RESEARCH ON SPOKEN LANGUAGE PROCESSING
Progress Report No. 22 (1998)
Indiana University

Performance of a Sample of Hearing-Impaired Children on an Auditory-Spatial Working Memory Task and its Relation to Open-Set Word Recognition Skills[1]

Miranda Cleary, David B. Pisoni[2] and Karen I. Kirk[2]

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

[1] This work was supported by NIH NIDCD Research Grant DC00111 and Training Grant DC00012 to Indiana University. We would like to thank Susan T. Seghal, Marcia McCutcheon, Luis R. Hernandez and Theresa S. Kerr for their help in data collection and organization.
[2] Also DeVault Otologic Research Laboratory, Department of Otolaryngology-Head & Neck Surgery, Indiana University School of Medicine, Indianapolis, IN.

Performance of a Sample of Hearing-Impaired Children on an Auditory-Spatial Working Memory Task and its Relation to Open-Set Word Recognition Skills

Abstract. This study briefly reports memory span data and open-set word recognition scores obtained from 19 hearing-impaired children enrolled at an oral school for the hearing impaired. The sample was composed of 13 Nucleus-22 cochlear implant users, 4 Clarion cochlear implant users, and 2 hearing aid users. Memory span measures used included the Digit Span Sub-test from the Wechsler Intelligence Scale for Children III, and three variants of a "memory span game" recently developed at our laboratory, which requires the participant to "reproduce" a sequence of items using a four-alternative response box. Open set tests employed included a live-voice version of the PB-K, as well as recorded single-talker versions of the Lexical Neighborhood Test and Multisyllabic Lexical Neighborhood Test. Results showed that within this sample, there was a small to moderate positive correlation between open set word recognition scores and performance on the auditory-plus-spatial version of the memory span game sequence reproduction task. The correlation of word recognition scores with performance on the spatial-input-only control version of this task was slightly negative. With age in months, duration of device use, and number of pre-test auditory identification errors statistically partialled out, the positive correlations still remained, and the slight negative correlations approached zero correlation. No consistent differences were observed across the open-set word recognition tests with respect to their relationship with memory span measures.

Introduction

Clinical study of pediatric cochlear implant users post-implantation has traditionally used tests of speech perception and production that make minimal demands on the mechanisms of memory, learning, and attention. With the long term impact of these factors becoming increasingly a matter of interest (Pisoni et al., 1997), we have recently begun a program of study based on the well-established premise that the acquisition of spoken language relies on species-typical cognitive function in addition to the sensory mechanisms of audition (e.g., see Locke, 1997). Surprisingly, little is known about how phonological short-term memory processes develop even in normal-hearing children, however (e.g., see Dempster 1981, and Kail, 1990, for reviews). One of the main problems has been to tease apart what components of this development are specific to the processing of information encoded from the auditory and/or speech modality, and what components are more closely related to general/central/non-modality-specific changes.

Young children with cochlear implants are potentially a rewarding population to study for at least two primary reasons. Firstly, individual cognitive processing differences (such as in short term memory) may be contributing to outcome differences in speech perception and production in this population, and if this is the case, it would probably be beneficial to gear rehabilitation strategies post-implant to reflect this. Secondly, it may be possible to learn more about how access to the auditory modality interfaces with working memory development and long-term memory organization in the normal-hearing population by examining a population that has lacked this sensory input pathway for some period of time but has had it since partially restored, in this case, through the use of a cochlear implant or hearing aid.

As a first step, therefore, we have in the last year and a half begun gathering some basic short-term memory measures from both pediatric cochlear implant users and their age-matched normal-hearing peers. An examination of the clinical literature suggests that many of the highly involved working memory measures that have been developed in the last decade or so, such as "listening span" (remembering the last word in each of a series of spoken sentences) (Daneman & Carpenter, 1980), would be difficult if not impossible for hearing-impaired children to carry out for reasons that might only indirectly be linked to memory. The first measure we have employed therefore is a simple memory span measure, requiring immediate reproduction of presented list items, using a variety of differentially discriminable and familiar items.

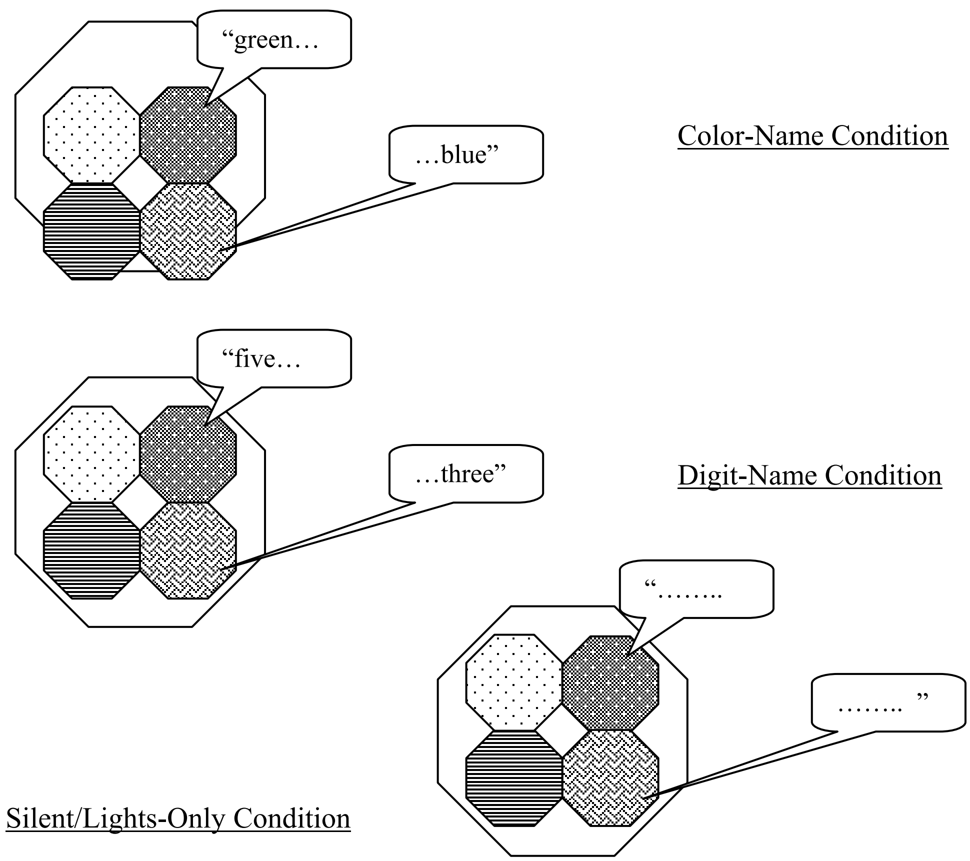

Figure 1. Diagram of memory game apparatus and experimental conditions given a list length of two items. Each shaded hexagon represents a large colored button back-lit by a light.

The task we are using involves both an auditory and visual-spatial component. Sequences of sounds, lights at particular locations, or combinations of both lights and sounds are presented to subjects who are asked to either provide verbal recall of the sequence or to press a sequence of buttons at the presented locations in order to reproduce the sequence (see Figure 1). One mode of response, therefore, requires articulatory production on output, while the other does not. To examine what factors influence performance on this type of task we have, in this and other studies, begun to look at whether different "hearing" groups (cochlear implant-users, hearing-aid users, normal-hearing individuals) and different age groups (preschool-age, young school-age, older school-age), perform differently on versions of the task that provide one particular modality of input versus another or both modalities of input, or that demand one or the other type of response format. We are gathering a gross measure of number of items able to be correctly repeated according to differentially strict criteria. We are especially interested in comparing performance on each of these different variants of the basic memory span task to measures of open-set word recognition.

Simple memory span tasks have been our starting point for a number of reasons—some better than others. They are easy to administer and score in a standard fashion and there is a large body of past literature on what types of simple span behavior can be elicited that can be referred to for purposes of comparison. Memory development in the hearing impaired and in signing populations has been a topic of research for decades (see Marschark, 1993, for example), but, for the relatively new population of young cochlear implant users, there has been little, if any, research on memory processes until now.

We are using scores on open-set word recognition as a comparison measure because these types of tests use a response format that distinguishes between more successful and less successful users of cochlear implants better than does the format of closed-set, forced-choice, multiple choice tests. (Closed-set tests often suffer from ceiling effects in this population, even though they have traditionally been widely used with other populations of hearing impaired children [Kirk, Diefendorf, Pisoni & Robbins, 1997].)

Method

Participants

Nineteen children participated in the study. All were students enrolled at St. Joseph's Institute for the Deaf in Chesterfield, Missouri. The data reported here were collected during an annual visit to the school by a team of trained speech-language pathologists and audiologists who have followed the progress of the participating children for a number of years (Kirk, Pisoni, & Miyamoto, in press). All children made primary use of the oral communication mode. Mean age was 8 years, 8 months, SD = 2 years, 1 ½ months. The oldest child was 11;11, the youngest, 5;7. Thirteen were Nucleus 22 cochlear implant users, 4 used the Clarion cochlear implant, and 2 used hearing aids. Average duration of experience with their respective devices was 3.5 years and ranged from a minimum of 1.5 years to a maximum of 7 years. All subjects used their respective devices during all testing procedures. Table I provides the ages, device type, and duration of use at time of testing for individual subjects. All participants were tested individually in a quiet location within the school facilities.

TABLE I

DEMOGRAPHIC BACKGROUND OF INDIVIDUAL SUBJECTS

Subject ID Number	Device Type	Age at Testing in Months	Duration of Device Use in "Intervals" of 6 Months
1	HA	67	6
8	HA	78	4
17*	Clarion	67	4
11	Clarion	83	5
9	Clarion	103	3
6	Clarion	111	3
4	Nucleus	72	8
15**	Nucleus	73	5
19	Nucleus	83	8
3	Nucleus	96	9
12	Nucleus	99	6
10	Nucleus	117	7
16	Nucleus	120	5
13	Nucleus	123	7
14	Nucleus	123	12
2	Nucleus	133	11
5	Nucleus	135	9
7	Nucleus	143	9
18	Nucleus	143	14

*This child received the live-voice version of the LNT and MLNT; his scores are omitted in analyses involving the LNT & MLNT. This child also did not complete the WISC Digit Span measure.
** This child did not complete any of the open-set word recognition tests.

Stimulus Materials and Procedure

Memory Span Game. The eight speech tokens used in the memory span game included the four digit-names "one" "three" "five" and "eight", and the four color-names "red" "blue" "green" and "yellow". These tokens were recorded from a single American English-speaking male talker speaking slowly and clearly. Recordings were made in a sound-attenuated single-walled anechoic recording chamber (Industrial Acoustics Company Audiometric Testing Room, Model 402), using a head-mounted Shure (SM98) microphone. The recordings were digitally sampled on-line at a rate of 22.05 kHz with 16 bit amplitude quantization using a Tucker-Davis Technologies (TDT) System II with an A-to-D converter (DD1), and low-pass filter of 10.4kHz (anti-aliasing filter, FT5), controlled by an updated version of Dedina's 1987 "Speech Acquisition Program" (Dedina, 1987; Hernandez, 1995). The amplitudes of the individual edited speech files were adjusted such that the average RMS amplitude for each file was approximately 70 dB.

To gauge the ability of each child to identify the items used in the two sets of four stimuli, a "pre-test" task was first administered. Prior to "playing the memory game" using a particular set of stimuli, each recorded stimulus item was played through a loudspeaker at the same free-field intensity (approximately 70 dB SPL) as used in the memory span game. In the case of the color-name stimuli, each child was asked to point to the one of four colored squares on a response sheet that matched the color-name being presented. In the case of the digit-names, the child was asked to point to the one of four squares containing the Arabic numeral matching the digit-name just heard. If the child made no errors on this identification task, the memory game version using the stimuli just tested was administered. If the child made one or more errors, the identification task was repeated three additional times (that is, the child was asked to identify each of the four stimulus items in three additional trials). Regardless of the child's performance on the remainder of the pre-test trials, the memory game task was administered immediately following.

The memory span game developed at our lab uses a custom-built response box topped with four large colored buttons each of which can be lit up via a signal from an attached computer. There is one button in each of the four colors, red, blue, green and yellow. A loudspeaker attached to the controlling computer is programmed to output the sound file designated as corresponding to a particular one of the four button locations while the button is lit during presentation, or when a button is depressed by the subject. During the presentation of the target list, items are played immediately in succession with only a little over 100 ms intervening between items. Since the items were recorded at a slow rate of speech, however, the overall rate of presentation is fairly slow, about one-and-a-half items per second.

Before playing the memory game, the child was instructed that he/she would hear sounds and see the lights on the game box light up. The child was told that his/her job was to "copy what the box does" by pressing the proper buttons. On each trial, a quasi-randomly generated sequence using the four possible stimuli and consistently matched button/light locations was presented. No target sequence generated was permitted to contain consecutively identical (repeated) items. The memory game trials began with the list length to be reproduced starting at length 1. The clinician was permitted to give feedback and encouragement if needed on the first three trials. After this, the child continued with the task without further instruction or feedback. The algorithm controlling sequence presentation stipulated that if the child got two lists of a given length correct consecutively, the presented list length would increase by one item in the next trial. If the child made any type of error in his/her response, the following trial would present a sequence that was one item shorter in length than the last. Each memory game condition, involving approximately 25 lists (trials), lasted approximately 3-4 minutes.

Each child completed the memory span game under three different conditions: using digit-names, using color-names, and using a "silent" lights-only condition. The digit-name and color-name conditions were counterbalanced in their order of administration across subjects; the silent condition was always administered last. The silent condition was simply a retest of the color-name condition with the loudspeaker turned off and served as a control condition for the auditory plus visual-spatial condition.

Wechsler Intelligence Scale for Children Digit Span Subtest. The WISC digit span subtest consists of lists of randomly arranged numbers, two lists at each list length, starting at list length two, up to a maximum of nine items in the forwards repetition condition, and eight items in the backwards condition. The backward condition requires the child to repeat the sequence in reverse order. The lists of numbers to be repeated by each child were spoken aloud by a female speech pathologist or audiologist at time of testing at a rate of approximately 1 item per second. A mesh screen was held such that the mouth of the clinician was hidden from sight of the child during presentation of the target list. If the child got one or both lists of a given length correct, lists one item longer in length were administered. List length increased until the child got both lists at a given length incorrect, at which point the procedure was terminated.

Open Set Word Recognition Tests. The Lexical Neighborhood Test (LNT) uses monosyllabic words known to be typical of the vocabulary of normally developing three to five year olds (Kirk et al., 1995). The LNT consists of four lists of 25 words each. Two of these lists contain relatively "Easy" to recognize spoken words, and two contain more difficult or "Hard" to recognize items. Ease of recognition was estimated using a model incorporating the influences of word frequency and phonetic similarity with other known words (Luce & Pisoni, 1998). The LNT is accompanied by an additional Multisyllabic Lexical Neighborhood Test (MLNT) which consists of four lists of multisyllabic two or three syllable words, two "Easy" and two "Hard" lists, with 12 words in each list. One list of "Easy" words and one list of "Hard" words from the LNT, and one list of "Easy" words and one list of "Hard" words from the MLNT was administered to each child.

The Phonetically Balanced Kindergarten Test (PB-K), a speech discrimination test routinely used in clinical practice, consists of three lists of 50 monosyllabic words each (Haskins, 1949; see also Meyer & Pisoni, 1997 for discussion). Only one PB-K word list was administered to each child.

The LNT and MLNT lists were administered in an audio-only format using words recorded by a single male talker. (See Kluck et al., 1997 for details of recording and playback.) The PB-K was administered live-voice by a clinician, with a mesh screen once again placed in front of the lower half of the clinician's face. After each word was spoken/played, the child's task in all cases was to repeat back the word intelligibly enough for the tester to recognize. The resulting score is expressed in terms of "percent of words correctly recognized," as is also the case for the scoring of the PB-K. While we term these tests "word recognition" tests, it can legitimately be argued that these are tests of "word perception," "word imitation" or "sound segment recognition" rather than "word recognition" per se, since what is required is that the child merely repeat back the item. It has been shown that even very young normal-hearing children can repeat back and imitate nonsense words that contain the sounds of their native language even if they have never heard the item before (e.g., Gathercole & Adams, 1993).

Results and Discussion

Stimulus Identification Pre-Test

Eight of the 19 children made zero errors when asked to identify each of the eight stimulus items. Four of the children made one error, but on repeating the discrimination set that contained the error, successfully identified all items. Of the remaining seven children, four of these identified all the color names without error on the first trial, only making errors on the digit-name set, with three of them misidentifying the number "eight" repeatedly, and the other misidentifying both "eight" and "three". The last three children, rounding out the set of nineteen, made errors on both the digit-name and color-name identification, with the most errors again being made for "eight" and "three". No color-name elicited noticeably more misidentifications than any other did across children, although one of these last three children repeatedly misidentified "green".

The stimulus "eight" was difficult for many of the children to identify. Seven of the nineteen missed this item at least once during the identification task. This may be due to the fact that "eight" has a somewhat shorter duration than the other digit-names used--approximately 300 ms in our case, compared to 400-500 ms for the other digit-names. In other research currently on-going in our lab, none of the 45+ normal-hearing children we have tested using this same set of stimuli have ever misidentified this item (or any of the others) during analogous identification testing (Cleary, Pisoni, Staley & Geers, in preparation).

While we initially considered analyzing the memory results only from children who successfully performed with the identification task, since all the children proved able to grasp the memory span task, we decided to retain all subjects in the analysis. We treated the pre-test identification results as simply another independent variable along which to compare and contrast the subjects.

For reference, the correlation between number of errors made during the pre-test identification task and performance on WISC-digits forwards was $r_{pearson} = + 0.04$. The correlation between the number of errors and spans obtained on digit-name version of the memory game was $r_{pearson} = - 0.11$. Factors contributing to the small size of these correlations will be discussed in sections to follow.

Auditory-Spatial Memory Span Performance

All participants were able to do the memory game task for a minimum of two items in at least one of the three conditions. The longest sequence ever reproduced by any participant was seven items.

Means between Vocabulary Conditions. Table II shows mean span across the three different conditions as scored using three differentially strict definitions of "span." While these differences are very small and not statistically significant, the pattern suggests that the higher means for the color-name condition regardless of scoring method provide evidence that the color-name condition is, in fact, a somewhat easier task, and that subjects make some use of the semantically reinforced mapping between the acoustic stimulus and the button location.

TABLE II

MEAN MEMORY GAME "SPAN" ACROSS ALL PARTICIPANTS AS A FUNCTION OF TYPE OF STIMULI USED

DEFINITION OF "SPAN"	X_{colors}	X_{digits}	X_{silent}
LONGEST LIST LENGTH CORRECTLY REPRODUCED AT LEAST ONCE DURING CONDITION	4.58	4.30	4.47
LONGEST LIST LENGTH CORRECTLY REPRODUCED ON AT LEAST HALF THE TRIALS AT THAT LENGTH	4.32	4.05	4.05
LONGEST LIST LENGTH ALWAYS CORRECTLY REPRODUCED ON ALL TRIALS AT THAT LENGTH	3.00	2.40	2.26

Using these relatively crude span measures, it should be noted that using the least-skewed set of span scores, that is, the most liberal definition of span ("at least once"), only 3 of the 19 subjects did at least one "span unit" worse on the silent task than either of the other two conditions. Three subjects did at least one unit better on the silent condition than on either of the two other conditions. And, despite the small difference in means favoring the color-name condition, only 4 of the 19 subjects did at least 1 unit better on the color-name condition than either of the two remaining conditions. No participant got scores that differed by more than two "span units" between conditions. Four of the 19 subjects got exactly the same span score on all three conditions. Figure 2 illustrates how the different device groups contributed to the means reported in Table II.

Insert Figure 2 about here

The above results suggest two alternative possibilities—the task may not be sensitive enough to the auditory component of the target sequence to result in differences across conditions using our measure. Alternatively, participants may differ amongst themselves as to what, if any, impact the presentation of auditory stimuli had during the task but have scores that distributed around near-equal means (see Figure 3). To test the second hypothesis, we subsequently analyzed each subject's performance on the memory game task in relation to their performance on open-set word recognition tests. Before reporting these results, however, we first present some data showing how closely t he

Memory Game results from these children matched traditional WISC forward digit spans gathered from the same children, as well as data on how strongly correlated the five different open set word recognition measures that we employed were in this sample (1 PB-K list, 1 LNT-Easy, 1 LNT-hard, 1 MLNT-Easy, 1 MLNT-hard).

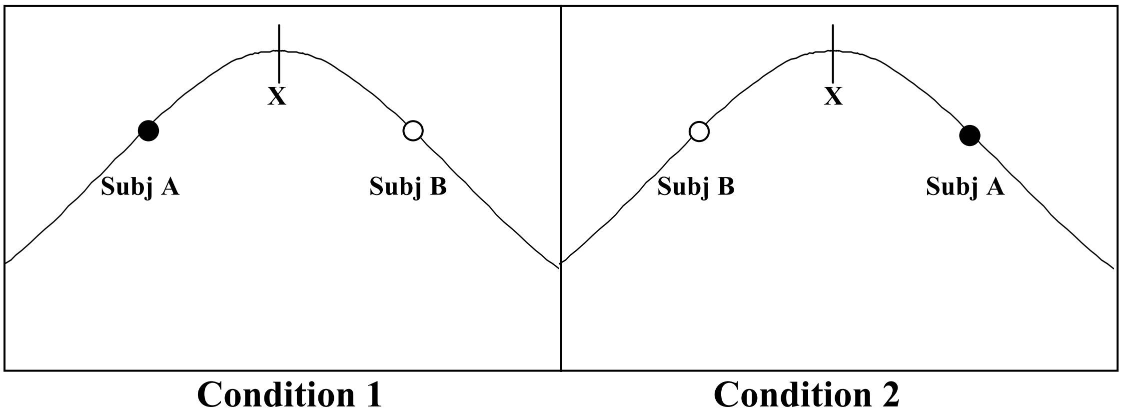

Figure 3. Illustrates how similar means could be obtained if individual children distributed themselves differently along the distributions. "X" represents a mean value that is identical or nearly identical in both conditions. (Assumes that Subject B is "helped" as much by Condition 1 as he/she is "hurt" by Condition 2 and as much as Subject A is "helped" by Condition 2.)

Comparison of Memory Game "Spans" and WISC Forward Digit Span. Table III lists the simple bivariate Pearson's r correlation between each child's score on the memory game for each condition scored in the least conservative manner and the longest list length the child correctly reproduced in the WISC forward digit span task. Since span measures are heavily influenced by the age of the child, the correlation between these same two measures with age in months partialled out is also listed in the table.

TABLE III

CORRELATIONS BETWEEN TRADITIONAL WISC FORWARD DIGIT SPANS AND MEMORY GAME SPANS

	SIMPLE BIVARIATE	WITH AGE STATISTICALLY PARTIALLED OUT
WISC FORWARD WITH GAME COLORS	0.67**	0.63**
WISC FORWARD WITH GAME DIGITS	0.48*	0.40
WISC FORWARD WITH GAME SILENT	0.39	0.25

**Significant at $p < .01$ level, but common variable problem in simple case.
*Significant at $p < .05$ level, but common variable problem.

We will not be focusing very much on the WISC Backwards digit spans obtained, however we did obtain one result that we found somewhat curious. This result was the lack of clearly separate distributions for the forward and backward WISC digit span scores. See Figure 4 to compare forward vs. backward WISC spans plotted as a function of age in months. Unlike the differences typically found for normal hearing children (For example, see Figure 2 in Carlson, Cleary & Pisoni, this volume), the forward and backward spans in our group have overlapping distributions. Nine of the 18 children who completed the WISC digit span test were able to repeat at least one item more in the forward condition than the backwards condition. Five children did not show any differences between the forwards and backwards conditions (note, none of these children were at floor on the task), and four children actually got a higher score in the backwards WISC condition. This pattern of results is not typical for the normal-hearing children with whom we have previously used these tasks.

Insert Figure 4 about here

Next, we preface our discussion of how our span measures relate to open-set word recognition measures by reporting how closely-related performance on the 50 word PB-K was to scores on each of the four LNT/MLNT tests.

Relationship Between Open-Set Word Recognition Measures. Tables IV and V show that the LNT and MLNT mirror a large amount of the variance that is seen in the PB-K scores. These results suggest that performance on the 50 word PB-K may resemble the 12 word "Hard" MLNT (which contains more acoustically confusable items) lists to a somewhat greater degree than it does the other Neighborhood tests. Note that the wide spread of ages in our sample does not appear to impact this result. (Table V is provided to reassure that general age effects are not an issue in the word recognition tests used here.)

TABLE IV

SIMPLE BIVARIATE CORRELATIONS BETWEEN PB-K AND LNT AND MLNT SCORED AS PERCENT CORRECT (ALL IN TERMS OF WORDS CORRECTLY RECOGNIZED)

PB-K with LNT Easy	**+0.76**
PB-K with LNT Hard	**+0.78**
PB-K with MLNT Easy	**+0.78**
PB-K with MLNT Hard	**+0.85**

TABLE V

CORRELATIONS BETWEEN PB-K AND LNT AND MLNT SCORED AS PERCENT CORRECT (ALL IN TERMS OF WORDS CORRECTLY RECOGNIZED) WITH AGE IN MONTHS STATISTICALLY PARTIALLED OUT

PB-K with LNT Easy	**+0.76**
PB-K with LNT Hard	**+0.78**
PB-K with MLNT Easy	**+0.79**
PB-K with MLNT Hard	**+0.86**

Relationship Between WISC Forward Digit Spans and Word Recognition Measures. Next, it may be helpful to examine whether the traditional WISC digit span task differentiates at all in how it correlates with the five different word recognition tests. For this particular analysis, we used a method of scoring the WISC task that involves crediting the child with one point for every list, forwards and backwards, which they recall correctly in the requested direction, and then summing these points to obtain a final score. This scoring method gives a somewhat wider distribution of scores than the methods we used to score performance on the Memory Game and also incorporates data from the backwards task of which we used no analogue in the Memory Game measures. As Tables VI and VII show, there are no

striking differences between the tests, although the LNT "Easy" scores appear to be somewhat less closely related.

TABLE VI

SIMPLE BIVARIATE CORRELATIONS BETWEEN WISC-DIGITS SPAN TOTAL POINT SCORES AND PB-K AND LNT & MLNT SCORED AS PERCENT CORRECT (ALL IN TERMS OF WORDS CORRECTLY RECOGNIZED)

Digit Span with PB-K	**+0.28**
Digit Span with LNT Easy	**+0.14**
Digit Span with LNT Hard	**+0.41**
Digit Span with MLNT Easy	**+0.42**
Digit Span with MLNT Hard	**+0.34**

* Significant at $p < .05$ level.
** Significant at $p < .01$ level.

TABLE VII

CORRELATIONS BETWEEN WISC-DIGITS SPAN TOTAL POINT SCORES AND PB-K AND LNT AND MLNT SCORED AS PERCENT CORRECT (ALL IN TERMS OF WORDS CORRECTLY RECOGNIZED) WITH AGE IN MONTHS STATISTICALLY PARTIALLED OUT

Digit Span with PB-K	**+0.30**
Digit Span with LNT Easy	**+0.22**
Digit Span with LNT Hard	**+0.42**
Digit Span with MLNT Easy	**+0.37**
Digit Span with MLNT Hard	**+0.30**

* Significant at $p < .05$ level.
** Significant at $p < .01$ level.

Contribution of Age Differences to WISC Memory Spans. As may already be clear from the results presented so far, then, it is not the case, in our sample, that the older children always did consistently better on the word recognition measures than the younger children. This likely has something to do with the fact that chronological age and duration of implant/aid use were correlated only $r_{pearson} = +0.58$ in our sample, and that duration of device use is a stronger contributor to word recognition performance than chronological age. On the other hand, however, at least in normal-hearing children, memory span performance is strongly correlated with chronological age up to around age 12 (Dempster, 1981), and, in our sample, the simple bivariate correlations between age and each of the memory span measures were sizable (see Table VIII below). The question of how memory span is related to word recognition performance therefore needs to take into account both chronological age and duration of device use, and we attempt to do this in the last section of this paper.

TABLE VIII

SIMPLE BIVARIATE CORRELATION BETWEEN AGE AND…	
WISC FORWARD DIGIT SPAN	+ 0.32
WISC BACKWARD DIGIT SPAN	+ 0.60**
WISC TOTAL POINTS SCORE	+ 0.57*
MEMORY GAME COLOR-NAMES	+ 0.56*
MEMORY GAME DIGIT-NAMES	+ 0.79**
MEMORY GAME SILENT/LIGHTS ONLY	+ 0.69**

* Significant at $p < .05$ level.
** Significant at $p < .01$ level.

Contribution of Age Differences to Memory Game Performance. Table IX specifically tries to illustrate how chronological age has a different effect on our word recognition measures than our Memory

Game measures. The numbers in each small box identify particular subjects. The numbers in the first row of the table labeled “Age in Months” are rank ordered in ascending age order. The shading assigned to each subject reflects their placement in this ranking. The eight rows that follow are also rank ordered in terms of where each subject fell in the distribution of scores for each measure. The shadings in these rows reflect where the child fell in the chronological age distribution in the first row. (For example, Subject 7 is most darkly shaded as the oldest child in the sample and retains this same shading in all the remaining rows.) This type of table was designed to condense in a small amount of space the same information as would be gleaned from a large number of scatterplots.

TABLE IX

RANK ORDER PLACEMENT ON DISTRIBUTION OF SCORES (NUMBERS ARE SUBJECT IDENTIFIERS)
SHADING ASSIGNED ACCORDING TO AGE IN MONTHS

TEST		LOW						MIDDLE								HIGH	
Age in Months	1	4	8	19	11	3	12	9	6	10	16	13	14	2	5	18	7
PB-K	16	1	6	18	9	8	5	13	14	11	10	7	19	3	4	12	2
LNT-Easy	16	6	18	9	8	1	14	11	5	13	10	19	3	4	2	7	12
LNT-Hard	9	1	16	18	8	6	5	10	14	11	19	3	4	13	12	2	7
MLNT-Easy	1	16	18	9	8	6	5	19	3	13	11	10	14	4	12	2	7
MLNT-Hard	18	1	6	8	16	11	9	19	10	5	3	13	14	7	2	4	12
Colors	19	11	1	8	3	14	16	18	6	5	13	10	4	7	9	12	2
Digits	19	11	1	8	4	3	14	13	9	16	18	10	6	5	7	12	2
Silent	19	11	4	1	8	13	3	16	18	10	6	12	2	14	5	7	9

Testing the Hypothesis Regarding Distribution of Scores Across Memory Game Conditions. Next, we examined whether a correlational analysis might support the hypothesis that participants may have differed amongst themselves as to what, if any, impact the presentation of auditory stimuli had on their performance during the Memory Game task (recall Figure 3), and that these differences between subjects might be reflected in where their scores fell in the open-set word recognition test distributions.

Tables X and XI display the correlations between the three Memory Game scores and the five word recognition tests, ignoring, and then statistically correcting for the influence of chronological age on memory span. The measure “Game Total” is somewhat similar to the WISC total point scoring already described and was simply derived from summing each child’s “span score” from all three Memory Game conditions. The most obvious point to be taken from these tables is that the Memory Game Silent/Lights Only condition now shows a different pattern of relationships with the other measures than the two Memory Game conditions that included an auditory component.

In and of themselves, the individual correlations are rather small and not very impressive. However, taken as a whole, the overall pattern offers some evidence that the better our subjects did on the open-set word recognition measures, the worse they tended to do on the Memory Game Silent condition relative to the rest of the sample, particularly the children who did less well on the word recognition tests.

TABLE X

SIMPLE BIVARIATE CORRELATIONS BETWEEN PB-K, LNT AND MLNT SCORED AS PERCENT CORRECT (ALL IN TERMS OF WORDS CORRECTLY RECOGNIZED) AND EACH OF THE MEMORY SPAN GAME CONDITIONS, SUMMED SPAN SCORE OF ALL GAME CONDITIONS

PB-K with Game Colors	**+0.21**
LNT Easy with Game Colors	**+0.05**
LNT Hard with Game Colors	**+0.18**
MLNT Easy with Game Colors	**+0.09**
MLNT Hard with Game Colors	**+0.21**
PB-K with Game Digits	**+0.17**
LNT Easy with Game Digits	**+0.01**
LNT Hard with Game Digits	**+0.24**
MLNT Easy with Game Digits	**+0.23**
MLNT Hard with Game Digits	**+0.28**
PB-K with Game Silent	***+0.05***
LNT Easy with Game Silent	***-0.26***
LNT Hard with Game Silent	***-0.08***
MLNT Easy with Game Silent	***-0.16***
MLNT Hard with Game Silent	***-0.01***
PB-K with Game Total	**+0.15**
LNT Easy with Game Total	**-0.09**
LNT Hard with Game Total	**+0.12**
MLNT Easy with Game Total	**+0.05**
MLNT Hard with Game Total	**+0.17**

TABLE XI

CORRELATIONS BETWEEN PB-K, LNT AND MLNT SCORED AS PERCENT CORRECT (ALL IN TERMS OF WORDS CORRECTLY RECOGNIZED) AND EACH OF THE MEMORY SPAN GAME CONDITIONS, SUMMED SPAN SCORE OF ALL GAME CONDITIONS WITH AGE IN MONTHS STATISTICALLY PARTIALLED OUT

PB-K with Game Colors	**+0.22**
LNT Easy with Game Colors	**+0.11**
LNT Hard with Game Colors	**+0.14**
MLNT Easy with Game Colors	**-0.03**
MLNT Hard with Game Colors	**+0.14**
PB-K with Game Digits	**+0.23**
LNT Easy with Game Digits	**+0.12**
LNT Hard with Game Digits	**+0.24**
MLNT Easy with Game Digits	**+0.11**
MLNT Hard with Game Digits	**+0.25**
PB-K with Game Silent	***+0.02***
LNT Easy with Game Silent	***-0.29***
LNT Hard with Game Silent	***-0.23***
MLNT Easy with Game Silent	***-0.44***
MLNT Hard with Game Silent	***-0.18***
PB-K with Game Total	**+0.18**
LNT Easy with Game Total	**-0.05**
LNT Hard with Game Total	**+0.03**
MLNT Easy with Game Total	**-0.18**
MLNT Hard with Game Total	**+0.07**

We attempt to use somewhat the same type of table as in IX to explore this graphically. Here, in Table XII, however, rather than making a table for each of our word recognition tests separately, we rank order performance on the five word recognition tests in rows 1-5, and then, since none of the subjects in the top three, bottom three and middle three ranks ever appear in any of these other two rank intervals on any word recognition test (for example, Subject 1 falls in the "Low" range in 4 of the 5 measures, once in the low-middle range, and never in Middle or High), shading colors were assigned to items that appeared at least once in these ranges, and any items that always fell in the intermediate ranges were assigned intermediate shades. Then, as before, these shadings were retained in the rank orderings of the Memory Game Scores in the bottom three rows of the table.

From Table XII one can see a weak tendency for some of the low scorers on word recognition to do a little better relative to the rest of the group on the Silent condition than the other Memory Game Conditions. (Take Subjects 5 & 14, and 8 and 1, for example. But also see Subjects 16 & 18, however.) Note that Subject 4 who did so well on the word recognition measures but relatively poorly on the Digits and Silent conditions and fairly well on the Colors condition was one of the youngest children in the sample. (See Table IX for reference.) Cases like Subject 4 and Subject 2 in combination with the scores of Subjects like 5, 14, 8 &1, are responsible for the pattern of correlations reported in Tables X and XI.

From this we can see that the proposal first made in Figure 3 may be somewhat reasonable.

TABLE XII

RANK ORDER PLACEMENT ON DISTRIBUTION OF SCORES (NUMBERS ARE SUBJECT IDENTIFIERS)

TEST		LOW							MIDDLE							HIGH	
LNT-Easy	16	1	6	18	9	8	5	13	14	11	10	7	19	3	4	12	2
LNT-Hard	16	6	18	9	8	1	14	11	5	13	10	19	3	4	2	7	12
MLNT-Easy	9	1	16	18	8	6	5	10	14	11	19	3	4	13	12	2	7
MLNT-Hard	1	16	18	9	8	6	5	19	3	13	11	10	14	4	12	2	7
PBK	18	1	6	8	16	11	9	19	10	5	3	13	14	7	2	4	12
Colors	19	11	1	8	3	14	16	18	6	5	13	10	4	7	9	12	2
Digits	19	11	1	8	4	3	14	13	9	16	18	10	6	5	7	12	2
Silent	19	11	4	1	8	13	3	16	18	10	6	12	2	14	5	7	9

Incorporating Effects of Duration of Device Use. Up to this point, we have not taken into account the possible influence of duration of device use. As we have already noted, chronological age and duration of device use were correlated about + 0.58. The relation between duration of device use and each of our word recognition and Memory Game measures not taking chronological age into account is illustrated in Table XIII. Unexpectedly, however, these correlations were not very large. This can be inferred from Table XIII and the correlations are explicitly reported in Table XIV, below. None of the correlations in Table XIV are large enough to be statistically significant.

TABLE XIII

RANK ORDER PLACEMENT ON DISTRIBUTION OF SCORES (NUMBERS ARE SUBJECT IDENTIFIERS)
SHADING ASSIGNED ACCORDING TO DURATION OF USE (SHORT→LONG)

TEST		LOW							MIDDLE							HIGH	
Interval of Use	9	6	8	11	16	1	12	10	13	4	19	3	5	7	2	14	18
PB-K	16	1	6	18	9	8	5	13	14	11	10	7	19	3	4	12	2
LNT-Easy	16	6	18	9	8	1	14	11	5	13	10	19	3	4	2	7	12
LNT-Hard	9	1	16	18	8	6	5	10	14	11	19	3	4	13	12	2	7
MLNT-Easy	1	16	18	9	8	6	5	19	3	13	11	10	14	4	12	2	7
MLNT-Hard	18	1	6	8	16	11	9	19	10	5	3	13	14	7	2	4	12
Colors	19	11	1	8	3	14	16	18	6	5	13	10	4	7	9	12	2
Digits	19	11	1	8	4	3	14	13	9	16	18	10	6	5	7	12	2
Silent	19	11	4	1	8	13	3	16	18	10	6	12	2	14	5	7	9

TABLE XIV

SIMPLE BIVARIATE CORRELATION BETWEEN DURATION OF DEVICE USE AND…	
PB-K	+ 0.29
LNT-EASY	+ 0.31
LNT-HARD	+ 0.31
MLNT-EASY	+ 0.37
MLNT-HARD	+ 0.28
MEMORY GAME COLORS	+ 0.11
MEMORY GAME DIGITS	+ 0.25
MEMORY SILENT/LIGHTS-ONLY	+ 0.22

* Significant at $p < .05$ level.
** Significant at $p < .01$ level.

Even so, the correlations between duration of device use and the word recognition measures appear to be strong enough that we would want to take this factor into account. In our next analysis, we computed correlations between each of the word recognition measures and the three Memory Game condition measures with both chronological age and duration of device use statistically partialled out. Table XV shows that the different pattern of correlations for the Silent/Lights-Only condition holds up, but with this sample size and data set, these correlations are not statistically significant.

TABLE XV

CORRELATIONS BETWEEN PB-K, LNT, MLNT AND EACH OF THE MEMORY SPAN GAME CONDITIONS, WITH AGE IN MONTHS AND DURATION OF DEVICE USE STATISTICALLY PARTIALLED OUT

PB-K with Game Colors	**+0.36**
LNT Easy with Game Colors	**+0.30**
LNT Hard with Game Colors	**+0.25**
MLNT Easy with Game Colors	**+0.07**
MLNT Hard with Game Colors	**+0.23**
PB-K with Game Digits	**+0.42**
LNT Easy with Game Digits	**+0.38**
LNT Hard with Game Digits	**+0.42**
MLNT Easy with Game Digits	**+0.27**
MLNT Hard with Game Digits	**+0.38**
PB-K with Game Silent	***+0.13***
LNT Easy with Game Silent	***-0.18***
LNT Hard with Game Silent	***-0.16***
MLNT Easy with Game Silent	***-0.38***
MLNT Hard with Game Silent	***-0.12***

* Significant at $p < .05$ level.
** Significant at $p < .01$ level.

TABLE XVI

CORRELATIONS BETWEEN PB-K, LNT, MLNT AND EACH OF THE MEMORY SPAN GAME CONDITIONS, WITH AGE IN MONTHS, DURATION OF DEVICE USE, AND NUMBER OF PRETEST IDENTIFICATION ERRORS STATISTICALLY PARTIALLED OUT

PB-K with Game Colors	**+0.40**
LNT Easy with Game Colors	**+0.34**
LNT Hard with Game Colors	**+0.34**
MLNT Easy with Game Colors	**+0.17**
MLNT Hard with Game Colors	**+0.32**
PB-K with Game Digits	**+0.39**
LNT Easy with Game Digits	**+0.32**
LNT Hard with Game Digits	**+0.32**
MLNT Easy with Game Digits	**+0.10**
MLNT Hard with Game Digits	**+0.28**
PB-K with Game Silent	***+0.25***
LNT Easy with Game Silent	***-0.09***
LNT Hard with Game Silent	***+0.03***
MLNT Easy with Game Silent	***-0.18***

MLNT Hard with Game Silent	***+0.09***

* Significant at $p < .05$ level.

** Significant at $p < .01$ level

Contribution of Reduced Identification of Particular Memory Game Stimuli. We conducted one last analysis to see how these relationships might be affected if we tried additionally to statistically "control" for number of identification errors made during the initial stimulus pretest. Presumably this would given some indication of the relationship between memory span and word recognition independent of the problems individual children had with a few of digit-name stimuli (age and device use aside). These results are given in Table XVI. Note that including a control for number of identification errors does, as one would expect, lower the correlations for the Digit-Name Memory Game condition slightly relative to those of Table XV, but raises the correlations of the Color-Name Memory Game condition.

Speculation Regarding Source of Distribution Differences. Even if Figure 3 is a reasonable reflection of fact, there are questions that remain. It seems quite possible that the children who are able to do well on word recognition tests might benefit from the added auditory input during the Memory Game, but why should the children that do worse on word recognition actually be "hurt" in a reciprocal fashion by the auditory input? (See caption, Figure 3.) Why shouldn't these children simply do the same on all Memory Game conditions? It appears that while some of these children do, in fact, do about the same on all conditions, there are a few children for whom the addition of sound actually acts as a hindrance. One possible explanation for this is that the sound input being provided by the implant to these children may be distracting or even annoying for some reason. The argument that the children with reduced word recognition skills may be better at coding spatial locations than the other children is not viable, because if this were the case, these children would have done about the same on all three Memory Game conditions, the remaining children would have done better on the auditory plus visual stimuli condition, and the span means for the Color-Name and Digit-Name conditions should have been higher on average than that for the Silent/Lights-Only condition. The results in Table I do not support this.

Apparent differences between the Color-Name and Digit-Name conditions are harder to interpret. It is fairly clear that while the children who did well on the word-recognition tasks had no trouble discriminating our digit-name stimuli, there were children in the sample that did have some difficulty with this task. The Color-Name condition, on the other hand, had the advantages of a semantically consistent mapping of auditory stimulus to button location, as well the greater discriminability, apparently, of its stimuli.

We did not find obvious distinctions between the different open-set word recognition tests used in this study with regards to their relation to memory span. Though it might be reasonable to hypothesize that recognizing and repeating back longer, somewhat less familiar and more acoustically confusable words might draw on phonological short-term memory resources more than would the same task using more familiar and easily discriminable short words, our results do not support this notion.

Summary and Conclusions. The results of this study suggest that even in our small sample of hearing impaired children, redundantly specified auditory information made available during a auditory-spatial target sequence was encoded and facilitated performance in the short term memory game reproduction task if the child had also developed open-set word recognition skills. If the child had less-well developed open-set word recognition skills, he/she was not helped particularly by the auditory supplement, and was perhaps even hindered by it. Our results also suggest that though the auditory-spatial memory game task employed here is moderately correlated with traditional forward digit span measures, other processing capacities, not employed in the purely verbal method, may be involved in performing the memory game task.

The data reported here include the first working memory measures gathered by this research group from pediatric cochlear implant and hearing aid users. Future studies are planned.

Among the shortcomings of this study is the small variance entailed by our discrete unit measure of span based on a single testing session. We are currently in the process of rescoring the data reported here in yet another way in an effort to slightly increase the range of scores obtained. We are also hoping to follow multiple administrations of this task over different sessions to assess the consistency and reliability of the memory game scores generated by hearing impaired children.

References

Daneman, M. & Carpenter, P.A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19,* 450-466.

Dedina, M.J. (1987). 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. (1981). Memory span: Sources of individual and developmental differences. *Psychological Bulletin, 89,* 63-100.

Gathercole, S.E. & Adams, A.M. (1993). Phonological working memory in very young children. *Developmental Psychology, 29,* 770-778.

Haskins, H. (1949). A phonetically balanced test of speech discrimination for children. Unpublished master's thesis, Northwestern University, Evanston, IL.

Hernandez, L.R. (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.V. (1990) *The Development of Memory in Children, 3rd Edition.* New York: W.H. Freeman.

Kirk, K I., Diefendorf, A.O., Pisoni, D.B. & Robbins, A.M. (1997). Assessing speech perception in children. In LL. Mendel & J.L. Danhauer (Eds.), *Speech Perception Assessment* (pp. 101-132). San Diego, CA: Singular.

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.

Kirk K.I., Pisoni, D.B. & Miyamoto R.T. (in press). Lexical discrimination by children with cochlear implants: Effects of age at implantation and commination mode. *Otolaryngology-Head & Neck Surgery.*

Kluck, M., Kirk, K.I, & Pisoni, D.B. (1997). Performance of normal-hearing children on open-set speech perception tests. In *Research on Spoken Language Processing Progress Report No. 21* (pp. 349-366). Bloomington, IN: Speech Research Laboratory, Indiana University.

Locke, J.L. (1997). A theory of neurolinguistic development. *Brain and Language, 58,* 265-326.

Luce, P.A. & Pisoni, D.B. (1998). Recognizing spoken words: The Neighborhood Activation Model. *Ear and Hearing, 19,* 1-39.

Marschark, M. (1993). *Psychological Development of Deaf Children.* New York: Oxford.

Meyer, T. & Pisoni, D.B. (1997). Some computational analyses of the PBK test: Effects of frequency and lexical density on spoken word recognition. In *Research on Spoken Language Processing Progress Report No. 21* (pp. 315-331). Bloomington, IN: Speech Research Laboratory, Indiana University.

Pisoni, D.B., Svirsky, M., 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. In *Research on Spoken Language Processing Progress Report No. 21* (pp. 51-91). Bloomington, IN: Speech Research Laboratory, Indiana University.