procedure with a group of 19 pediatric CI users, ranging in age from 5; 7-11; 11 (Cleary, Pisoni & Kirk, 1998). The results from this previous study were, however, difficult to interpret due to the wide variation in age, experience with the implant and duration of hearing loss present within the sample. The pediatric CI users in the current study constituted a much larger and far more homogenous sample. Since all children in the current study had used a cochlear implant for at least four and a half years, we also judged it more likely that the mechanisms of phonological working memory might have developed at least partially in some members of this sample, than if relatively inexperienced users had been selected.

We believed that our new choice of stimulus materials, access to a relatively homogeneous CI group, and the use of an age group that was consistently able to do the task would permit us to examine the effects of interest. We expected to find improved performance as a function of multi-modal stimulus presentation to be less apparent in the hearing-impaired group as a whole, although we expected the CI users with better open-set word recognition skills to behave more like the normal-hearing children in utilizing this redundant information. We were particularly interested in comparing the performance of the subset of cochlear implant users who were able to correctly discriminate/identify all the auditory stimuli when presented in isolation, with the normal-hearing group's performance on the memory game task. Although the previous research on visual monitoring in pediatric CI users was suggestive, the CI group was not necessarily expected to perform differently from the normal-hearing children on the *visual-spatial-only* version of the memory game task, unless the encoding of the button locations was perhaps attempted by one or both groups using a verbal encoding strategy.

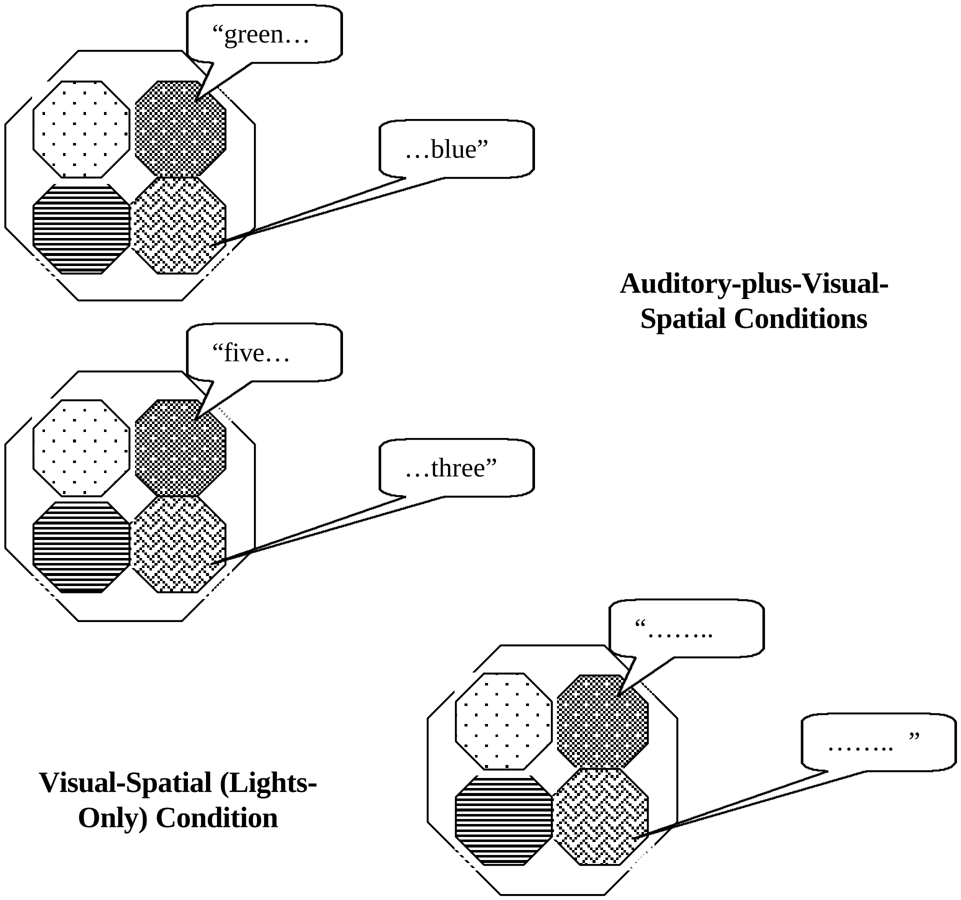

Figure 1. Diagram of memory game apparatus and experimental conditions given a list length of two items. Each shaded hexagon represents a large colored button back-lit by a light. All auditory stimuli were presented via a loud speaker located just behind the memory game response box. The verbal labels simply illustrate the consistent mapping between a particular auditory stimulus and a given button location.

A comparison of performance between traditional verbal digit span measures and the three different conditions of our memory game task in both groups of children was also planned. Since the traditional verbal 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.

Method

Participants

Forty-five pediatric cochlear implant users were recruited as part of a large ongoing study by the Central Institute for the Deaf (CID). Participants were pre-selected by CID to demonstrate relatively low variability in chronological age (between eight and nine years of age) and device experience (at least four years of use) (see Geers, 1999 for details). The forty-four children who were retained in the final analysis evenly spanned the age range between 8 years, 1 month and 9 years, 10 months. Nineteen were female and 25 were male. The average age at onset of deafness ranged from 0 - 36 months. The mean age at onset of hearing-loss was four months of age with the majority of participants reported as congenitally deaf. Experience with the CI device varied between 4 years, 3 months, to 6 years, 9 months. The mean duration of CI use was approximately 5 years, 5 months. The duration of deafness prior to implant ranged from three months to five years, the mean being just slightly over three years. Each child's experience with oral vs. manual communication methods was quantified by determining the type of communication environment experienced by the child in the year just prior implantation and then each year over the four years of CI use prior to the current testing. A score was assigned to each year, with a "1" corresponding to the use of "total communication" with a sign emphasis (that is, extensive use of manual signs in addition to spoken language using an English, not ASL, grammar), and a "6" indicating an auditory-verbal environment with a strong emphasis on auditory communication without the aid of lipreading (see Geers et al., 1998 for details). Communication methods intermediate between these two extremes were assigned intermediate scores ranging from 2 to 5. These scores were then summed over the five points in time to produce a communication mode score ranging from 5 to 30. The mean summed communication mode score for the forty-four participants was approximately 19 on this scale. The cochlear implant devices used by the children contained anywhere between 6 to 20 active electrodes, with the group mean being 17+ active electrodes.

Forty-five normal-hearing (NH) children were also recruited for this study as a comparison group. The normal-hearing children were matched for gender and chronological age with the CID group. The mean age for both groups was 106 months (8 years, 10 months). A hearing screening was conducted for each child at 250, 500, 1000, 2000 and 4000 Hz at a level of 20 dB HL using a Maico Hearing Instruments pure-tone audiometer (MA27) and TDH-39P headphones. (A response at 25 dB HL was accepted for 250 Hz due to ambient room noise). Left and right ears were screened separately. Of fifty-three NH participants recruited, data from eight children were not included in the analysis due to one of the following reasons: the child failed the hearing screening, equipment malfunction, experimenter error, or a suitable age and or gender match was not among the hearing impaired CI group (some recruitment for this study began before the CID testing was complete).

Materials and Procedure

The auditory stimuli were created by recording a single male speaker of American English in a sound-attenuated, single-walled anechoic recording chamber (Industrial Acoustics Company Audiometric Testing Room, Model 402) using a head-mounted close-talking microphone (Shure, Model SM98). The talker was recorded saying the words "red," "blue," "green," "yellow," "one," "three," "five," and "eight" in a clear voice at a moderate to slow rate of speech. Each word was spoken in isolation. The recordings were digitally sampled on-line at 22.05 kHz with 16-bit amplitude quantization using a Tucker-Davis Technologies (TDT) System II with an A-to-D converter (DD1), and a low-pass filter of 10.4 kHz (anti-aliasing filter, FT5), controlled by an updated version of Dedina's 1987 "Speech Acquisition Program" (Dedina, 1987; Hernandez, 1995). The amplitudes of the individually edited speech files were then adjusted using a digital leveling procedure such that the average RMS amplitudes for each file were approximately equated. All auditory materials were presented via a single loudspeaker (Advent AV280, 10 Watts amplifier output power, THD < 1%, frequency response 70 Hz-20 kHz) at approximately 70 dB SPL as determined via a hand-held sound level meter (Triplett Model 370) held at approximately the level of the child's head.

Presentation of the stimuli was controlled by a computer program specially created for this purpose, running on a PC computer. The response box used to collect the child's button presses consisted of a large round disk-like plastic case approximately ten inches in diameter housing four wide plastic buttons on its surface. The four buttons were each approximately one quarter of the surface area of the response box in size and could be easily depressed by a child. Each button was made of a different color plastic and could be illuminated by a light located beneath its surface. The colors of the buttons matched the color-names that were recorded as stimuli. The button response box was interfaced to the PC computer so that the control program could illuminate the lights when the sound stimuli were played, and dim the lights once the stimuli ceased outputting. The computer also recorded all button presses and automatically tracked the subject's performance using an adaptive testing procedure further described below.

The CI users were all tested by professional clinicians and researchers experienced in working with hearing-impaired children as part of a larger study being conducted by the Central Institute for the Deaf (see Geers, 1999). The normal-hearing participants were tested at the Speech Research Laboratory at Indiana University by graduate and undergraduate research assistants. All children were tested individually in a quiet room. Each condition of the memory game task took approximately four minutes to complete.

Identification Testing. Before the memory game was administered, each child was asked to identify the recorded tokens of the digits and color names by pointing to one of four numerals printed in large lettering on a piece of paper or one of four large colored squares. These tokens were presented one at a time through the same loudspeaker as used for the memory game. The digit-names and color-names were presented separately in two sets. If a child correctly identified all four items in a set on the first attempt, no further identification testing was administered. If one or more errors were made, the identification task was repeated up to three times, or until zero mistakes were made on a given set of stimuli, whichever occurred first. Twenty-one CI children identified all four digit-names correctly on their first try. Twenty-two CI children did the same for the four color-names. Identification of the stimulus "eight" appeared to pose a problem for many of the pediatric CI users. Eighteen of the forty-four CI children misidentified this item one or more times during this pretest. Errors on the set of color-names were randomly distributed across the set of four stimuli. None of the normal-hearing children misidentified any of the stimuli from either set during the same identification task. Regardless of identification errors made, the memory game task was administered next.

Memory Game Task. Participants were shown how the buttons on the response box could be pressed and were told that they would be hearing sounds through the loudspeaker and seeing the buttons light up. They were then instructed to "pay attention and copy exactly what the computer does by pressing on the buttons." A hypothetical example was given to insure that the child understood what was being of asked of them: "So for example, if you hear 'blue' ('one') and then 'green' ('three') (pointing consecutively to two buttons), I want you press the blue button/this button and *then* the green/that one. Do you understand?"

Sequences used for the memory game task were generated pseudo-randomly by a computer program, with the stipulation that no single item would be repeated consecutively in a given list. A very brief inter-stimulus interval of 200 ms was used between sequence items. However, since the individual stimuli had been recorded at a relatively slow speech rate, the rate of presentation was about 1.5 items per second. Each child started with a list length of one item. If two lists in a row at a given length were correctly reproduced, the next list presented was increased by one item in length. If on any trial the list was incorrectly reproduced, the next trial used a list one item shorter in length. This "adaptive tracking procedure" is similar to methods typically used in psycho-acoustic testing (Levitt, 1970). If the child made no response within four seconds after the last target item was presented, the sequence was presented again up to two additional times. The child was not told what rules were governing the presentation of the stimulus items. The strategy of waiting for re-presentation of the sequence (e.g., a second, or third time) was not permitted by the tester. The computer recorded when and if a child was permitted an extra repetition of the list. Very few trials involved such repetitions. Twenty unique trials were presented total, for a maximum possible list length of ten items. The experimenter provided no explicit feedback regarding the accuracy of the child's responses. Verbal encouragement was given only to keep the child on task during the procedure.

The independent variable of stimulus type (color-names vs. digit-names vs. silence/lights-only) was administered within subject. All children were presented with twenty lists to reproduce in each of these three conditions. The silent/lights-only condition was always completed last in the series of three conditions, but the two auditory-plus-visual-spatial conditions (color-names and digit-names) were counterbalanced across subjects. This procedure was followed based on practice effects evident in pilot testing, and a desire to not encourage purely visual-spatial encoding in a third of the children by introducing them first to the task in which no auditory stimuli were presented. Since the silent/lights-only condition was assumed to be the most difficult of the three conditions, placing it last in the series, when coupled with practice effects raising scores later in the testing session, can be reasoned to conservatively work against finding significant differences between the conditions.

WISC Digit Span. Children in both the CI and normal-hearing groups also completed the WISC Digit Span Supplementary Verbal Sub-test of the Wechsler Intelligence Scale for Children, Third Edition (WISC-III) (Wechsler, 1991). This task requires the child to repeat back a list of digits as spoken live-voice by an experimenter at a rate of approximately one digit per second (WISC-III Manual, Wechsler, 1991). In the "digits-forward" section of the task, the child is required to simply repeat back the list as heard. In the "digits-backward" section of the task, the child is told to "say the list backward." An example of reversing a list length of two items is provided and a practice trial is given for the backward task. In both parts of the WISC task, the lists begin with two items, and are increased in length upon successful repetition until a child gets two lists incorrect at a given length, at which point testing stops. Points are awarded for each list correctly repeated with no partial credit. The WISC-III testing manual provides two lists for use at each list length, with the possible list length ranging from two to nine items in the forward condition, and from two to eight items in the backward condition. Items are not repeated consecutively within any list and each list is unique.

Although the CID research group gathered a large number of other language-related measures from the CI children as part of a larger study (Geers, 1999), only the short-term/working memory tasks (the memory game and WISC digit span) are reported here. Other analyses will appear in a future report.

Vocabulary Screening Measure. Finally, the Peabody Picture Vocabulary Test, a measure of receptive vocabulary (PPVT-III Form A, Dunn & Dunn, 1997) was administered to all normal-hearing children to obtain a general measure of verbal language development. In this task, a word is spoken by the experimenter and the child is asked to "point to the picture that means the same thing" from a selection of four different line drawings. The child begins the task hearing words known to be familiar to children in his/her age group, and the vocabulary is then adjusted in difficulty for the individual child until "floor" and "ceiling" word sets are established. Every NH child tested obtained a standardized score above one standard deviation below the mean.

Results and Discussion

One CI participant (98313) failed to complete the memory game task, reducing the number of participants in that group to 44. The matched hearing child (8251) was also dropped from the analysis. Our primary dependent measure for performance on the memory game task in each condition was the longest list length that the child was able to correctly reproduce at least once during that condition. However, we also computed the longest list length each child was able to correctly repeat on at least half the trials at that length for each condition, as well as the longest list length he/she correctly reproduced on *every* trial administered at a given length. After our initial analysis however, we became concerned that our planned scoring methods might be overly "coarse" and could be collapsing meaningful differences between individual children. Therefore, we also computed a "weighted" score for each child. This weighted score was calculated by finding the proportion of lists correct at each list length (e.g., the child correctly reproduced four of six lists presented at a list length of four items = 0.667), and this proportion was summed across all list lengths. (The use of an adaptive testing algorithm entailed that different subjects experienced a variable number of lists of any one given length.) Across all 88 children, this weighted scoring method correlates $r = +.95$ with the "at least once" measure, $r = +.93$ with "half the time" measure and $r = +.80$ with the "all lists at that length" measure. The weighted score is also more continuously distributed and results in a more normal-looking, less jagged distribution of scores--a necessary characteristic if correlational analyses are to be attempted. Figure 2 provides a comparison of results from the two groups using the four different scoring methods for the data. We will not consider the "half" or "always" scoring methods any further, but similar conclusions can be drawn from these alternative ways of analyzing the data.

An alpha level of .05 was adopted for all statistical tests reported below. A 2 x 3 mixed factorial repeated measures analysis of variance for hearing status (NH vs. CI) and stimulus condition (digit-names, color-names, lights-only) on the "at least once" memory game scores demonstrated a within-subjects main effect of stimulus type, $F(2, 172) = 7.02$, $p = 0.001$, and a between-subjects main effect of hearing status, $F(1, 86) = 23.41$, $p < .001$. Normal-hearing children obtained significantly higher scores than the pediatric CI users in every condition of the memory game task. No significant interaction was found between stimulus type and hearing status ($F\ (2, 172) < 1$, $p = 0.47$) indicating that the advantage of the NH children was not significantly greater in the auditory-plus-visual/spatial conditions than in the visual-only conditions. Post-hoc Bonferroni pair-wise comparisons between the three stimulus type conditions over both hearing status groups indicated a significant difference between the means for the color-name and silent/lights-only conditions (adjusted $p = .01$), and a marginally significant difference between the color-name and digit-name conditions (adjusted $p = .054$). No statistically significant difference was obtained between the digit-name and silent/lights-only conditions (adjusted $p = .69$). This same analysis using the weighted scores resulted in an analogous set of results: main effects of stimulus type ($F(2, 172) = 11.77$, $p < .001$) and hearing status ($F(1, 86) = 32.9$, $p < .001$), and no significant interaction ($p = .24$).

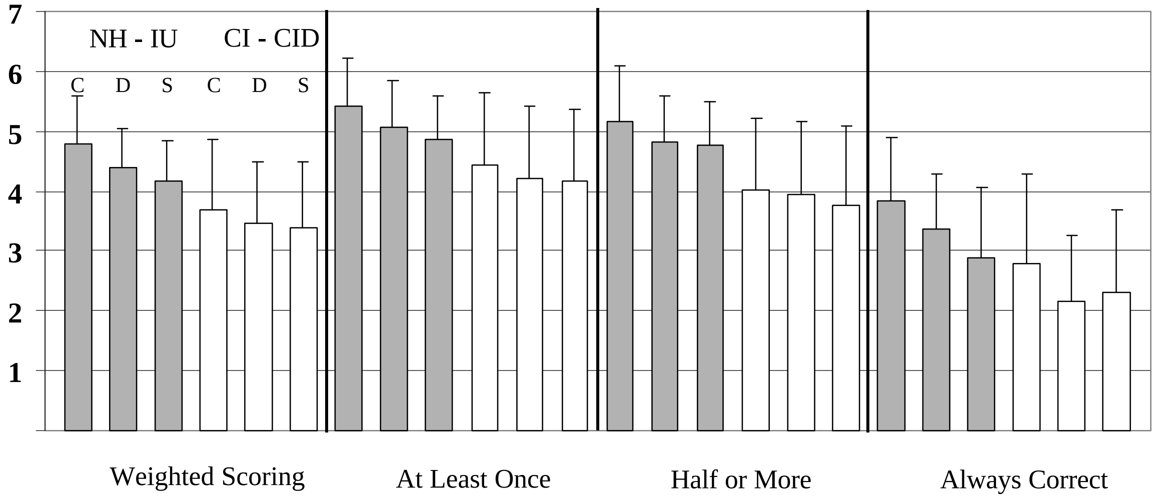

Figure 2. Comparison of performance on the memory game task across different stimulus types in normal-hearing and pediatric cochlear implant users. Hatched bars indicate the normal-hearing participants. Light bars indicate the CI users. "C" = color-names, "D" = digit-names, "S" = silent/lights-only. Heavy weight vertical lines separate the four different scoring methods described in the text. Error bars indicate one standard deviation.

A one-way repeated measures ANOVA and three pair-wise comparisons between the stimulus conditions were then conducted individually within each group of children (NH, CI) to determine if the main effect of stimulus type held up within each group considered independently. Using the "at least once" dependent measure, no significant effect of stimulus type was found for the CI group (p = .21). Using the "weighted score" measure, this effect still did not reach significance (p = .08). Within the normal-hearing group, however, the effect of stimulus type on the "at least once" measure was significant, $F(2, 86) = 6.34$, p = .003. Post-hoc Bonferroni pair-wise comparisons indicated that within this NH group, only the difference between color-name and silent/lights-only conditions was statistically reliable--(adjusted p = .002). The comparison between color-names and the digit-name conditions yielded an adjusted p = .11, between digit-names and silent/lights-only, adjusted p = .61. When the "weighted scoring" method was used, the difference between the color-name and digit-name conditions reached statistical significance (p = .026), otherwise duplicating the above results.

As expected, these results show that the normal-hearing children did obtain longer "spans" on average, when auditory stimuli were presented in conjunction with the visual-spatial light sequence. However, this advantage was only statistically reliable when the verbal cues were "semantically redundant" with salient characteristics of the spatial-locations to be remembered. That is to say, merely providing a consistently matched auditory stimulus (i.e. the spoken digit-names) did not provide reliable benefit. Examination of Figure 2 suggests that while the differences in performance among the stimulus conditions followed the same overall pattern in the CI group, the within group variability among the pediatric CI users was too large for the stimulus type manipulation to yield reliable differences. Children in the CI group did not appear to use the informationally redundant auditory cues as effectively as the normal hearing children.

We had, however, naturally expected that the CI children who were obtaining lesser benefit from their implant would be less able to utilize the supplementary auditory information during sequence presentation and would therefore do similarly on all three memory game conditions. To test whether the stimulus type manipulation had any differential impact depending on the children's level of auditory speech perception skill, the CI group was subsequently divided in two subgroups according to whether or not errors were made on the stimulus identification pretest. As shown in Figure 3, *no* significant differences in memory game performance were found between the two groups. The small differences obtained between means were not even consistently in one direction, although somewhat greater variability was evident within the CI group that made one or more identification errors on the pretest. We were surprised by this result, since we had had strong expectations that the CI users who had better word identification skills would behave more like the normal-hearing children. We then conducted two other splits of the CI group that we thought should also yield the expected pattern. The first split was by number of color-name identification errors (zero vs. one or more errors). No difference was found between the groups. In the second split we sorted the CI users into two groups using an independent measure of open-set word recognition ability. The CID research group had obtained these open-set word recognition scores from the children for a separate purpose within about a week of the memory game testing. Children that scored above 40% correct on the Lexical Neighborhood Test “Easy” word lists (Kirk, Pisoni, & Osberger, 1995) were placed in one group, and those that scored below 40%, in the other. Once again, contrary to expectation, the two CI groups created in this manner performed equivalently on the memory game task regardless of stimulus type.

This pattern of results suggested to us that most of the CI children who were *able* to consistently identify the memory game speech tokens were *not using* auditory information to do the memory game task. That is to say, despite the fact that a subset of the pediatric CI users had fairly good auditory-only word recognition skills, these children were performing our memory game task in a manner more similar to the CI users with poor word recognition skills, than to our age-matched normal-hearing controls. We suspected that this result might have to do with the visual/spatial component that is present in all conditions of the memory game task. To further test this notion, we retained the split of the CI users into two groups according to each child’s identification of the four digit-names: zero errors (n=21), one or more errors (n=22). We then compared the performance of the two groups on the verbal WISC digit span measure, a task that includes little to no visual-spatial component. This memory span measure is, however, scored in a different manner than our memory game measure: the child is tested on two lists at each list length starting at three items, with the list length increasing after every two trials until both lists at a given length are incorrectly repeated, at which point, testing stops. A point is awarded for every list correctly reproduced. Thus, this score cannot be directly equated with a “list length” measure of “span capacity.” The two right-most bars in Figure 4 show the obtained difference in scores between the two CI groups. A t-test for independent groups showed this difference to be statistically reliable ($t(41) = 2.57$, $p = 0.014$).

A difference between the two CI groups is thus clearly evident when the memory task used is primarily auditory and requires verbal coding (i.e., the WISC digit span task), but not when performance on the memory game task (with its visual-spatial component) is examined. This result is consistent with the fact that although significant correlations existed in this CI group between communication mode and WISC verbal digit spans (Pisoni & Geers, 1998),[5] these correlations were not replicated with any of our memory game measures and communication mode. All correlations computed between the memory game task conditions and communication mode were in fact, negative, though negligible in size. (Recall that high communication mode scores reflect a more oral communication emphasis, and lower

---

[5] The correlations between communication mode and forward WISC digit span were as follows: simple bivariate $r = +.42$; with speech feature discrimination and age partialed out, $r = +.30$; with speech feature discrimination, age and open set-word recognition scores partialed out, $r =+.12$.

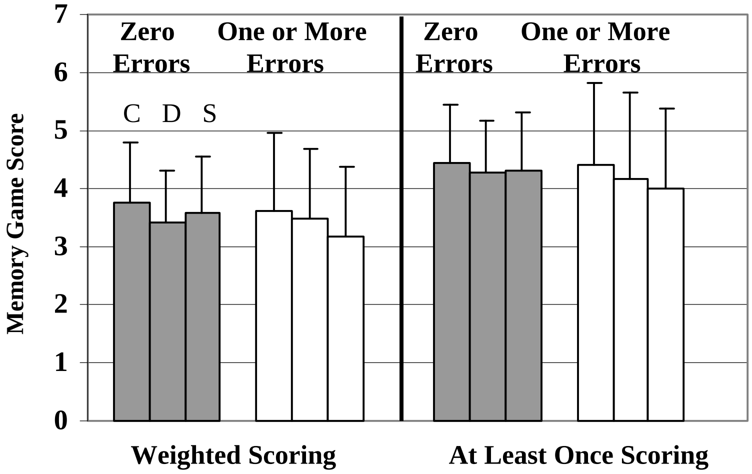

Figure 3. Performance on the memory game task in the group of pediatric cochlear implant users split by number of errors made in the digit-name identification pre-test. Striped bars indicate mean spans for the twenty-two children that made no errors. White bars indicate mean spans for the twenty-two children that made one or more errors. "C" = color-names, "D" = digit-names, "S" = silent/lights-only. The dark vertical line separates two different scoring methods as described in the text. Error bars indicate one standard deviation.

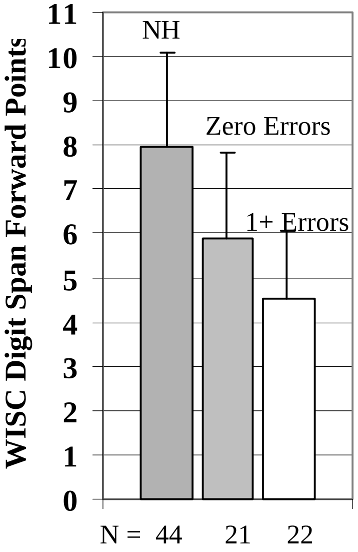

Figure 4. A comparison of the WISC forward verbal digit spans across groups. NH = normal-hearing. The CI group is subdivided into two sub-groups depending on whether zero vs. one or more errors were made identifying the four digit-names used in the memory game task. One CI child (98114) did not complete the WISC verbal digit span task although memory game spans were obtained from this child. This child's data is not included in Figure 2. Error bars indicate one standard deviation from the mean.

communication mode scores, a more manual-sign oriented emphasis.) This result indicates that greater experience with oral/aural methods of communication did not predict improved performance on the memory game conditions involving auditory stimuli.

Table I lists the intercorrelations between the children's scores in the three different within-subject conditions of the memory game task. The observed high intercorrelations between the different conditions of the memory game would be expected in the CI group, if it were the case that the children in this group were approaching each of the three conditions in the same manner using a visual-spatial coding strategy regardless of whether the additional auditory component were present. On the other hand, the normal-hearing children demonstrate low correlations between the memory game conditions, suggesting the use of different strategies in each condition. This proposal is somewhat weakened by the lack of substantial correlation between the two conditions using auditory stimuli. The data indicate, however, that although the normal-hearing children found hearing the color-names to be helpful, the digit-names produced less of a redundancy gain because they were arbitrarily, not semantically, paired to each colored button location.

Table I also shows that the WISC verbal digit span measure in general showed little correlation with the memory game measure. This lack of correlation cannot be attributed to lack of range in the scores, because the "points" method of scoring the WISC forward span task, and the weighted method used to score the memory game task are both normally distributed enough to permit correlation calculations. The only indication of a sizable positive correlation is between WISC forward digit span and the memory game color-name scores in the normal-hearing group – probably the only set of conditions under which verbal strategies contributed measurably to performance on the memory game task. The failure to find this same pattern of correlations among the CI participants, taken together with this group’s failure to demonstrate a redundancy gain in the color-name condition, suggests that the pediatric CI users tended to use primarily visual-spatial cues to perform the memory game task.

Table I also includes a column that lists the correlations of the memory tasks just discussed with WISC *backward* digit span (WISC-BPTS). This task requires the child to reverse the order of the numbers when recalling the presented list and is scored in the same manner as the forward digit span measure. The common theoretical interpretation of the backward span task is that since it requires an effortful strategic manipulation of the presented items, it is a better measure of “working memory” than the immediate forward repetition digit span task (Lezak, 1995). Table I shows that although there are consistent small to moderate correlations between the memory game task conditions and WISC backward digit span, there is almost zero correlation between the memory game task conditions and WISC forward digit span in five of the six correlations computed between these measures. This pattern of correlations suggests that the memory game task has more in common with the backward WISC digit span task than with the forward digit span task. This certainly appears to be true in the case of the CI users, and less strongly so, in the normal-hearing group as well. We speculate that this may have to do with component of the reversal task that could be described as “spatial manipulation” of the items in order to effect the reversed list. Perhaps this shared visual-spatial aspect is responsible for the larger correlations between the memory game and the backward rather than forward verbal digit span task in these children.

From the results thus far presented, then, several findings emerge that may have general implications beyond the circumstances of our particular study. Firstly, the normal-hearing children demonstrate a redundancy gain--longer memory spans for auditory-plus-visual-spatial sequences than for visual-spatial-only sequences--when the auditory stimuli bear semantic relevance to characteristics of the matched button locations. When the auditory stimuli are paired in an unfamiliar, seemingly arbitrary way

Table I.

Intercorrelations between WISC forward digit spans (WISC-FPTS), the three memory game conditions ("weighted" scoring), and WISC backward digit spans (WISC-BPTS).

	Cochlear Implant Group, N=43					Normal-Hearing Group, N=44				
	WISC-FPTS	**Colors**	**Digits**	**Silent**	**WISC -BPTS**	**WISC -FPTS**	**Colors**	**Digits**	**Silent**	**WISC -BPTS**
WISC-FPTS										
Colors	.09					.58**				
Digits	-.02	.66**				.08	.16			
Silent	-.02	.71**	.64 **			.01	.20	.09		
WISC-BPTS	.52**	.46**	.23	.48**		.32*	.36*	.17	.19	

Note: *p < .05. **p < .01. Although age in months has been partialed out of the calculations, age showed only a small positive correlation in the NH group and a near-zero correlation in the CI group, making the simple correlations almost identical to those in Table I.

to the spatial locations, even normal-hearing children show little benefit from having multi-modal sources of input. From these results we are also led conclude that within the CI group our memory game task is yielding measures primarily of visual-spatial memory span. If this is the case, however, we still need to account for the fact that the hearing-impaired children as a group did less well than the normal-hearing children, not just on the conditions of the memory game task that utilized auditory stimuli, but also on the visual-spatial "lights-only" condition. This is an interesting and somewhat unexpected finding. We discuss this point further below and offer some tentative explanations why this result was obtained.

Gender Differences in Performance. Next we briefly report one analysis that was conducted post-hoc stemming from an inquiry we received regarding possible gender differences in the development of verbal vs. visual-spatial short-term memory skills. In previous research, males have been reported to show an advantage over females on measures of spatial memory span (e.g., Grossi, Orsini, Monetti, & De Michele, 1979). It has also been claimed that female children tend to have more advanced verbal skills compared to their age-matched male peers (Kramer, Delis, Kaplan, O'Donnell, & Prifitera, 1997), with the origin of this difference being hotly debated. Several studies however, report *no* advantage of females over males on the traditional verbal digit span task (e.g., Grossi et al., 1979).

No significant gender differences were found in either group on the memory game tasks, although in the CI group the males did somewhat better on all conditions of the memory game (see Table II). There was, however a significant difference between the male and female groups overall on the WISC verbal forward digit span measure, with the females (n=37) scoring significantly higher than males (n=50), t(67.596--adjusted df, equal variances not assumed) = 3.06, p < .01. This gender difference shows up independently in both the NH and CI groups. Note that this result differs from the usual lack of difference reported in some of the literature previously cited.

Table II.

Memory Game mean scores as a function of Gender and Hearing Status. The normal-hearing group's Vocabulary scores (PPVT-III) are also shown.

		Female		Male	
Normal-hearing		Mean	SD	Mean	SD
Vocabulary	Vocab. Raw Score	130.74	12.48	131.96	18.18
	Vocab. Standard Scr.	111.63	9.45	112.40	14.21
Memory Game Weighted Scoring	Color-names	4.88	1.02	4.72	.63
	Digit-name	4.45	.75	4.36	.57
	Silent/Lights-Only	4.15	.65	4.16	.75
Memory Game At Least Once Scoring	Color-names	5.47	.96	5.36	.70
	Digit-name	5.05	.85	5.08	.76
	Silent/Lights-Only	4.84	.69	4.88	.78
CI Users					
Memory Game Weighted Scoring	Color-names	3.42	1.21	3.89	1.15
	Digit-name	3.34	1.07	3.54	1.02
	Silent/Lights-Only	3.08	1.19	3.62	.98
Memory Game At Least Once Scoring	Color-names	4.21	1.27	4.60	1.15
	Digit-name	4.11	1.24	4.32	1.18
	Silent/Lights-Only	3.79	1.18	4.44	1.16

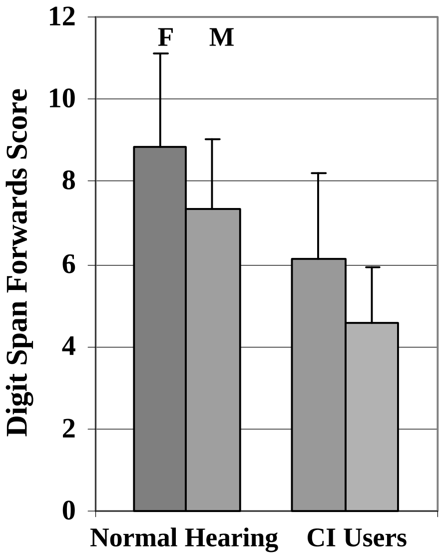

Figure 5. Differences in Forward WISC verbal digit span (scored by points) as a function of gender ("F" = female, "M" = male) and hearing status.

Figure 5 displays the main effects of gender and hearing status, and lack of any interaction. An overall age difference between the male and female groups can be ruled out, because the means and range of ages for all four sub-groups (gender x hearing status) are virtually identical. (The groups are however, unequal in size.) As can be seen in Table II, the standardized vocabulary scores obtained for our NH group showed no difference as a function of gender. This may have to do with how the PPVT-III is constructed—namely to avoid the inclusion of gender-biased test-items. Although we think it is worth mentioning these findings here, the gender-related results require further study before any firm conclusions can be drawn since they were conducted entirely post-hoc and could well be due to chance. The one conclusion that we feel *can* be safely drawn from these results, however, is that once again, we have evidence that results using our memory game task fail to resemble results obtained using an auditory-only short-term/working memory task such as WISC forward digit span, since only the latter showed clear gender-based differences.

Conclusions

In summary, we were able to show in Experiment 1 that normal-hearing school-age children were sensitive to the informational redundancy present in the color-name condition of the memory game task. The hearing-impaired pediatric CI users that participated in our study did not reliably demonstrate this same sensitivity. Contrary to expectation, the CI users that demonstrated good open-set word recognition skills failed to behave similarly to the normal-hearing comparison group. The data also indicated that the hearing-impaired children did less well than hearing children even on a condition of the memory game task that provided only visual-spatial target sequences to be remembered.

From the results obtained from the CI group, we realized that the large visual-spatial component of our memory game task might endanger its utility as a means of obtaining measures of auditory short-term/working memory in CI users. We therefore decided to explore ways of making the memory game task more “auditory” in nature without having to dispense with the manual response method. To address this issue, a subset of our normal-hearing subjects were asked to complete an additional condition of the memory game task, as described below in Experiment 2.

EXPERIMENT 2

In order to try to discourage purely visual-spatial processing of the target sequences, a subset of the normal-hearing participants tested in Experiment 1 was asked to play an additional “round” of the memory game in which sequences of color-names were played through the loudspeaker. This time however, the auditory stimuli were presented *without* the lights flashing synchronously on the memory game response box. Thus, on a given trial, a child might hear the list “red, green, blue, red,” output via the loudspeaker, but no lights would be presented on the response box as the target sequence was played. The child would then have to manually reproduce the sequence by pressing the appropriately colored buttons on the response box.

We planned to compare memory spans obtained in this condition to spans obtained when lights *were* presented at the same time as the color-names. Lower spans were expected for the “auditory-only” condition. This finding, if obtained, would provide additional demonstration of the informational redundancy present in the original color-name condition used in Experiment 1.

Method

Participants

Twenty-seven of the original forty-five normal-hearing subjects participated in this condition. This task was added after the data from the CI users in Experiment 1 had been collected, and the collection of data from the matched group of normal-hearing children had already begun. Thus, this task was not planned as part of the experiment proper, but rather as a procedure to be piloted for future use (as will be reported in Experiment 3).

Materials and Procedure

On each trial, the target sequence consisted of an auditory list of color-names presented without illumination of the colored lights. The mapping between auditory stimulus and spatial button location was thus made less visually salient during the target list presentation. The child's task was still to reproduce the sequence by pressing the color-matched buttons in the proper order. Both sound and light were initiated by the subject’s button press responses in order to convey that each press had registered and to provide the subject with the same minimal amount of feedback as had been present in the original task.

The administration of this task was not counterbalanced across subjects, but was always run after the three memory game conditions described had been completed, following a short break. Admittedly, due to the lack of counterbalancing, it is possible that any differences obtained might be artifactual.

All hardware and stimulus materials were otherwise identical to those used with the normal-hearing children in Experiment 1. The child was told before starting that “you will not see the lights light up this time, so listen carefully, and copy what you hear by pressing on the buttons just like before.”

Results and Discussion

Figure 6 (left panel) shows the mean span for the new “audio-only” version of the task (“A”) plotted next to the mean spans from Experiment 1 for color-names in the auditory-plus-visual-spatial condition (“A+V-S”) and the visual-spatial-only condition (“V-S”). This comparison suggests that although the sound-only condition means are reduced, the normal-hearing children are clearly able to complete the task without the visual stimuli present in the target sequence. A paired-samples t-test on the weighted scores in the “A” vs. “A+V-S” conditions approached significance ($t(26) = 1.82$, $p = 0.08$). Figure 6 also shows that the normal-hearing children’s mean performance for the “audio-only” condition was actually quite similar to this group’s mean span in the visual-spatial-only condition. Since the conditions were not counterbalanced in administration, the conclusions we can draw from this finding are limited. We suggest however, that this result provides some further evidence that the difference in performance shown by the normal-hearing children in the single-modality vs. multi-modal cue conditions used in Experiment 1 was, in fact, due to the presence of redundant information in the later condition. Use of only a single modality of presentation appears to reduce the NH children’s performance on this task by about the same amount, regardless of which modality is omitted.

From this last set of results, we were eager to try the “audio-only” version of the memory game task with a sample of pediatric CI users. In order to reproduce the sequence of color-names, the CI users would be forced to encode the auditory stimuli since no visual-spatial information would be available.

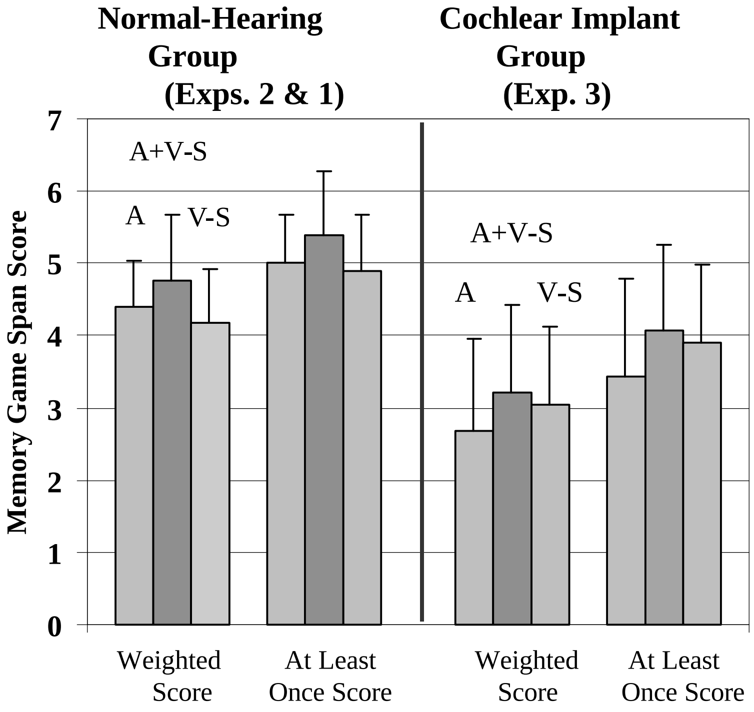

Figure 6. Comparison of group means for the audio-only version of the memory game using color-name stimuli ("A"), with the original version of the memory game using both sounds and lights ("A+V-S"), and the silent/lights-only visual-spatial condition ("V-S"). The left panel contains results relevant to the discussion of Experiment 2 and contains data repeated from Figure 2 (Experiment 1). The right panel presents results relevant to Experiment 3, to follow. Error bars indicate one standard deviation from the mean.

EXPERIMENT 3

Experiment 1 showed that the memory game task in its original form provided measures of primarily visual-spatial memory span from the pediatric CI users rather than tapping mechanisms for auditory short-term/working memory. Experiment 3 gave us the opportunity to confirm this finding in a new sample of 28 eight- and nine-year old users of cochlear implants, but also, more interestingly, to test their performance using the audio-only version of the memory game task as introduced in Experiment 2.

Methods

Participants

Twenty-eight hearing-impaired pediatric users of cochlear implants participated in this study. None of the children in the current experiment took part in Experiment 1. All children were participants in a larger study currently being conducted at the Central Institute for the Deaf. The backgrounds of these children were similar to the pediatric CI users reported on in Experiment 1. Thirteen female and fifteen male children completed the task. The children ranged in age between 8 years 2 months, to 9 years 11 months. The mean summed communication mode score for the twenty-eight participants was approximately

19 on the scale described in Experiment 1, thus once again indicating a group tendency slightly towards more oral communication methods.

Materials and Procedure

At time of writing, only the memory game data from these children are available. Other measures were also collected from this group but will be reported on in a future paper.

Identification Testing. The stimulus identification pre-test was run as described in Experiment 1 except that each child was only asked to identify each stimulus once. Twelve of the twenty-eight children made at least one error on the digit-name identification task. Five children made one or more errors on the color-name identification task. Fourteen of the twenty-eight children that participated identified all eight stimuli correctly.

Memory Game Task. The stimulus materials and hardware used for this study were the same as in Experiments 1 and 2, except that a different PC computer was used to run the program controlling the stimulus presentation. Due to a problem with the setup of this second computer, on some trials, the computer registered a double press when the child pressed a given button for too long. There was a risk therefore of the child being inappropriately penalized for such trials. In tabulating the data collected using this setup, we counted the number of times each child appeared to have inappropriately registered a double press. On average, for each child, this occurred on about two of twenty trials per condition. Some children never encountered this problem. Due to the liberal way in which scores were tabulated, the effect of this technical problem on the "at least once" method of scoring was quite small. The audio-only condition was not affected by this problem and scores on this condition were not similarly influenced.[6] As with the normal-hearing children, the audio-only condition was run last, after all other conditions of the memory game task had been administered.

Results and Discussion

For this new sample of CI users, once again, no significant differences were obtained between the original memory game task conditions (color-names, digit-names, vs. silent/lights-only) although the group means were in the predicted direction (color-names > digit-names > silent/lights only). The group of fourteen children that made zero errors on the identification task did not benefit any more from the redundant auditory information than the children who made one or more identification errors. The correlations among the three original memory game measures were again found to be quite high, as might be predicted if the same strategies were being used in all three tasks. From this result we can be fairly certain that most of the CI users, even those with the ability to identify the auditory stimuli, were not using this redundant auditory information to aid them in doing the original memory game task. Instead, what we obtained from the original task was a measure of visual-spatial short-term/working memory span.

More interesting was the group's performance on the auditory-only color-name condition. Many of the CI users proved able to do this new task with some facility. The right-hand panel of Figure 6, above, provides a comparison of the CI group's performance in the auditory-only color-name condition as compared to the auditory-plus-visual-spatial condition using color-names, and the visual-spatial lights-only condition. (Note that the aforementioned technical problem could only have increased the difference

---

[6] Since the technical problem could only have resulted in lower-than-normal span scores for the original set of stimulus conditions, the difference obtained between the original audio-plus-visual-spatial conditions vs. the new audio-only condition would probably have been somewhat larger if this problem not occurred.

between the bar on the far left of each cluster ("A") as compared to the two bars to the right of each cluster ("A+V-S" and "V-S").) The data shown in Figure 6 indicate that the hearing-impaired children did less well on the auditory-only condition of the memory game. Their memory game spans in this condition were quite reduced as compared to the conditions in which they were provided with visual-spatial cues: planned comparisons (paired-samples t-tests) between the audio-only condition and the audio-plus-visual-spatial condition using color-names yielded a $t(27) = 2.17$, $p = .04$, and between the audio-only condition and the lights-only condition, $t(27) = 1.61$, $p = .12$. Moreover, unlike Experiment 1, those children who had made errors during the stimuli identification pre-test (n=14) did significantly less well on the audio-only version of the memory game task than children who had made no errors (n=14) (t(21.1-equal variances not assumed) = 2.11, $p = .047$). These results provide evidence that it is feasible to use this manual response task with a CI population with the assurance that it will measure phonological working memory span to some degree rather than purely visual-spatial memory span. While it is true that the audio-only condition as described here does not necessarily preclude the child from looking at the appropriate buttons on the response box as the auditory stimuli are played, the elimination of the lights clearly made the task more difficult than when both modalities of input were provided, or when just the visual-spatial input was provided.

An additional analysis was conducted to try to shed further light on whether the revised task truly utilized the desired modality. Since Pisoni and Geers (1998) had reported significant correlations between WISC forward digit span and communication mode, as discussed previously, we computed simple correlations between communication mode and each of the memory game tasks. Again, as in Experiment 1, we found negligible to mildly negative correlations between each of the three original memory game tasks and communication mode. (Recall, once again that high communication scores are associated with more oral/aural communication environments.) The new audio-only variant of the memory game task, on the other hand, showed a small but positive correlation with communication mode ($r = +.30$, $p = .11$). Rather surprisingly, this correlation is actually stronger when only those children who made no errors on the identification task (n=14) were considered alone ($r = +.50$, $p = .06$). From this result we conclude that the auditory-only version of the memory game task can be used to assess auditory short-term/working memory span in a manner similar to the WISC digit span task. The memory game task in this form may in fact, be preferable in some cases, as it avoids the articulatory component inherent in the WISC digit span response format.

Finally, as a point of interest, we present in Figure 7, a profile of the individual subject scores for the auditory-only memory game task for both the normal-hearing subjects in Experiment 2 (N=27) as well as the cochlear implant users in Experiment 3 (N=28). These groups are only approximately matched for age and gender, but there is an interesting conclusion that we feel can legitimately be drawn from this figure. Note that despite their profound deafness as infants and subsequent use of a cochlear implant, the top one-third of the CI children in the distribution of white bars are demonstrating auditory memory spans *equivalent* to the lower one-third of children in the normal-hearing distribution (dark bars). Plotting the WISC forward digit spans of the two groups of children tested in Experiment 1 yields a very similar graph with about the same amount of overlap in scores between the CI and normal-hearing groups. This is a considerable achievement on the part of the pediatric CI users, in light of the circumstances.

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 area 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

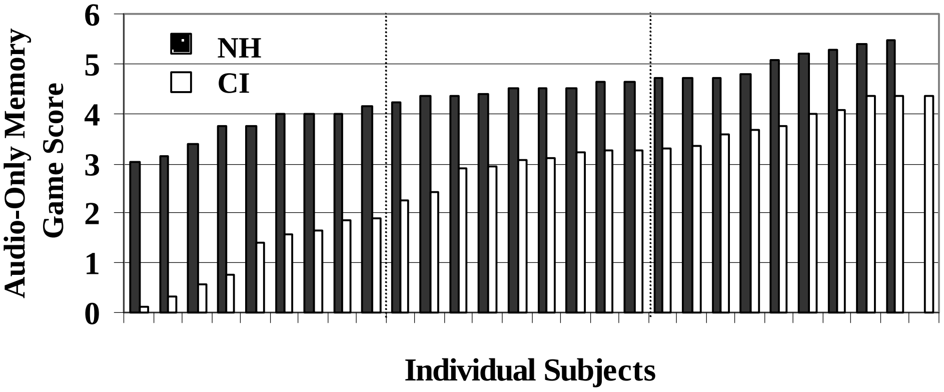

Figure 7. Individual subject data for all children who completed the audio-only version of the memory game task. Normal-hearing children are shown by the dark bars, pediatric CI users using clear bars. The scores for each of the two groups of children have been sorted in rank order of performance. The memory game scores were tabulated using the weighted method as described in the text.

in this paper address some methodological issues regarding the assessment of short-term/working memory in a special population of children for whom the auditory modality has been partially compromised. We conclude that given the opportunity to utilize an intact sensory modality, even experienced school-age users of a cochlear implant will not “automatically” make use of auditory information and verbal rehearsal that might aid them in performing a short-term memory task. That is to say, unlike normal-hearing children, the pediatric cochlear implant users we tested showed little evidence of “integrating” semantically related auditory and visual/spatial stimuli in order to complete the original version of the memory game task. This suggests that fundamentally different sensory coding and/or rehearsal processes may exist in these two populations. Although the cochlear implant is now providing the CI children with access to sound and spoken language, the atypical early experiences of these children are still evident in how they perceive and encode sensory information.

The argument that the cochlear implant users failed to make use of the auditory information simply because it was inaccessible to their sensory systems must account for the results reported for the auditory-only version of the memory game task. Given only the auditory information, most of the cochlear implant using children were able to do reasonably well on the task, as evidenced by a direct comparison to the distribution of scores obtained from normal-hearing children of the same age. This finding supports a tentative account that the CI users were less likely than NH children to draw benefit from the multi-modal form of stimulus presentation due to idiosyncratic habits of information processing and sensory integration across modalities. These differences in processing informationally redundant signals may have developed as a result of the early auditory deprivation experienced by the pediatric CI users.

The CI children reported on in this study performed significantly less well as a group overall than the normal-hearing children even when the memory game task utilized only visual-spatial stimuli. This was somewhat unexpected as the literature regarding the development of short-term memory in hearing-impaired populations suggests that the performance of deaf children on span tasks lacking a verbal component should not be impaired relative to that of normal-hearing children (Furth, 1966; Mayberry, 1992). When differences are, in fact found, investigators tend to find that the visual/spatial stimuli used in the particular task lent themselves to linguistic labeling. When linguistic labeling is possible, hearing-impaired children appear to be at a disadvantage relative to their normal-hearing counterparts (see discussion in Mayberry, 1992). Various studies have also suggested that hearing-impaired children who have grown up around spoken language sometimes attempt rehearsal/encoding strategies used by normal-hearing persons, involving self-generated verbal labels for even visual-spatial stimuli.[7] Since the verbal skills of hearing-impaired children with oral/aural backgrounds are often not as fully developed as normal-hearing children their age (i.e., with regards to processing speed, efficiency, robustness, etc.), their performance on a memory span task that could be approached in terms of even self-generated verbal labels might be reduced relative to that of NH children. It is possible that this occurred in the Quittner et al. (1994) study involving visual monitoring of a stream of orthographically presented digits discussed in our introduction. This situation could also have arisen in the current study—the CI users may have attempted to encode the sequence of lights in the "visual-spatial-only" condition using verbal names for the colors being illuminated even though the auditory stimuli were not explicitly presented.

We acknowledge this as a possible explanation for the reduced spans of the CI group in the visual-spatial-only condition, but if this relatively sophisticated verbal approach was truly being attempted, we would have expected the effect of informational redundancy to have had greater impact in the CI group. The fact that no significant differences were found as a function of stimulus-cue type using the original version of the memory game task strongly suggested to us that the CI group carried out all three conditions as purely visual/spatial tasks. Many of these CI children *were* capable of completing auditory versions of both the WISC digit span task and the modified memory game, and yet these same children did not perform any differently on the original memory game than the CI children that made errors in simply identifying the number names. This result was surprising and again suggests that the artificially imposed time synchrony between the light presentation and sound presentation was simply ignored by a majority of the CI children. This did not occur with the normal-hearing children in these same tasks.

In summary, the present results suggest that even those CI children who are able to accurately identify speech signals as they are heard, may not have phonological working memory mechanisms or processing strategies that are developed to a point equivalent to chronologically age-matched normal hearing counterparts. This outcome would not exactly be surprising, as many important milestones in the development of speech perception and memory are reached during the first two years of life. Despite their prelingually-deafened status, most of the CI users reported on here received their implant at a point in time when the FDA did not permit implantation of children under two years of age. Additionally, since 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 eight- and nine-year-old children were without any sensory input from the auditory modality for one quarter to one third of their lives. It should not be surprising, then, that the encoding strategies and working memory mechanisms of pediatric CI users *are,* in fact fundamentally different from those of normal-hearing children. Ongoing research in our lab is attempting to answer the question of *how* these coding/rehearsal mechanisms differ, and what kind of developmental changes can be observed or effected in these children. Increasingly, clinicians are beginning to see pediatric CI users that have reached ceiling levels of performance on traditional standardized measures of speech perception and spoken word recognition that are usually 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

---

[7] In contrast to fluent users of a sign language as their first language, who many researchers report as having normal to above average memory for visual-spatial sequences (see reviews in Mayberry, 1992).

reintroduced sensory input modality may help us provide new evaluation and treatment techniques (Pisoni, 1997). Eventually we would like to settle the question of whether individual differences in modality-*in*dependent aspects of working memory within the pediatric CI population might have a meaningful causal relation to the level of verbal language skill attained by individual children. The present research begins to address this issue since it provides some of the first data on short-term/working memory in pediatric cochlear implant users involving tasks in which the potential contribution of each available modality was varied.

References

Baddeley, A. D. (1986). *Working Memory.* London: Oxford University Press.

Baddeley, A. D. (1992). Working memory. *Science, 255,* 556-559.

Baddeley, A. D., Gathercole, S., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105,* 158-173.

Brandimonte, M. A., Hitch, G. J., & Bishop, D. V. (1992). Verbal recoding of visual stimuli impairs mental image transformations. *Memory and Cognition, 20,* 449-455.

Carlson, J. L, Cleary, M., & Pisoni, D. B. (1998). Performance of normal-hearing children on a new working memory span task. In *Research on Spoken Language Processing Progress Report No. 22* (pp. 251-275). Bloomington, IN: Speech Research Laboratory, Indiana University.

Carmichael, L, Hogan, H. P., & Walter, A. A. (1932). An experimental study of the effect of language on the reproduction of visually perceived forms. *Journal of Experimental Psychology, 15,* 73-86.

Cleary, M. (1997). Measures of phonological memory span for sounds differing in discriminability: Some preliminary findings. In *Research on Spoken Language Processing Progress Report No. 21* (pp. 93-138). Bloomington, IN: Speech Research Laboratory, Indiana University.

Cleary, M. Pisoni, D.B., & Kirk, K. I. (1998). Performance of a sample of hearing-impaired children on an auditory-spatial working memory task and its relation to open-set word recognition skills. In *Research on Spoken Language Processing Progress Report No. 22* (pp. 231-250). Bloomington, IN: Speech Research Laboratory, Indiana University.

Conrad, R. (1972). Short-term memory in the deaf: A test for speech coding. *British Journal of Psychology, 63,* 173-180.

Dedina, M. J. (1987). SAP: A speech acquisition program for the SRL-VAX. In *Research on Speech Perception Progress Report No. 13* (pp. 331-337). Bloomington, IN: Speech Research Laboratory, Indiana University.

Dempster, F. N. (1981). Memory span: Sources of individual and developmental differences. *Psychological Bulletin, 89,* 63-100

Dowell, R. C., Blamey, P. J., & Clark, G. M. (1995). Potential and limitations of cochlear implants in children. *Annals of Otology, Rhinol Laryngology Suppl. 166,* 324-327.

Dunn, L. M. & Dunn, L. M. (1997). *Peabody Picture Vocabulary Test, Third Edition.* Circle Pines, Minnesota: American Guidance Service.

Fastenau, P. S., Conant, L. L., & Lauer, R. E. (1998). Working memory in young children: Evidence for modality-specificity and implications for cerebral reorganization in early childhood. *Neuropsychologia, 36,* 643-652.

Fryauf-Bertschy, H., Tyler, R. S., Kelsay, D. M., Gantz, B. J., & Woodworth, G. G. (1997). Cochlear implant use by prelingually deafened children: The influences of age at implant and length of device use. *Journal of Speech, Language, and Hearing Research, 40,* 183-199.

Furth, H. G. (1966). *Thinking Without Language: Psychological Implications of Deafness*. The Free Press: New York.

Gantz, B. J., Woodworth, G.G., Abbas, P. J., Knutson, J. F., Tyler, R. S., (1993) Multivariate predictors of audiological success with multichannel cochlear implants. *Ann Otol. Rhinol. Laryngol., 102,* 909-916.

Geers, A. (1999). Factors contributing to speech perception in children before age 5. Presented at the *138th Meeting of the Acoustical Society of America.* Columbus, OH, November 1-5, 1999.

Geers, A., Nicholas, J., Tye-Murray, N., Uchanski, R., Brenner, C., Davidson, L, Torretta, G. M. (1998). Effects of communication mode on skills of long-term cochlear implant users. Presented at the *Seventh Symposium on Cochlear Implants in Children*. Iowa City, IA, June 4-7, 1998.

Grossi, D., Orsini, A., Monetti, C., & De Michele, G. (1979). Sex differences in children's spatial and verbal memory span. *Cortex, 16,* 667-670.

Gupta, P. & Dell, G. S. (1999). The emergence of language from serial order and procedural memory. In B. MacWhinney (Ed.), *The Emergence of Language* (pp. 447-481). Mahwah, NJ: Lawrence Erlbaum.

Hale, S., Bronik, M.D., Fry, A.F. (1997). Verbal and spatial working memory in school-age children: Developmental differences in susceptibility to interference. *Developmental Psychology. 33,* 364-371.

Hanson, V. L. (1990). Recall of order information by deaf signers: Phonetic coding in temporal order recall. *Memory and Cognition, 18,* 604-610.

Hanson, V. L. & Lichtenstein, E. H. (1990). Short-term memory coding by deaf signers: The primary language coding hypothesis reconsidered. *Cognitive Psychology. 22,* 211-224.

Hernandez, L. (1995). Current computer facilities in the Speech Research Laboratory. In *Research on Spoken Language Processing Progress Report No. 20* (pp.389-393). Bloomington, IN: Speech Research Laboratory, Indiana University.

Kail, R. (1991). Developmental changes in speed of processing during childhood and adolescence. *Psychological Bulletin, 109,* 490-501.

Kirk, K. I., Pisoni, D. B., & Osberger, M. J. (1995). Lexical effects on spoken word recognition by pediatric cochlear implant users. *Ear & Hearing, 16,* 470-481.

Knutson, J. F., Boyd, R. C., Goldman, M., & Sullivan, P. M. (1997). Psychological characteristics of child cochlear implant candidates and children with hearing impairments. *Ear & Hearing. 18,* 355-63.

Knutson, J. F., Hinrichs, J. V., Tyler, R. S., Gantz, B.J., Shartz, H.A., & Woodworth, G. (1991). Psychological predictors of audiological outcomes of multichannel cochlear implants. *Annals of Otology, Rhinology and Laryngology, 100,* 817-822.

Kramer, J. H., Delis, D. C., Kaplan, E., O'Donnell, L., & Prifitera, A. (1997). Developmental sex differences in verbal learning. *Neuropsychology, 11,* 577-584.

Levitt, H. (1970). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49,* 467-477.

Lewkowicz, D. J. & Lickliter, R. (1994). *The Development of Intersensory Perception: Comparative Perspectives.* Hillsdale, NJ: Lawrence Erlbaum.

Lezak, M. D. (1995). *Neuropsychological Assessment, Third Edition.* New York: Oxford University Press.

Lyxell, B., Andersson, J., Arlinger, S., Bredberg, G., Harder, H., & Ronnberg, J. (1996). Verbal information-processing capabilities and cochlear implants: Implications for preoperative predictors of speech understanding. *Journal of Deaf Studies and Deaf Education, 1,* 190-203.

Marschark, M. & Mayer, T. S. (1998). Mental representation and memory in deaf adults and children. In *Psychological Perspectives on Deafness: Volume 2.* J. Marschark & M. D. Clark, (Eds.) Mahwah, NJ, USA: Lawrence Erlbaum Associates.

Mayberry, R. I. (1992). The cognitive development of deaf children: recent insights. In *Handbook of Neuropsychology, Vol 7.* S. J. Segalowitz & I. Rapin (Eds.). Elsevier Science Publishers.

Miyamoto, R., Robbins, A. M., & Osberger, M. J. (1993). Cochlear Implants. In Cummings et al. (Eds.), *Otolaryngology, Head and Neck Surgery, 2nd Edition, Vol. 4.* St.Louis, MO: Mosby Publishers.

Miyamoto, R. T., Osberger, J. J., Todd, S. L., Robbins, A. M., Stroer, B. S., Zimmerman-Phillips, S., Carney, A. E. (1994). Variables affecting implant performance in children. *Laryngoscope, 104,* 1120-1124.

Naus, M. J. & Ornstein, P. A. (1983). Development of memory strategies: Analysis, questions, and issues. In M. T. Chi (Ed.), *Trends in memory development research* (pp.1-30). New York: Karger.

Nikolopoulos, T. P., O'Donoghue, G. M., & Archbold, S. (1999). Age at implantation: its importance in pediatric cochlear implantation. *Laryngoscope, 109,* 595-9.

Pisoni, D. B. (1997). Cognitive factors and cochlear implants: An overview of the role of perception, attention, learning, and memory in speech perception. *Research on Spoken Language Processing Progress Report No. 21.* Bloomington, IN: Speech Research Laboratory, (pp. 335-347).

Pisoni, D. B. (1999). Some measures of working memory span in deaf children with cochlear implants. Talk presented at Central Institute for the Deaf, Summer 1999.

Pisoni, D. B. & Geers, A. E. (1998). Working memory in deaf children with cochlear implants: Correlations between digit span and measures of spoken language. *Research on Spoken Language Processing Progress Report No. 22.* Bloomington, IN: Speech Research Laboratory, (pp. 336-343).

Pisoni, D. B., Svirsky, M. A., Kirk, K. I., & Miyamoto, R. T. (1997). Looking at the "Stars": A first report on the intercorrelations among measures of speech perception, intelligibility, and language development in pediatric cochlear implant users. *Research on Spoken Language Processing Progress Report No. 21.* Bloomington, IN: Speech Research Laboratory, (pp. 51-91).

Quittner, A. L., Smith, L. B., Osberger, M. J., Mitchell, T. V., & Katz, D. N. (1994). The impact of audition on the development of visual attention. *Psychological Science, 5,* 347-353.

Quittner, A. L. & Steck, J. T. (1991). Predictors of cochlear implant use in children. *The American Journal of Otology, 12(Supplement),* 89-94.

Sehgal, S. T., Kirk, K. I., Pisoni, D. B., Miyamoto, R. T. (1997). Effect of residual hearing on children's speech perception abilities with a cochlear implant. Poster presented at *the Vth International Cochlear Implant Conference*, New York City, New York, May 1-3, 1997.

Shand, M. A. (1982). Sign-based short-term coding of American Sign Language signs and printed English words by congenitally deaf signers. *Cognitive Psychology, 14,* 1-12.

Smith, E. E. & Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science, 283,* 1657-1661.

Snik, A.F., Vermeulen, A.M., Geelen, C. P., Brokx, J. P., & van den Broek, P. (1997). Speech perception performance of children with a cochlear implant compared to that of children with conventional hearing aids. II. Results of prelingually deaf children. *Acta-Otolaryngol-Stockh., 117,* 755-9.

Stein, B. E. & Meredith, M. A. (1993). *The Merging of the Senses.* Cambridge, MA: MIT Press.

Svirsky, M. A., Robbins, A. M., Kirk, K. I., Pisoni, D. B., & Miyamoto, R. T. (in press). Language development in profoundly deaf children with cochlear implants. *Psychological Science.*

Swanson, H. L. (1996). Individual and age-related differences in children's working memory. *Memory and Cognition, 24,* 70-82.

Tiber, N. (1985). A psychological evaluation of cochlear implants in children. *Ear & Hearing, 6(Supplement)*, 48S-51S.

Tyler, R. S., Fryauf-Bertschy, H., Kelsay, D. M. R., Gantz, B. J., Woodworth, G. P., & Parkinson, A. (1997). Speech perception by prelingually deaf children using cochlear implants. *Otolaryngology Head and Neck Surgery, 117,* 180-187.

Wechsler. D. (1991). *Wechsler Intelligence Scale for Children, Third Edition (WISC-III).* San Antonio, TX: The Psychological Corporation.

Zwolan, T. A., Zimmerman-Phillips, S., Ashbaugh, C. J., Hieber, S. J., Kileny, P. R., & Telian, S. A. (1997). Cochlear implantation of children with minimal open-set speech recognition skills. *Ear & Hearing, 18*, 240-251.