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Individual Differences in Effectiveness of Cochlear Implants in Prelingually Deaf Children: Some New Process Measures of Performance[1]

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Abstract. The “efficacy” of cochlear implants in deaf children has been firmly established in the literature. However, the “effectiveness” of cochlear implants varies widely and is influenced by demographic and experiential factors. Several “key” findings suggest new directions for research on central auditory factors that underlie the effectiveness of cochlear implants. First, there are enormous individual differences in both adults and children on audiological outcome measures. Some patients show large increases in speech perception scores after implantation whereas others display only modest gains on standardized tests. Second, age of implantation and length of deafness affect all outcome measures. Children implanted at younger ages do better than children implanted at older ages and children who have been deaf for shorter periods of time do better than children who have been deaf for longer periods of time. Third, communication mode affects outcome measures. Children from “oral-only” environments do much better on standardized tests that assess phonological processing skills than children who use “total communication.” Fourth, there are no preimplant predictors of outcome performance in young children. The underlying perceptual, cognitive and linguistic abilities and skills “emerge” after implantation and improve over time. Finally, there are no significant differences in audiological outcome measures among current implant devices or processing strategies. Taken together, this overall pattern of results suggests that higher-level central cognitive processes such as perception, attention, learning and memory may play important roles in explaining the enormous individual differences observed among users of cochlear implants. Investigations of the content and flow of information in the central nervous system and interactions between sensory input and stored knowledge may provide new insights into individual differences. Knowledge about the underlying basis of individual differences may also help in developing new intervention strategies to improve the effectiveness of cochlear implants in children who show relatively poor development of oral/aural language skills.

Introduction

When I first started to work on cochlear implants, I was immediately struck by the enormous variation in outcome and the large individual differences in performance. I wondered why some children do so well with their cochlear implant and why do other children do so poorly. I thought about this problem on and off for a couple of years and asked a lot of questions at our weekly clinical meetings. The clinicians in our group—the audiologists and speech pathologists who hook up and adjust the implants and test the children day in and day out could always count on me to come up with some unusual questions whenever an interesting child was discussed.

The problem of individual differences in the “effectiveness” of cochlear implants has been in the back of mind for a long time and has always intrigued me because of the challenge it presents for researchers interested in speech perception and spoken language processing. The NIDCD also considers the problem of individual differences to be an important area of research. The 1995 Consensus Statement on

Cochlear Implants in Adults and Children identified this topic as one of the major new directions for research. And, the study of individual differences is also a goal of our research program at the IU School of Medicine. We have moved into a number of new directions in order to understand the sensory, perceptual and cognitive basis for these differences. In the sections below, I give a summary of some of our most recent findings and some implications for future research on this issue.

At the present time, there are very few questions about the "efficacy" of cochlear implants in profoundly deaf children. Cochlear implants work and for some children they work well enough to permit them to develop spoken language through the auditory modality (Waltzman & Cohen, 2000). One of the most difficult problems with cochlear implants in deaf children, however, concerns the "clinical effectiveness" of these devices. Cochlear implants work well in some children but not others and no one seems to have come up with a very good explanation of why this happens. If we eliminate differences due to the number of active electrodes that provides the initial sensory information, there are not a lot of additional factors to investigate other than demographics and device characteristics. Psychophysical differences in frequency and intensity resolution may play an important role in setting initial constraints on how the sensory information is encoded at the auditory periphery but this is not the whole story. Something else is going on at more central levels of processing beyond the auditory nerve. We think individual variation in performance on outcome measures may be related to processing information at more central levels of analysis that are strongly affected by cognitive processes such as perception, attention, learning and memory. But there is very little, if any, research on these factors yet.

Almost all of the past research on cochlear implants has focused on demographic variables and traditional outcome measures using assessment tools developed by clinical audiologists and speech pathologists. Outcome measures of performance are the final product of a large number of complex sensory, perceptual, cognitive and linguistic processes that may be responsible for the observed variation among cochlear implant users. Until our recent studies reported below, no research has focused on "process" or examined the underlying mechanisms used to perceive and produce spoken language. Understanding these intermediate processes may provide new insights into the basis for these individual differences.

In addition to the enormous individual differences in outcome measures, several other findings have been consistently reported in the literature on cochlear implants in children. Age of Implantation has also been shown to affect outcome measures. Children who receive an implant at a young age after short periods of auditory deprivation do much better on a whole range of performance measures than children who are implanted at an older age after longer periods of sensory deprivation. Length of deprivation or length of deafness also predicts outcome. Children who have been deaf for shorter periods of time do much better on a variety of outcome measures than children who have been deaf for longer periods of time. Both findings demonstrate the important contribution of sensitive periods in development and the close links between neural development and behavior, especially, hearing, speech and language development (Ball & Hulse, 1998; Konishi, 1985; Konishi & Nottebohm, 1969; Marler & Peters, 1988).

Communication Mode also affects performance on a wide range of outcome measures. Implanted children who are immersed in "Oral-only" communication environments do much better on standardized tests than implanted children who are in "Total Communication" programs. The differences in performance between these two groups of children are seen most prominently in both receptive and expressive language tasks that involve phonological coding and phonological processing skills such as open-set spoken word recognition, comprehension and speech production.

Until just recently, researchers have been unable to identify reliable preimplant predictors of outcome and success with a cochlear implant. This is a critical theoretical finding because it demonstrates the existence of complex interactions between the newly acquired sensory capabilities of a child after a period of sensory deprivation, attributes of the language-learning environment and the interactions that the child is exposed to early on after receiving a cochlear implant. The lack of preimplant predictors also makes it difficult for both researchers and clinicians to identify those children who are doing poorly at a time in development when changes can be made to improve their language processing skills.

Finally, when all of the outcome and demographic measures are considered together, the evidence strongly suggests that the underlying abilities for speech and language "emerge" after implantation and that performance with a cochlear implant improves over time. Success with a cochlear implant therefore appears to be due to several different kinds of "learning" and exposure to the target language in the environment. Because success with a cochlear implant cannot be predicted reliably from traditional behavioral measures obtained before implantation, any improvement in performance observed after implantation must be due to learning processes that are correlated with maturational changes in neural and perceptual development.

Taken together, these "five key" findings suggest several general conclusions about the way cochlear implants work to facilitate the acquisition and development of spoken language. These findings also point to several underlying factors that affect performance on various outcome measures. Our current hypothesis about the source of individual differences is that while some proportion of the total variance in performance is clearly due to peripheral factors related to audibility and the initial sensory encoding of the speech signal into "information-bearing" sensory channels in the auditory nerve, an additional source of variance may also come from more central "cognitive" factors that are related to processes such as perception, attention, learning and memory. This source of variance is related to information processing operations and cognitive demands—that is, how the child uses the initial sensory input he/she receives from the cochlear implant and how the environment modulates, shapes and facilitates this learning process. These processes are, of course, topics that are the "meat and potatoes" of what cognitive psychologists and cognitive scientists study, namely, the encoding, rehearsal, storage and retrieval of information and the transformation and manipulation of memory codes and neural representations of the initial sensory input in a wide range of language processing tasks.

About three years ago, my colleagues and I began analyzing a set of data from our longitudinal project on cochlear implants in children to get a better handle on the issue of individual differences and variation in outcome. We began by looking at the "exceptionally" good users of cochlear implants—the so-called "Stars." These are the children who did extraordinarily well with their cochlear implants two years after implantation. They were able to acquire spoken language relatively quickly and easily and seemed to be on a developmental trajectory that parallels normal-hearing children. In many ways, at first glance, they look like normal hearing and normally developing children who simply have language delays.

Our interest and motivation in studying the "Stars" came, in part, from an extensive body of research in cognitive psychology over the last twenty-five years on "expertise" and "expert systems" theory (Ericsson & Pennington, 1993; Ericsson & Smith, 1991). Many important insights have come from studying expert chess players, radiologists and other people who have highly developed skills in specific knowledge domains like computer programming, spectrogram readings and even chicken sexing!! The rationale underlying our approach to the problem of individual differences was that if we could learn something about the "Stars" and the reasons why they do so well with their cochlear implants by adopting the orientation of expert systems theory, perhaps we could use this knowledge to develop new intervention techniques with children who are not doing very well with their implants. Knowledge and understanding of the "Stars" would also be very useful in developing new pre-implant predictors of performance, in modifying current criteria for candidacy and in creating better and more precise methods of assessing performance and measuring outcome over time.

An initial report describing our findings on the "Stars" was presented in NYC in 1997 at the Xth International Cochlear Implant conference (Waltzman & Cohen, 2000). At that time, I presented longitudinal data collected over a period three years after implantation. We now have additional data on these children over six years that I will present below. Since that time, our research on individual differences has continued and expanded into several new directions as we try to understand the nature of these underlying factors. I was also very fortunate to begin collaborating with Ann Geers and her colleagues at CID who obtained some new data on working memory from forty-five 8 and 9 year olds who had used their cochlear implant for five years. New data on digit spans provided an opportunity to test a critical hypothesis about differences in information processing in children with cochlear implants. The work on digit spans then led to other analyses, development of new methodologies to measure working memory and several additional experiments on coding and rehearsal strategies that will be summarized below. We have developed a new methodology to study verbal and spatial coding in children with cochlear implants. Our initial findings were very encouraging and the results have provided some new insights into the underlying basis for the large individual differences observed in these children.

Theoretical Approach

Before I present the results of these studies, it is appropriate to say a few words about the theoretical motivation that underlies our research program on individual differences. Previous research on cochlear implants has relied very heavily on traditional outcome measures of performance that were developed within the field of clinical audiology. Historically, this research orientation focused on static assessment measures based on accuracy, device characteristics and demographic variables. In the past, there has been little if any concern or interest in "process" or a description of the underlying perceptual, cognitive or linguistic mechanisms that mediate performance. Researchers working on cochlear implants are interested in measuring change in performance over time but they have not studied change with an interest in describing the underling neural or behavioral mechanisms or the flow and contents of information in the nervous system.

In contrast, our research program on individual differences is motivated by several general theoretical principles that come from the field of human information processing and cognitive science. We are interested in describing and understanding the kinds of sensory and perceptual information that a child gets from his/her implant. We investigate and try to understand the nature of the phonetic, phonological and lexical representations that the child creates and how these are used in various language processing tasks. In adopting the information processing approach, our goal is to describe the "stages of processing" and to trace out the "time-course" of the various transformations this information takes from stimulus input to an observer's overt response in a specific task. This theoretical perspective is very different from the traditional approach used in clinical research on patients with cochlear implants that has focused almost exclusively on assessment and outcome measures. We hope that our approach will provide new knowledge about the underlying source of the individual differences observed among children and some of the factors that affect performance on traditional outcome measures.

Analysis of The "Stars"

Now let me turn to a summary of the major findings we obtained in our analyses of the “Stars.” We have analyzed data obtained from several different outcome measures over a period of six years from the time of implantation in order to examine changes in performance over time. Before I present these results, however, I will describe how we originally identified and selected the “Stars” and the comparison group for our analyses.

The criterion used to identify the “Stars,” the exceptionally good users of their cochlear implant, was based on performance on one particular perceptual test, the Phonetically Balanced Kindergarten (PBK) Words test (Haskins, 1949), which is an open-set test of spoken word recognition (also see Meyer & Pisoni, 1999). Among clinicians, this particular test is considered to be very difficult for prelingually deaf children compared to other, closed-set perceptual tests that are routinely included in a standard assessment battery (Zwolan, Zimmerman-Phillips, Asbaugh, Hieber, Kileny & Telian, 1997). The children who do moderately well on the PBK test frequently display ceiling levels of performance on all of the other closed-set speech perception tests that measure speech pattern discrimination. In contrast, open-set tests like the PBK measure word recognition and lexical discrimination and require the child to search and retrieve the phonological representations of the test words from lexical memory. Open-set tests of word recognition are extremely difficult for hearing-impaired children and adults with cochlear implants because the procedure and task demands require the listener to perceive and encode fine phonetic differences based entirely on information present in the speech signal without the aid of any external context or retrieval cues. The listener must then discriminate and select a unique pattern, a phonological representation, from a large number of equivalence classes in lexical memory (see Luce & Pisoni, 1998). This may seem like a simple task at first glance but it is very difficult for a child who has a cochlear implant. Children with normal hearing have very little difficulty with open-set tests like the PBK and they routinely display ceiling levels of performance in recognizing words under these presentation conditions (Kluck et al., 1997).

To learn more about the “Stars,” we analyzed outcome data from pediatric cochlear implant users who scored exceptionally well on the PBK test two years after implantation. The PBK score was used as the “criterial variable” to identify and select two groups of subjects for subsequent analysis using an extreme groups design. After these subjects were selected and sorted into groups, we examined their performance on a variety of outcome measures already obtained from these children as part of our large-scale longitudinal study. The measures included tests of speech perception, comprehension, word recognition, receptive vocabulary knowledge, receptive and expressive language development and speech intelligibility.

Methods

Subjects

Scores for the two groups of pediatric cochlear implant users were obtained from a large longitudinal database containing a variety of demographic and outcome measures from 160 deaf children. Subjects in both groups were all prelingually deafened (mean =0.4 years onset). Each child received a cochlear implant because he/she was profoundly deaf and was unable to derive any benefit from conventional hearing aids. The criterion used to identify the “Stars” was based entirely on word recognition scores from the PBK test. This group consisted of 27 children who scored in the upper 20% on the PBK test two years post-implant. A “comparison” group of subjects consisting of 23 children who scored in the bottom 20% on the PBK test two years post-implant was also created for the analysis. The mean percentage of words correctly recognized on the PBK test was 25.64 for the “Stars” and 0.0 for the “comparison” group. A summary of the demographic characteristics of the two groups is shown in Table I.

No attempt was made to match the subjects on any other demographic variable other than length of implant use that was fixed at two years post implantation at the time these analyses were carried out. As a result of this selection procedure, the two groups turned out to be roughly comparable in terms of age of onset of deafness and length of implant use. However, as shown in Table I, the two groups did differ in terms of age at implantation, length of deprivation and communication mode.

For ease of exposition, the results of these analyses will be presented in three sections, one for the receptive scores and one for the expressive scores. The interrelations among these various measures using correlational methods are summarized in the last section.

Table I

Summary of Demographic Information

	Stars **(N = 27)**	***Controls*** **(N = 23)**
Mean Age at Onset (Years)	.3	.8
Mean Age at Implantation (FIT) (Years)	5.8	4.4
Mean Length of Deprivation (Years)	5.5	3.6
Mean Length of Implant Use (Years)	.9	1.0
Communication Mode:		
Oral Communication	N=19	N=8
Total Communication	N=8	N=15

Outcome Measures of Performance

Receptive Measures: Speech Perception and Spoken Word Recognition

Minimal Pairs Test. Measures of speech feature discrimination for both consonants and vowels were obtained for both groups of subjects with the Minimal Pairs Test (Robbins et al., 1988). This test uses a two-alternative forced-choice picture pointing procedure. The child hears a single word spoken in isolation on each trial by the examiner using live voice presentation and is required to select one of the pictures that correspond to the test item.

A summary of the consonant discrimination results for both groups of subjects is shown in Figure 1. Percent correct discrimination is displayed separately for the distinctive features of manner, voicing and place of articulation as a function of implant use in years. Data for the “Stars” are shown by the filled bars; data for the “Controls” are shown by the open bars in this figure. Chance performance on this task is 50 percent correct as shown by a dotted horizontal line. A second dotted horizontal line is also shown in this figure at 70 percent correct corresponding to scores that are significantly above chance using the binominal distribution.

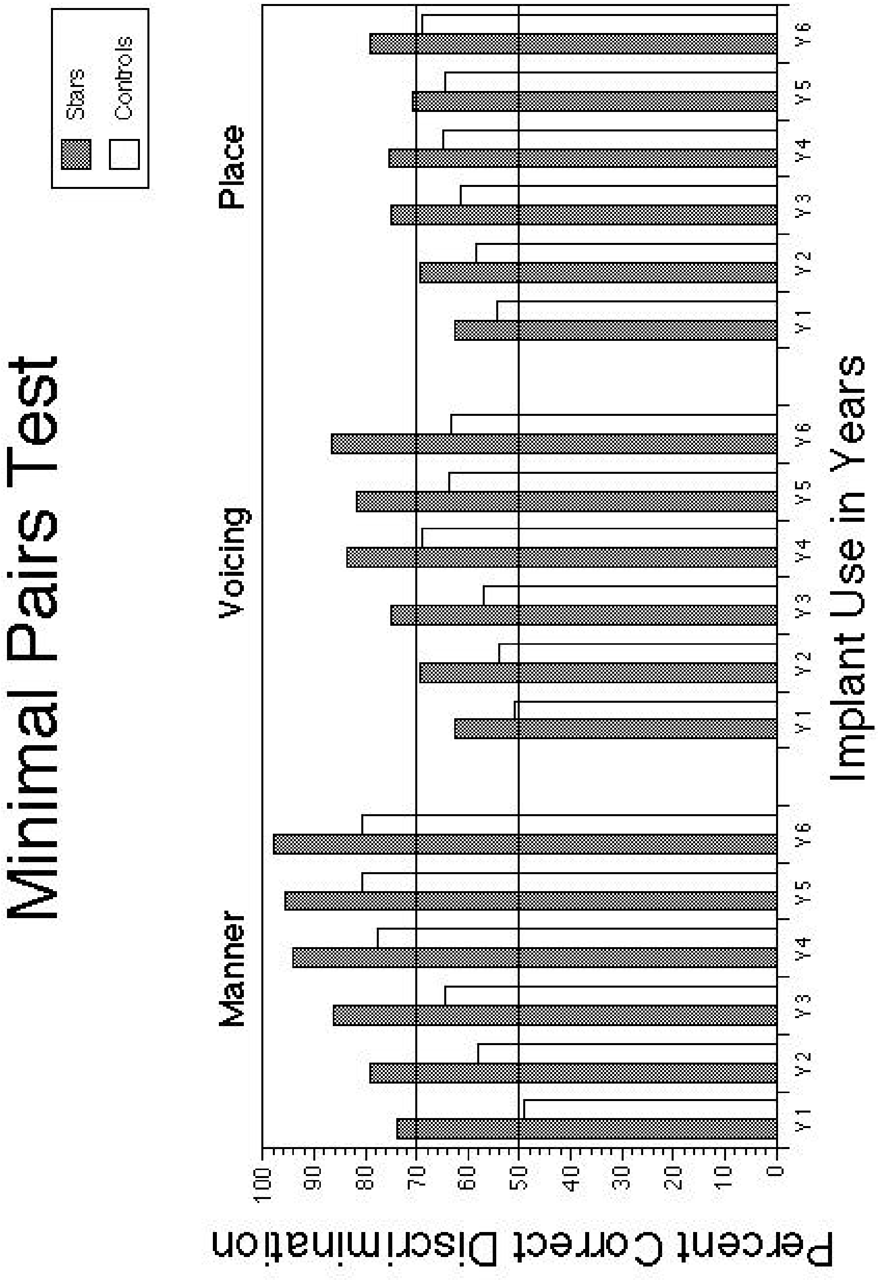

Figure 1. Percent correct discrimination on the minimal pairs (MPT) test for manner, voicing and place as a function of implant use. The "Stars" are shown by filled bars, the "Controls" are shown by shaded bars.

Inspection of the results for the Minimal Pairs Test obtained over a period of six years of implant use reveals several finding. First, performance of the "Stars" was consistently better than the control subjects for every comparison across all three consonant features. Second, discrimination performance improved over time with implant use for both groups, although the increases were primarily due to improvements in discrimination of manner and voicing by the “Stars.” All of the datapoints for the control subjects were at or below chance expectation for discrimination of the voicing and place features. Although there were increases in performance over time for the control subjects, their discrimination scores never reached the levels observed with the “Stars,” even for the manner contrasts that eventually exceeded chance performance in years 4, 5 and 6.

The results of the Minimal Pairs Test indicate that both groups of children have difficulty perceiving, encoding and discriminating fine phonetic details of isolated spoken words even in a closed-set testing format. The “Stars” were able to discriminate differences in manner of articulation after one year of implant use and they showed consistent improvements in performance over time for both manner and voicing contrasts but they still had difficulty reliably discriminating differences in place of articulation, even after five years of experience with their implants. In contrast, the “Control” subjects were just barely able to discriminate differences in manner of articulation after four years of implant use and they still had serious problems with voicing and place of articulation even after five or six years of use.

The pattern of speech feature discrimination results shown here suggests that both groups of children are encoding spoken words using “coarse” phonetic representations that contain much less fine-grained acoustic-phonetic detail than normal hearing children typically do. The “Stars” are able to reliably discriminate manner and to some extent voicing much sooner after implantation than the “Controls” and the “Stars” display consistent improvements in speech feature discrimination over time. These speech feature discrimination skills are assumed to place initial constraints on the basic sensory information that can be used for subsequent word learning and lexical development. It is very likely that if a child cannot reliably discriminate differences between pairs of spoken words that are acoustically similar under these relatively easy forced-choice test conditions, they will subsequently have great difficulty recognizing words in isolation with no context or retrieving the phonological representations of these sound patterns from memory for use in simple speech production tasks such as imitation or immediate repetition.

Common Phrases Test. Spoken language comprehension performance was measured using the Common Phrases Test (Osberger et al., 1991). This is an open-set test that employs three presentation formats: auditory-only (CPA), visual-only (CPV) and combined auditory plus visual (CPAV). Children are asked questions or given commands to follow with instructions under these conditions. The results of this test are shown in Figure 2 for both groups of subjects, “Stars” and “Controls” as a function of implant use for the three different presentation formats. Inspection of this figure shows that the “Stars” performed consistently better than the “Controls” in all three presentation conditions and across all six years of implant use although performance begins to approach ceiling levels for both groups in the combined auditory plus visual conditions (CPAV) after five years of implant use. The multi-modal presentation conditions (CPAV) were always better than either the auditory-only or visual-only conditions. This pattern was observed for both groups of subjects. In addition, both groups displayed improvements in performance over time in all three-presentation conditions. Not surprisingly, the largest differences in performance between the two groups occurred in the auditory-only conditions. Even after three years of implant use, the “Control” subjects were barely able to perform this comprehension task above 25 percent correct when they had to rely entirely on auditory cues in the speech signal to carry out the task.

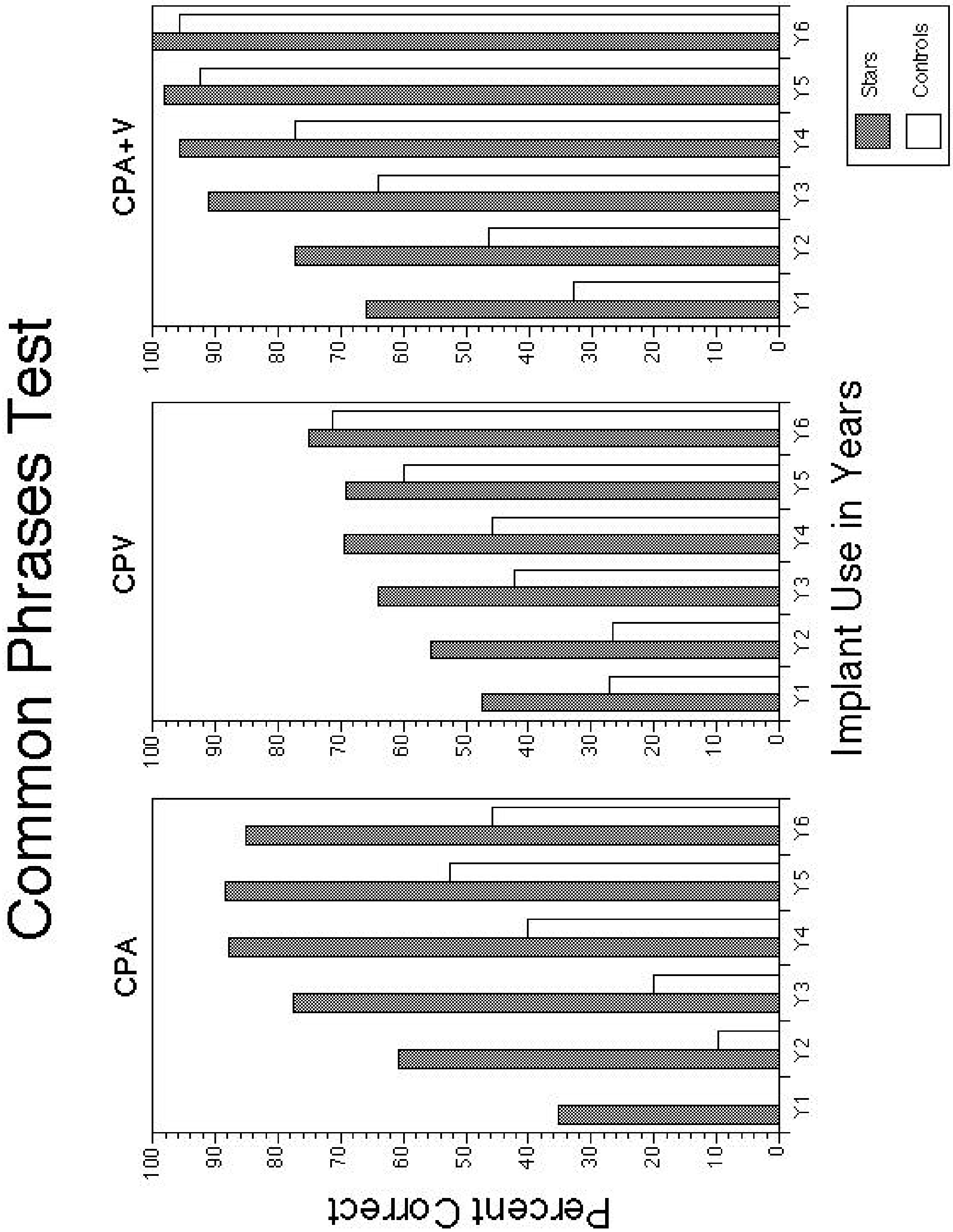

Figure 2. Percent correct performance on the common phrases (CPT) test for auditory-only (CPA), visual-only (CPV) and combined auditory plus visual presentation modes (CPA+V) as a function of implant use. The "Stars" are shown by filled bars, the "Controls" are shown by shaded bars.

Word Recognition Tests. Two new word recognition tests, the Lexical Neighborhood Test (LNT) and the Multi-syllabic Lexical Neighborhood test (MLNT), were used to measure open-set word recognition skills in both groups of subjects (Kirk, Pisoni & Osberger, 1995). Both tests use words that are familiar to preschool age children. The LNT contains short monosyllabic words, the MLNT contains longer polysyllabic words. Both of these tests use two different sets of items in order to measure lexical discrimination and provide details about how the lexical selection process is being carried out. Half of the items in each test consist of lexically “easy” words and half consist of lexically “hard” words. The differences in performance on these two sets of items in each test provide an index of how well a listener is able to make fine phonetic discriminations among acoustically similar words in their lexicons. Differences in performance between the LNT and the MLNT provide a measure of the extent to which the listener is able to make use of word length cues to recognize and access words from the mental lexicon. The items on both tests are presented in isolation one at a time by the examiner using auditory-only format. The child is required to imitate and immediately repeat back the test item after it is presented on each trial.

Figures 3 and 4 show the results, expressed as percent correct word recognition, obtained on the LNT and the MLNT for both groups of subjects as a function of implant use. The data for the “Stars” are shown in the top panel of each figure; the data for the “Controls” are shown in the bottom panels. Scores for the “easy” and “hard” words are shown within each panel. Several important differences in performance are shown in these two figures that provide some insights into the task demands and processing operations used in open-set tests. First, the “Stars” consistently demonstrate higher levels of word recognition performance on both the LNT and the MLNT than the “Controls.” These differences are present across all six years but they are most prominent during the first three years after implantation. Word recognition scores for the “Controls” on both the LNT and the MLNT are very low and close to the floor compared to the performance observed for the “Stars” who are doing moderately well on this test although they never reached ceiling levels of performance on either the LNT or MLNT even after six years of implant use. Normal-hearing children typically display ceiling levels of performance on these same tests by age 4 (Kluck et al., 1997).

Another theoretically important finding is also shown in these figures. The “Stars” displayed a word length effect at each testing interval. Recognition was always better for the long words on the MLNT than the short words on the LNT. This pattern is obscured by a floor effect for the “Controls” who were unable to do this open-set task at all during the first three years. The presence of a word length effect for the “Stars” suggests that they are recognizing words “relationally” in the context of other words that they have in their lexicon (Luce & Pisoni, 1998). If these listeners were just recognizing words in isolation, feature by feature or segment-by-segment, without reference to words they already know and can access from lexical memory, one would predict that performance should be worse for longer words than shorter words because longer words simply contain more information. The pattern of findings observed here is exactly the opposite of this prediction and parallels earlier results obtained with normal-hearing adults and children (Luce & Pisoni, 1998; Kirk et al., 1995; Kluck et al., 1997). Longer words are easier to recognize than shorter words because they are more distinctive and less confusable with other phonetically similar words. The present findings suggest that the “Stars” are recognizing words based on their knowledge of other words in the language using processing strategies that are similar to those used by normal-hearing listeners.

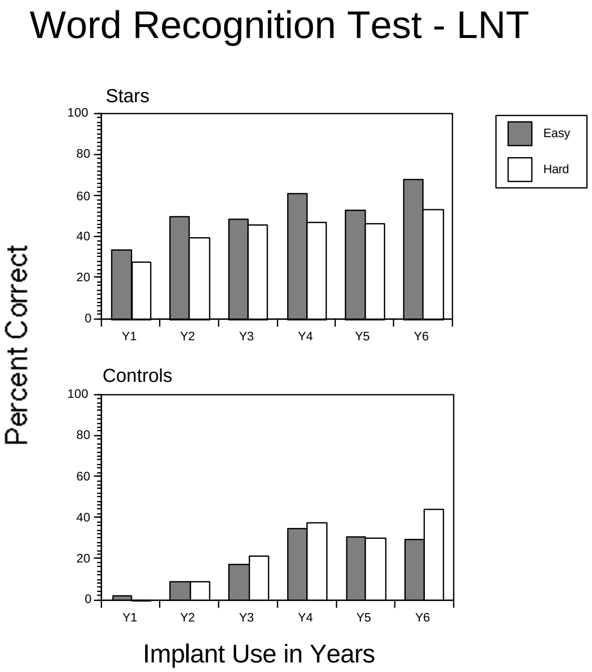

Figure 3. Percent correct word recognition performance for the LNT monosyllabic word lists as a function of implant use and lexical difficulty. "Easy Words" are shown by filled bars, "Hard Words" are shown by shaded bars. Data for the "Stars" are displayed in the top panel; "Controls" are displayed in the bottom panel.

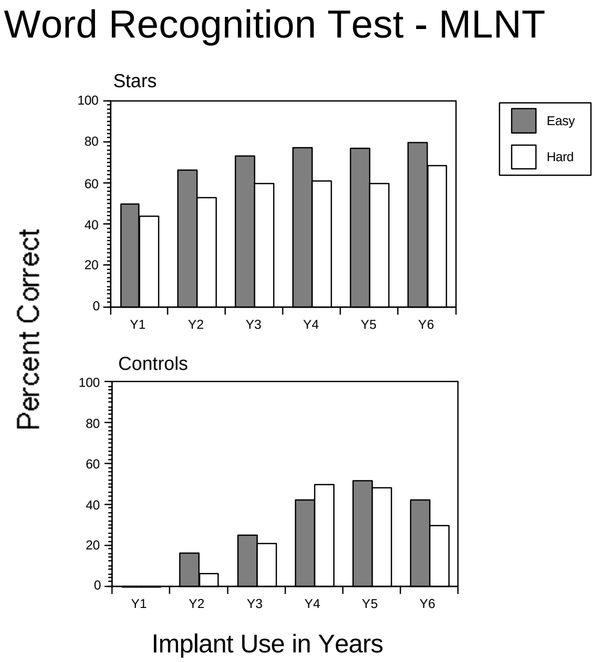

Figure 4. Percent correct word recognition performance for the MLNT multi-syllabic word lists as a function of implant use and lexical difficulty. "Easy Words" are shown by filled bars, "Hard Words" are shown by shaded bars. Data for the "Stars" are displayed in the top panel; "Controls" are displayed in the bottom panel.

Additional support for role of the lexicon and the use of lexical knowledge in open-set word recognition is also provided by another finding shown in both figures. The "Stars" also showed a consistent effect of "lexical discrimination" for both sets of words on the LNT and the MLNT tests. Examination of Figures 3 and 4 reveals that the "Stars" recognize lexically "easy" words better than lexically "hard" words. The difference in performance between "easy" words and "hard" words is present for both the LNT and the MLNT vocabularies but it is larger and more consistent over time for the words on the MLNT test. Because of floor effects, the "Controls" did not display the same consistent pattern of performance or sensitivity to lexical competition among the test words.

The differences observed between these two groups of children on both open-set word recognition tests are not at all surprising and were expected because these two extreme groups were initially created based on their PBK scores. But the overall pattern of the results is theoretically important at this time because the findings obtained with these two new open-set word recognition tests, the LNT and the MLNT, demonstrate that the skills and abilities used to recognize isolated spoken words are not specific to the test items used on the PBK test or the experimental procedures used in open set tests of spoken word recognition. The original differences between the two groups readily generalized to other open-set word recognition tests using different words. This pattern of results strongly suggests the operation and use of some common underlying set of cognitive and linguistic processes that are employed in recognizing, imitating and immediately repeating back spoken words presented in isolation. As suggested below, identifying and understanding the processing mechanisms that are used in these kinds of tasks may provide some new insights into the underlying basis of the large individual differences observed in outcome measures in children with cochlear implants. It is probably no accident that the PBK test has had some important diagnostic utility in identifying the exceptionally good users of cochlear implants over the years (see Kirk et al., 1995; Meyer & Pisoni, 1999). The PBK test is clearly measuring several important language processing skills that may generalize well beyond the specific repetition task used in open-set tests. The most important conceptual issue now is to explain why this happens to be the case and to begin to identify the underlying cognitive and linguistic mechanisms that are being used in open-set word recognition tasks as well as other tasks that draw on the same set of processing resources and operations.

Receptive Vocabulary Knowledge. Vocabulary knowledge was assessed using the Peabody Picture Vocabulary Test (PPVT), a standardized test that provides a measure of receptive language development based on word knowledge (Dunn & Dunn, 1997). Test items were presented using the child's preferred mode of communication, either speech or sign, depending on whether the child is immersed in an Oral-only (OC) or Total-Communication (TC) environment. The scores on the PPVT are shown in Figure 5 for both groups of subjects as a function of implant use. The top panel of this figure shows the raw scores; the bottom panel shows the same data expressed as language quotients that were obtained by dividing the child's language age by his/her chronological age. Language age is based on norms from normal-hearing children. Normal-hearing children with typical age-appropriate language skills would be expected to achieve scores of 1.0 on this scale. Inspection of the top panel shows that when expressed in terms of raw scores, both groups improve over time with implant use. However, the "Stars" score consistently better than the "Controls," although the differences are not as large as those observed on the previous word recognition tests. This pattern may be due to the fact that this test as well as the other standardized language tests are routinely administered in the child's preferred communication mode. As displayed in Table I, most of the "Controls" included in this group were enrolled in TC programs whereas most of the "Stars" were enrolled in OC programs. Examination of the language quotients shown in the bottom panel indicates that both groups of children display comparable scores that remain the same over time. This is not surprising because chronological age was used to normalize the language scores.

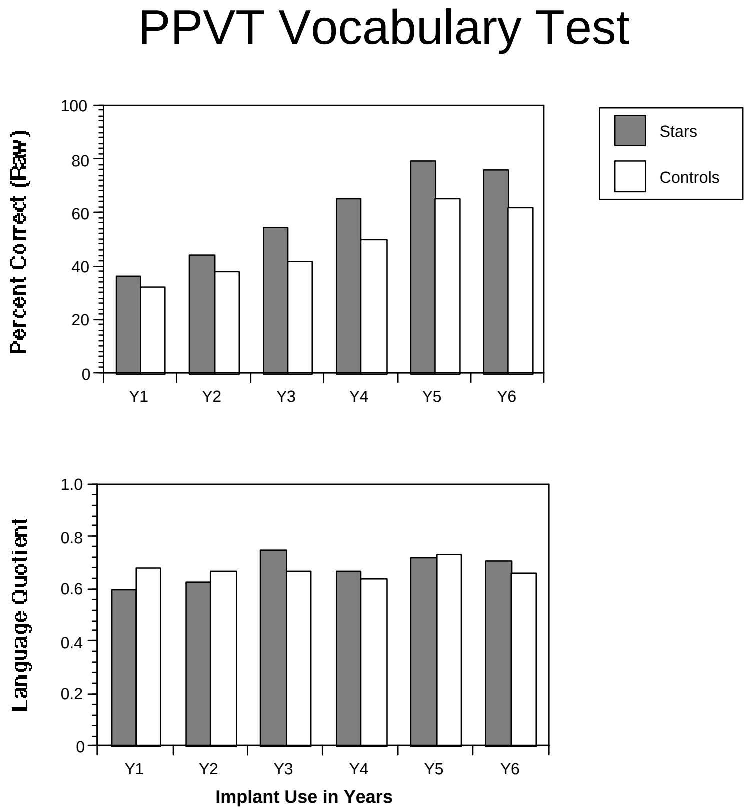

Figure 5. Raw scores (top panel) and language quotients (bottom panel) for the "Stars" and "Controls" on the Peabody Picture Vocabulary Test (PPVT) as a function of implant use in years.

Measures of Language Development

Measures of receptive and expressive language development were obtained for both groups of subjects using the Reynell Developmental Language Scales (Reynell & Huntley, 1985). These scales assess receptive and expressive language skills independently using tasks involving object manipulation and description based on questions that vary in length and linguistic complexity. The Reynell tests have been used extensively with deaf children and are appropriate for a broad age range of children from one to eight years old. Normative data have also been collected on normal-hearing children so appropriate comparisons can be drawn (see Svirsky et al., in press).

Figures 6 and 7 show scores for the Reynell receptive and expressive scales for both groups of children as a function of implant use. The top panel in each figure shows the raw scores for each measure, the bottom panel shows the corresponding language quotients. Scores for the "Stars" in Y6 in each figure are based on projected estimates because these children had reached ceiling levels of performance for their age and the tests were no longer routinely administered at the yearly assessments. Both sets of data for the Reynell show gradual improvement in language over time. Once again, the differences in performance between the two groups were not very large, although the "Stars" achieved higher scores on both receptive and expressive scales than the controls. In our earlier analyses of the performance of the “Stars,” after the first three years of implantation (Pisoni et al., 1997), we found a main effect for communication mode and an interaction of communication mode with group. Overall, TC children scored higher than OC children but this was observed only for the “Control” subjects and not the “Stars.”

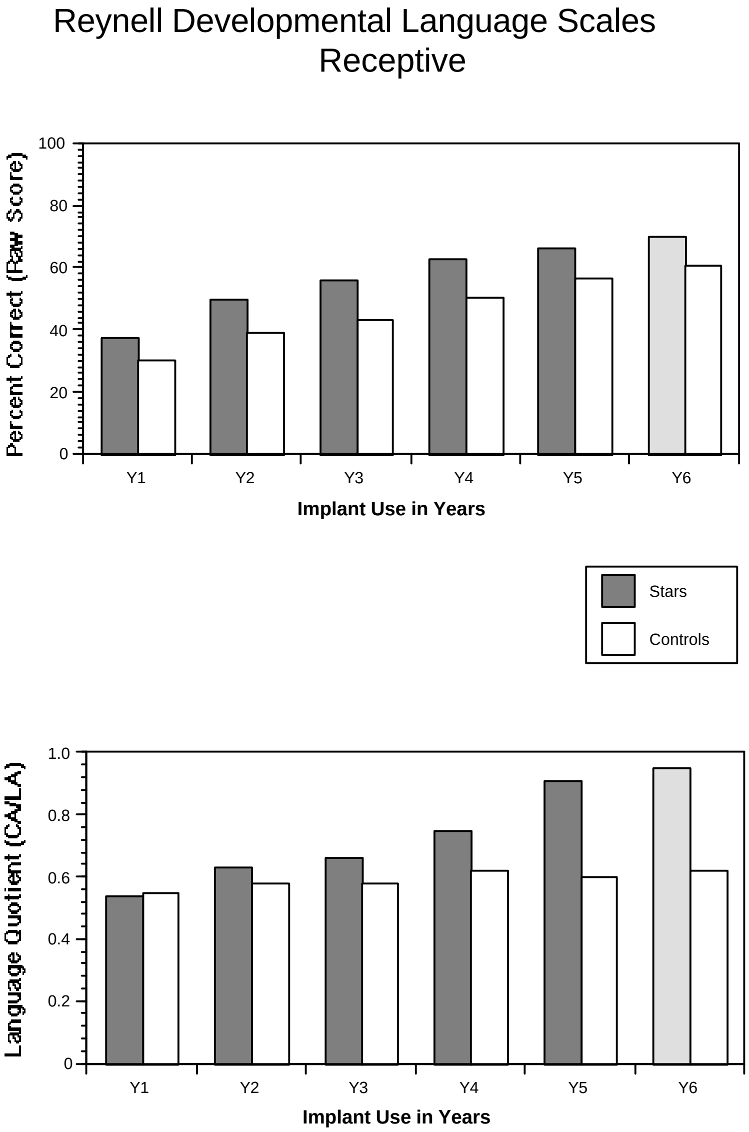
Reynell Developmental Language Scales
Receptive

Figure 6. Reynell receptive language scores for “Stars” and “Controls” as a function of implant use. Top panel shows raw scores, bottom panel shows language quotients.

Taken together with the earlier PPVT scores, the present results suggest that communication mode does influence outcome measures on standardized tests that assess language and language-related abilities such as vocabulary knowledge and language use. It is clear that the specific types of social and linguistic interactions that take place in the child’s language learning environment after implantation play an important role in promoting and facilitating language development, vocabulary acquisition and overall success with a cochlear implant. Children with cochlear implants who are placed in OC environments consistently show large gains in oral language skills on tasks that specifically require the use of phonological representations and phonological processing strategies in speech perception and speech production tasks

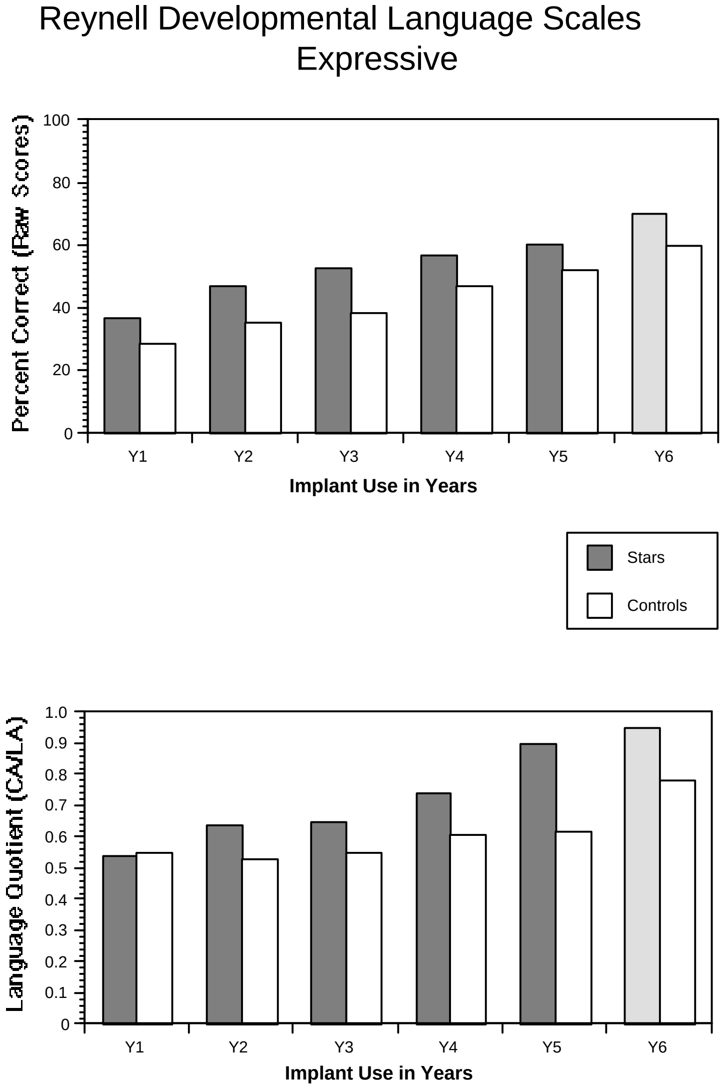

Figure 7. Reynell expressive language scores for "Stars" and "Controls" as a function of implant use. Top panel shows raw scores, bottom panel shows language quotients.

Speech Intelligibility

Measures of speech intelligibility were also obtained for both groups of subjects using a transcription task. Speech samples were first obtained from each child using standardized elicitation materials. Each child produced 10 sentences that were repeated after an examiner's spoken model. One list from the Beginners Intelligibility Test (BIT) was administered to obtain the speech samples from each child. This test uses objects and pictures to convey the target sentence (Osberger et al., 1994). The speech samples were then played back to small groups of normal-hearing adult listeners who were asked to listen and transcribe what the child had said. A composite score based on the number of words correctly transcribed for each child was obtained from the responses provided by three listeners who heard each child's utterance.

Figure 8 shows the percent correct transcription for the "Stars" and "Controls" as a function of implant use. Examination of this figure shows that the "Stars" display much better speech intelligibility than the "Controls." Although both groups show improvements in speech intelligibility over time, the difference in performance between the "Stars" and "Controls" remains roughly constant even after six years of implant use. The differences in speech intelligibility found here demonstrate that variation in performance between the "Stars" and "Controls" is not restricted to only receptive measures of language processing such as speech perception, spoken word recognition, receptive vocabulary knowledge or comprehension. The present findings on speech intelligibility provide evidence for transfer of knowledge from one linguistic domain to another and suggest an overlap and commonality between perception and production (see O'Donoghue et al., 1999). This overlap of receptive and expressive language function reflects a knowledge of the sound/meaning contrasts in the language and a common underlying linguistic system, a grammar, that the child constructs from the linguistic input he/she is exposed to in the ambient environment. As we observed earlier, the "Stars" showed large and consistent improvements in both receptive and expressive measures of language including speech feature perception, spoken word recognition, vocabulary knowledge, comprehension and speech intelligibility. In contrast, the "Control" subjects not only showed much lower levels of performance overall on these tests but the rate of their improvement in performance was much slower over time.

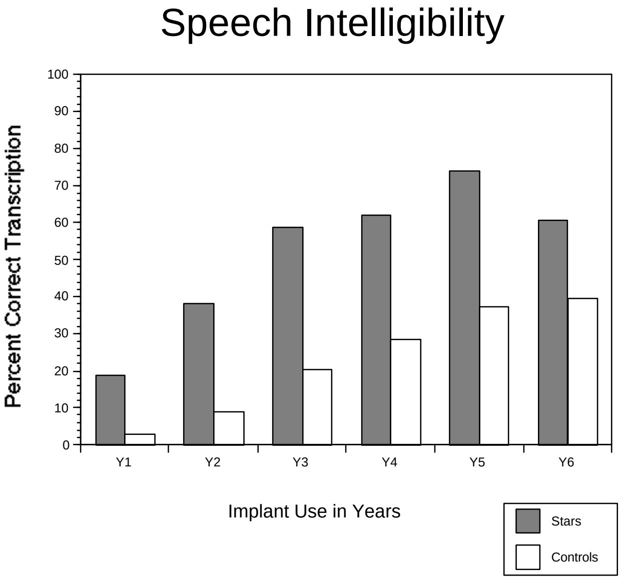

Figure 8. Percent correct transcription scores for "Stars" and "Controls" as a function of implant use in years.

Correlations Among Test Measures

Examination of these descriptive results show that the exceptionally good children, the "Stars," appear to do well on a wide variety of outcome measures including speech feature perception, comprehension, spoken word recognition, receptive and expressive language as well as measures of speech intelligibility. This pattern of findings was very encouraging because it suggested that there may be some common source of variance that underlies the exceptionally good performance of these children on many different outcome measures. Our working hypothesis is that this particular source of variance reflects "modality-specific" fundamental information processing operations that are involved in the phonological coding of sensory inputs and the construction of phonological representations of speech (see Pisoni et al., 1997).

Until our analyses of these scores from the "Stars," very little previous research was directed specifically at the study of individual differences among pediatric cochlear implant users or an examination of the perceptual, cognitive and linguistic abilities of the exceptionally good subjects. Our analyses of speech perception, word recognition, spoken language comprehension, vocabulary knowledge and language development demonstrate that a child who displays exceptionally good performance on the PBK test also shows very good scores on a variety of other speech and language measures as well. This is a theoretically important finding. The differences in performance observed here between the "Stars" and "Controls" are of substantial interest because it may now be possible to determine precisely how and why the "Stars" differ from other less successful cochlear implant users. If we have knowledge of the factors that are responsible for individual differences in performance among deaf children who receive cochlear implants, particularly the variables that underlie the extraordinarily good performance of the "Stars," we may be able to help those children who are not doing as well with their implant at an early point in development. Moreover, our findings on individual differences may have direct clinical relevance in terms of recommending specific changes in the child's language-learning environment and in modifying the nature of the sensory inputs and linguistic interactions a child has with his/her parents, teachers and speech therapists who provide the primary language model for the child. Our findings on individual differences may also help in providing clinicians and parents with a principled basis for generating realistic expectations about outcome measures, particularly measures of speech perception, comprehension, language development and speech intelligibility in deaf children with cochlear implants.

One of the most interesting and informative analyses that we carried out on these data was a series of simple correlations among the different dependent measures summarized above. We were interested in the following questions: Does a child who performs exceptionally well on the PBK test also perform exceptionally well on other tests of speech feature discrimination, word recognition and language? What is the relationship between performance on the PBK test and speech intelligibility? Is the extraordinarily good performance of the "Stars" restricted to only open-set word recognition tests like the PBK or is it possible to identify a common underlying variable or process that can account for the relationships observed among several different dependent measures? In order to answer these kinds of questions, we examined the intercorrelations for each of the dependent variables described earlier. Simple bivariate correlations were carried out separately for the "Stars" and "Controls" using the test scores obtained after only one year of implant use. A detailed summary of these findings was reported in Pisoni et al., 1997. In this section, we present the correlations for three of the dependent measures, open-set word recognition using the LNT, receptive and expressive language based on the Reynell and speech intelligibility scores using measures of transcription in order to illustrate the general pattern that was found across the other dependent measures. More details are provided in the earlier report.

Open-set Word Recognition. Table II shows the correlations of the LNT word recognition scores with each of the other dependent measures for the "Stars." The correlations for the lexically "easy" words are shown in the left-hand column; the correlations for the lexically "hard" words are shown in the right-hand column. Because the "Control" subjects were unable to recognize any of the words on the LNT after one year of implant use, it was not possible to compute any correlations with the other test measures. An examination of this table shows that performance on the LNT is highly correlated with comprehension scores, receptive vocabulary knowledge, both receptive and expressive measures of language development and speech intelligibility scores. The pattern of intercorrelations among these dependent measures strongly suggests a common underlying source of variance that is shared by all these different tasks. The extremely high correlations of the LNT word recognition scores with the Common Phrases-Auditory-only scores and both language measures on the Reynell suggests that this common source of variance may be related in some way to the encoding, storage, retrieval and rehearsal of spoken words, specifically, the phonological representations of spoken words in lexical memory. The fundamental cognitive and linguistic processes used to recognize spoken words in an open-set format like the PBK or LNT test where there is no context other than the acoustic-phonetic information in the signal are probably also used in other language processing tasks as well such as comprehension and speech production which draw on various sources of information about spoken words in the lexicon.

Table II

CORRELATIONS: WORD RECOGNITION - YEAR 1

	Lexical Neighborhood Test *(LNT)*			
	Easy Words		***Hard Words***	
	Stars	Controls	Stars	Controls
SPEECH PERCEPTION:	*r* =	*r* =	*r* =	*r* =
Minimal Pairs-Manner	.34	----	.51	----
Minimal Pairs-Voicing	.20	----	.58	----
Minimal Pairs-Place	.16	----	-.06	----
COMPREHENSION:				
Common Phrases-Auditory only	.81***	----	.85***	----
Common Phrases-Visual-only	.41	----	.57	----
Common Phrases-Auditory+Visual	.42	----	.55	----
VOCABULARY:				
PPVT-R	.62*	----	.63*	----
LANGUAGE:				
Reynell Receptive Language Quotient	.86***	----	.81**	----
Reynell Expressive Language Quotient	.83***	----	.82**	----
SPEECH INTELLIGIBILITY:				
Transcription	.89**	----	.80**	----

* ***p*** <.05; ** ***p*** <.01; *** ***p*** <.001

Reynell Language Scales. The correlations obtained for the receptive and expressive scales of the Reynell and the other dependent measures are shown in Table III for the "Stars" and the "Controls." Once again, a systematic pattern of intercorrelations can be observed among almost all of the test scores for the "Stars." These correlations are extremely high and statistically significant given the relatively small sample sizes used here. The strong correlations of both the Reynell receptive and expressive scores with the open-set word recognition scores on the LNT suggest a common underlying factor that is related, in some way, to spoken word recognition and lexical access. The correlations between the language scores and speech intelligibility may reflect a common or shared representational system and a set of phonological processing skills that are used in both receptive and expressive language processing tasks.

TABLE III

CORRELATIONS: LANGUAGE - YEAR 1

	Reynell Language Scales (Language Quotient)			
	Receptive		***Expressive***	
	Stars	Controls	Stars	Controls
SPEECH PERCEPTION:	*r =*	*r =*	*r =*	*r =*
Minimal Pairs-Manner	.77**	.08	.78**	-.28
Minimal Pairs-Voicing	.69*	-.63	.61*	-.49
Minimal Pairs-Place	.20	-.01	.31	.33
COMPREHENSION:				
Common Phrases-Auditory	.82**	----	.85***	----
Common Phrases-Visual-only	.64*	----	.79**	----
Common Phrases-Auditory+Visual	.64*	.33	.67*	.36
WORD RECOGNITION:				
LNT-Easy words	.86***	----	.83***	----
LNT-Hard words	.81**	----	.82**	----
MLNT-Easy words	.84**	----	.87***	----
MLNT-Hard words	.66*	----	.76	----
VOCABULARY:				
PPVT-R	.81***	.69**	.68**	.56*
SPEECH INTELLIGIBILITY:				
Transcription	.80**	-.39	.85**	-.13

* p <.05; ** p <.01; *** p <.001

Speech Intelligibility. The correlations between the speech intelligibility scores and the other dependent measures are shown in Table IV separately for the "Stars" and "Controls." Examination of this table also shows once again a pattern of correlations that is very similar to those observed in the previous two tables. Speech intelligibility is highly correlated with language comprehension, spoken word recognition and language development suggesting a common underlying source of variance (see also

O'Donoghue et al., 1999 for recent findings on the relationship between speech perception and production in young children with cochlear implants).

The results of the present set of analyses suggest several hypotheses about the source of the differences in performance between the "Stars" and the "Controls." We believe these accounts are worth pursuing and evaluating in much greater depth because they suggest new and unexplored areas of basic and clinical research on pediatric cochlear implant users. Our working hypothesis places the locus of the differences in performance between the "Stars" and "Controls" at central rather than peripheral processes. This account of the source of the individual differences focuses on how the initial sensory information is encoded, stored, retrieved and manipulated in various kinds of information processing tasks such as speech feature discrimination, spoken word recognition, language comprehension and speech production. The emphasis here is on higher-level perceptual and cognitive factors that play a critical role in how the sensory, perceptual and linguistic information input is processed, organized and used in various psychological tasks. One of the key components that link these various processes and operations together and serves as the "interface" between the initial sensory input and stored knowledge in memory is the working memory system. The properties of this particular memory system may provide further insights into the nature and locus of the individual differences observed among users of cochlear implants (see Carpenter, Miyake & Just, 1994; Baddeley, Gathercole, & Papagno, 1998; Gupta & MacWhinney, 1997). Unfortunately, at the time these analyses were carried out, we did not have any memory data from the "Stars" and "Controls" to test this proposal, but several new studies have been carried out recently using new measures of performance and these results are reported in the sections below.

TABLE IV

CORRELATIONS: SPEECH INTELLIGIBILITY - YEAR 1

	Transcription Scores	
	Stars	**Controls**
SPEECH PERCEPTION:	*r =*	*r =*
Minimal Pairs-Manner	.55	.19
Minimal Pairs-Voicing	.53	-.11
Minimal Pairs-Place	.41	-.09
COMPREHENSION:		
Common Phrases-Auditory	.65**	.04
Common Phrases-Visual-only	.87**	.25
Common Phrases-Auditory+Visual	.43	.07
WORD RECOGNITION:		
LNT-Easy Words	.89**	----
LNT-Hard Words	.80*	----
MLNT-Easy Words	.87**	----
MLNT-Hard Words	.72	----
VOCABULARY:		
PPVT-R	.45	-.01
LANGUAGE:		
Reynell Receptive Language Quotient	.80**	-.39
Reynell Expressive Language Quotient	.85**	-.13

* p <.05; ** p <.01; *** p <.001

Some New Process Measures of Performance

It is very easy to say that children who "hear" better through their cochlear implant just learn language better and subsequently recognize words better. But it is much more difficult to explain the observed differences in speech intelligibility on the basis of better hearing and language skills without a more detailed description of exactly what these underlying skills and abilities are and what specific cognitive processes they draw on. To account for the differences in speech intelligibility performance and expressive language, it is necessary to assume some underlying linguistic structure and process that mediates between speech perception and speech production. Without access to and use of a common underlying linguistic system—a "grammar," separate receptive and expressive language abilities and skills such as these would not be so closely coordinated and mutually dependent. Reciprocal links exist between speech perception, production and a whole range of language-related abilities and these links reflect the child's linguistic knowledge of phonology, morphology and syntax. Speech perception, spoken word recognition and language comprehension are not isolated autonomous perceptual abilities or skills that are independent of language and the child's developing linguistic system. The same observation is true for speech production, reading and lip-reading. An account framed in terms of hearing, audibility or sensory discrimination abilities cannot provide a satisfactory explanation of all of the results or an adequate description of the "process" of how early auditory experience affects speech perception and language development in these children. Something else underlies the commonalities observed across these diverse tasks.

In order to provide a unified account of these findings, it is necessary to obtain additional performance measures that assess how deaf children with cochlear implants actually "process" and "code" the sensory, perceptual and linguistic information they receive through their implants and how they store, retrieve and use this information in a variety of information processing tasks. The outcome measures in our database were scores on traditional standardized tests that were used for assessment of specific speech and language skills thought to be important for measuring change and success after implantation. The battery of these tests was designed and constructed many years ago when theoretical issues about individual differences and underlying processing strategies were not an important research priority. As a result, there are no data available on psychological/cognitive processes such as memory, learning, attention, automaticity or modes of processing. These are new topics that need to be studied in greater detail. We also need to learn more about the role of early auditory experience on perceptual and cognitive development, especially spoken word recognition, lexical development, language comprehension and speech intelligibility. These have also not been an important priority in earlier research on cochlear implants in children.

If we were going to look at process measures, that is, measures of what a child does with the sensory information he/she receives through the CI, where would we look first? There are several different areas we could explore: perception, attention, learning and memory. And, there are many different techniques and procedures we could use. For a variety of theoretical reasons, we selected "working memory" because this is known to be a very important component of the human information processing system and serves as the interface between sensory input and stored knowledge in long-term memory. Working memory has also been shown to be the source of individual differences observed across a wide range of domains from perception to memory to language (Ackerman, Kyllonen & Roberts, 1999). To obtain some initial measures of working memory from children with cochlear implants, we began collaborating with Ann Geers and her research group at the Central Institute for the Deaf (CID) in St. Louis. The children in the CID study described in the next section are older than the children I reported on earlier. The children at CID were 8 and 9 years old and they all used their cochlear implant for at least 5 years. Thus, chronological age and implant use were controlled in this study.

Working Memory Span

Methods

Subjects

Forty-three 8 and 9 year old cochlear implant users were recruited for this study from a much larger on-going project conducted at Central Institute for the Deaf (CID) in St. Louis, Missouri. All of these children had used their implant for at least five years before testing was carried out.

Procedure

In addition to the auditory digit span measures that were collected specifically for this study, the children also received an extensive battery of speech, language and reading tests that were part of the original large-scale project. The forward and backward digit spans were obtained using the digit-span subtests of the WISC-III (Weschler, 1991). The forward span task requires the child to repeat back a list of digits in the order in which the sequence was presented. In the backward span task, the child is instructed to say the list of digits backwards. Digit spans were obtained using live voice presentation with lip-reading cues available. In both parts of the WISC digit span task, the lists began with two items and increased in length until the child recalled two lists at a given length incorrectly at which point the procedure was terminated. Items were not repeated within any list and each list of digits was unique. The child was required to recall all of the digits in a given list consecutively in the correct temporal order in order to receive full credit for a given list length. Each child was run individually.

Results

Several measures of memory span performance were obtained from the response protocols. For the present analysis, digit span was defined as the longest length sequence of digits that the child could recall correctly two times in a row preserving both item and order information. This dependent measure was used in all of the analyses reported below. The forward digit spans ranged from zero to eight items correct with a mean span length of 5.3 items averaged over 43 subjects. Only one child failed to carry out the digit span task and his data were not included in any of the final analyses.

TABLE V

CORRELATIONS: SPEECH PERCEPTION
(from Pisoni & Geers, 1998)

	Forward Auditory Digit Span (N=43)
	r
SPOKEN WORD RECOGNITION:	

WIPI	**+.71**
LNT	**+.64**
BKB	**+.59**
Auditory+Visual:	
Chive V (lip-reading)	**+.52**
Chive VE (visual enhancement)	**+.66**
Speech Feature Discrimination:	
VIDSPAC	**+.59**

Table V shows the correlations of the forward auditory digit spans with several measures of speech perception performance that were obtained from these children as part of the larger project at CID. These measures included scores on both closed-set (WIPI) and open-set (LNT) word recognition tests, a sentence perception test (BKB), tests of auditory-visual integration (Chive) as well as speech feature discrimination (VIDSPAC). The correlations are all positive and generally moderate to quite strong, suggesting a common underlying source of variance. In interpreting these simple first-order correlations, it is possible to account for the memory span results in terms of purely sensory factors like audibility and basic speech discrimination skills that propagate and cascade up the processing system. According to this account, children who display longer digit spans simply perceive speech better and have more detailed and robust sensory representations of the speech waveforms than the children who have shorter digit spans.

In order to assess this explanation, a series of partial correlations were also computed using performance on the VIDSPAC, a test of speech feature discrimination, as a measure of overall speech discrimination performance. When the variance due to speech feature discrimination was partialed out, the correlations were reduced in size but they were still statistically significant suggesting that the results were not due to audibility or basic sensory discrimination skills but were related to the way in which the initial sensory information is processed, encoded and retrieved from memory. Processing differences among these children may reflect fundamental limitations on the capacity of working memory in terms of the speed and efficiency that sensory information can be encoded using a cochlear implant. These differences in information processing may affect the initial encoding, rehearsal and the scanning of information in working memory. The pattern of correlations also suggests the presence of a source of variance in these tests that is associated in some way with processing operations—that is, what the child does with the initial sensory information he/she received through the cochlear implant.

Two other theoretically important findings were also obtained in this study of working memory using the WISC digit span task. As part of the larger project at CID, measures of speech intelligibility were also obtained from these children using the elicitation materials developed by McGarr (1981). Using methods that were similar to the intelligibility study described earlier, utterances were obtained from each child and played back to normal-hearing adults who were asked to transcribe the sentences. The transcription scores based on words correctly recognized from three listeners were pooled for each child and a composite measure of speech intelligibility was obtained. Through the kind cooperation of Professor Emily Tobey, we were able to obtain these intelligibility scores along with measures of the sentence durations. We then computed a correlation between the auditory digit spans from the WISC and the speech intelligibility scores for these children. A scatterplot of the individual subjects is shown in the top panel of Figure 9. The WISC digit span is represented on the ordinate and the McGarr Intelligibility score is represented on the abscissa. Examination of this figure shows a very orderly relationship between these two measures. Subjects with longer digit spans tend to display higher levels of speech intelligibility. The correlation was $r = +.69$, ($p < .001$), suggesting a strong association between working memory span and processes used in speech production. This particular correlation is especially important because it suggests a reciprocal relationship between speech perception and speech production and implies that the two processes are closely linked and draw on a common set of processing resources that are related to the retrieval and maintenance of phonological representations of spoken words in working memory.

In addition to the speech intelligibility scores, duration measurements were obtained for the McGarr sentences from each child and these data were also analyzed. Correlations were carried out between the WISC digit span measures and the average sentence durations for these materials produced by each child. A scatterplot of the individual subject data is shown in the bottom panel of Figure 9. The WISC digit span is shown on the ordinate; the average sentence duration is shown on the abscissa. Once again, we see a very orderly and systematic relationship between working memory span and sentence duration. Subjects who display longer digit spans tend to produce sentences with shorter overall durations. The correlation between these two variables was $r = -.64$, ($p < .001$). This finding suggests that children who speak faster may have a faster rehearsal speeds in working memory and this may be the reason why these subjects are able to recall longer sequences of digits.

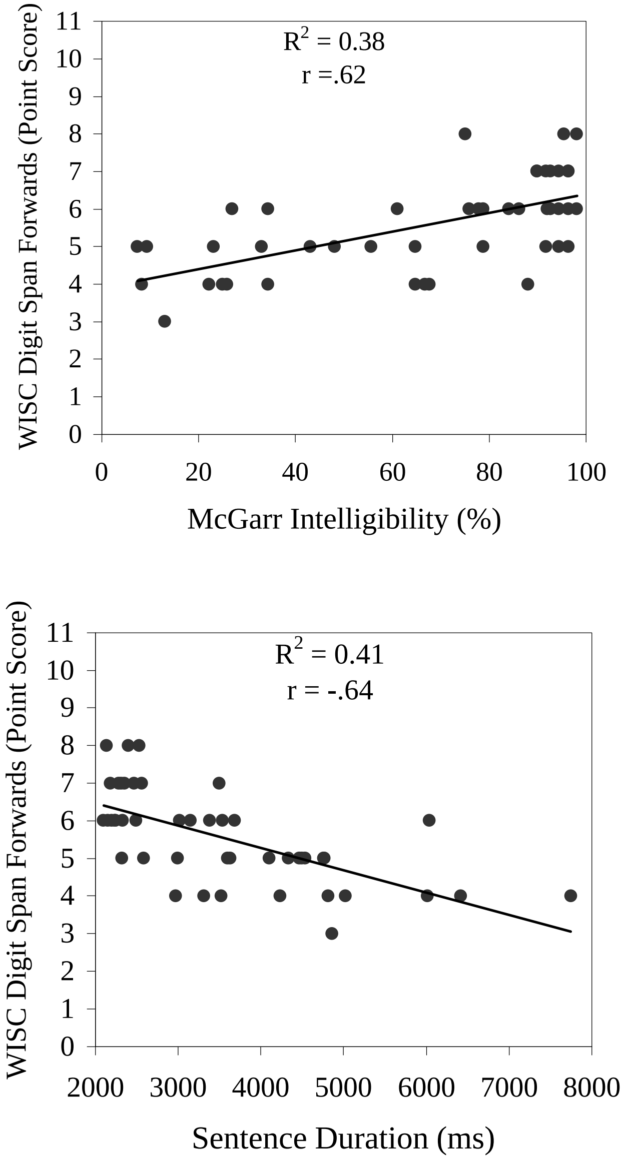

Figure 9. Top panel shows a scatterplot of WISC forward digit spans in points as a function of speech intelligibility; the bottom panel shows the WISC forward digit spans in points as a function of sentence duration in ms.

This finding is consistent with a large body of earlier research on verbal short-term memory which demonstrates a close relation between memory span and the fastest rate at which a person con pronounce a short list of words (Baddeley, Thomson & Buchanan, 1975; Chase, 1977; Schweickert & Boruff, 1986). Several recent studies have suggested that this global information processing rate may actually reflect the combined effects of two independent processes, one related to speed of articulation and the other related to the retrieval of words from short-term memory (Schweickert et al., 1990; Cowan et al., 1998). Cowan et al. (1998) suggest that while both of these processes affect memory span, they are actually independent of each other. Thus, memory span may depend on several component processes that are occurring simultaneously. Without additional data, it is not possible to dissociate the contribution of these two effects in the present analyses but the results clearly demonstrate a strong relation between digit span and a specific processing mechanism related to the rate at which information is encoded, rehearsed and subsequently output in an immediate serial recall task. These findings provide additional converging support for the proposal that the variation in the underlying processes may account for the large differences in outcome performance on a wide range of audiological tests.

The correlations between WISC digit span and the four sets of outcome measures obtained from these children demonstrate very clearly that the working memory component of the human information processing system is involved in some way in mediating, modulating and controlling performance across a wide range of language related tasks like speech perception, speech production, spoken word recognition, language comprehension and reading. Thus, processes related to the encoding, rehearsal and short-term storage of spoken words appear to play an important role in the component underlying abilities and skills that are actually being measured by the four different language-related outcome measures.

The correlations observed between the WISC digit spans and the two measures obtained form the speech production task, the speech intelligibility scores and the sentence durations, provided some extremely valuable new information about the specific processing mechanism that may be responsible for the differences in working memory capacity and the correlations found with other language processing measures. Both findings suggest that the rehearsal process may be the locus of the individual difference observed in these children. Although these are only correlational data, and must be interpreted cautiously, the relationship between WISC digit span and rehearsal speed suggests a number of new research directions to pursue in order to test this hypothesis more directly. The next experiment was designed to investigate coding and rehearsal strategies using a new procedure to measure sequence memory.

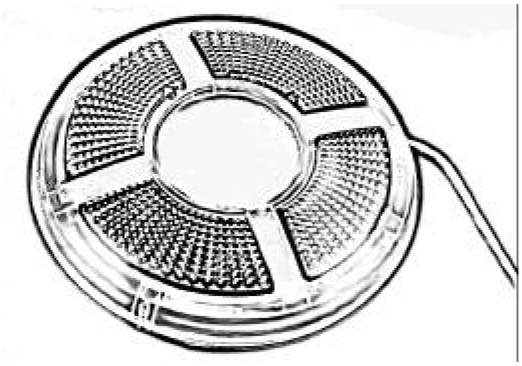

Figure 10. Schematic picture of the modified Simon ™ memory box game originally manufactured by Milton Bradley.

Coding and Rehearsal Processes in Working Memory

The findings obtained using the WISC auditory digit span as a measure of short-term memory capacity were very informative and suggested that some processing variable related to working memory may underlie the large individual differences in outcome measures observed in children with cochlear implants. Gaining a detailed understanding how young children encode and manipulate the phonological representations of spoken words may provide further insights into the development of their spoken language abilities and skills and may help to explain the underlying basis of the variability in performance in terms of information processing variables.

Because some children with cochlear implants may have difficulty producing intelligible speech due to differences in speaking rate and fluency of articulation, it was necessary to find a procedure that did not require the child to produce an explicit verbal output response. In order to meet this need, we recently developed a new procedure to measure working memory span that was modeled after the popular electronic game called “Simon” developed by Milton Bradley. The apparatus has four large colored response buttons and is shown in Figure 10. Children are presented with a sequence of sounds in conjunction with a sequence of colored lights and are asked to immediately reproduce the sequence in the order in which it was originally presented by depressing the appropriate response buttons.

The Simon memory game apparatus and experimental procedures we developed have a number of useful attributes that were explored in the experiment described below. First, the difficulty of the task can be adjusted by simply increasing the length of the sequence to be reproduced. Second, using an adaptive testing procedure running under computer control, it is possible to quickly locate the longest sequence that a child can reproduce under a given test condition and use that value as a measure of the child’s memory span. Finally, it is possible, as shown below, to manipulate both the visual and auditory stimuli separately or in combination and the contingencies between them at the time a sequence is presented. This particular feature permitted us to study how redundancies between visual and auditory cues are perceived, encoded and processed and how correlations between these two stimulus dimensions would affect memory span for reproducing sequences of sounds or sequences of lights or sequences of sounds and lights together. In the experiment described below, we obtained reproductive spans using the Simon memory game under three presentation conditions that manipulated the redundancies across dimensions. In the first condition, whenever one of the four colored lights was illuminated on the display, the color-name of the response button was also simultaneously output as an auditory signal. In the second condition, whenever a colored light was illuminated, a digit-name was output as an auditory signal. The digits were always consistently mapped to a response button and remained invariant for a individual child. Finally, in the third condition, visual patterns were generated using only the lights with no auditory stimuli. This last condition, light-only presentation, served as an important control condition to assess the extent to which a child would be able to take advantage of the cross-correlations between stimulus dimensions presented in two different modalities. In earlier research using these procedures with normal-hearing adults and children, Cleary (1997) and Carlson et al. (1998) observed a “redundancy gain” when the lights and sounds were both correlated together. Reproduction spans increased in length for the combined (A+V) condition compared to either auditory-only or visual-only presentation.

Methods

Subjects

Two groups of 45 children were recruited for this study. Another group of 45 prelingually deaf children with cochlear implants was obtained from the large-scale project underway at CID. All of these children were between eight and nine years of age and all of them had used their cochlear implant for at least five years. None of the children served in the previous experiment. Forty-five normal-hearing children were also recruited as a comparison group. They were matched for gender and chronological age with the children from CID. The normal-hearing children were obtained from the Bloomington, Indiana community using names recorded from birth announcements that were published in the local newspaper. A hearing screening was carried out on each normal-hearing child to insure that there were no hearing problems at the time of testing. Left and right ears were screened separately using a Maico audiometer (Model MA 27) and TDH-39 headphones.

Procedures

The auditory signals used in this experiment were obtained from recordings made by a male talker. He recorded tokens of the following eight words: “red,” “blue,” “green,” “yellow,” “one,” “three,” “five,” and “eight.” The words were spoken in a clear voice at a moderate-to-slow speaking rate and were recorded digitally in real-time using 16-bit A-D converter running at 22 KHz. The amplitudes of the digital speech files were equated using software to achieve equal loudness. All of the auditory stimuli were output using a SoundBlaster AWE64 sound card and were presented over a loudspeaker at approximately 70 dB SPL.

Forward and backward WISC digit spans were obtained from each child using the procedures described earlier in the previous experiment. Digit spans were obtained using live voice presentation by the examiner with visual cues to lip-reading present. Presentation of the auditory and visual sequences in the Simon memory game and collection of the child’s responses was controlled by a computer program running on a PC. The response box consisted of a highly modified version of the Simon game that had been rebuilt and interfaced to the computer so that the lights and sounds could be varied and controlled independently by the experimenter under program control. The computer program automatically tracked the child’s performance in a given condition using an adaptive testing procedure developed by Levitt (1970) that is frequently used in psychophysical experiments.

This experiment was designed to measure reproduction spans using sequences of stimuli presented under three conditions, color-names and lights, digit-names and lights and lights-only. Both groups of subjects received all three conditions using a within subject design. The lights-only condition was always completed last in the series; the other two conditions were counterbalanced across subjects. In addition to the memory game task, both groups of children were administered the WISC forward and backward digit span tasks.

The children with cochlear implants were tested in St. Louis by clinicians and researchers who were highly experienced in working with hearing-impaired children. The normal-hearing children were tested in the Speech Research Laboratory at Indiana University in Bloomington by graduate students and undergraduate research assistants. All children were tested individually in a quite room. Subjects were introduced to the experimental task as a “memory game” and were shown how to press the buttons on the Simon response box. The subjects were told that they would be hearing sounds through the loudspeaker on the table in front of them and also seeing the buttons on the memory box light up. They were then instructed to pay attention to the computer and try to copy exactly what the computer does by pressing a sequence of buttons on the memory game box.

Results

WISC Digit Spans. Table VI shows the means, standard deviations and ranges for the forward, backward and total WISC digit spans for both groups of children. The spans displayed here were scored by total points using the procedures outlined in the WISC manual. Points are awarded for each list correctly repeated and no partial credit is given for incomplete lists. The left-hand panel of the table shows the digit spans for the children with cochlear implants, the right-hand panel shows the spans for the normal-hearing children. The forward, backward and total summed digit spans were consistently shorter for the children with cochlear implants than the normal-hearing children replicating the previous findings reported by Pisoni and Geers (1998) with another group of cochlear implant users.

The results of the WISC digit span tests shown here demonstrate fundamental differences in working memory capacity between these two groups of children using highly familiar stimulus materials. Unfortunately, at this time without manipulating some other variable, it is not possible to identify precisely which specific aspect of working memory differs between the two groups. It is possible these differences in digit span are due to initial encoding operations, rehearsal processes, scanning or response output and retrieval of motor control programs used in speech articulation. Despite the ambiguity, however, the differences shown here are large and consistent and point to one possible locus of individual differences in processing stimulus input. The results of the Simon memory game provide additional information about the sources of these differences in working memory capacity.

Table VI

Summary of WISC Digit Spans for Implant Users and Normal-hearing Children

	WISC Digit Spans (N=43)			**WISC Digit Spans (N=44)**		
	Cochlear-Implant Users			**Normal-Hearing Children**		
	Summed Total	Direction of Recall		Summed Total	Direction of Recall	
	Points	Forwards	Backwards	Points	Forwards	Backwards
Maximum:	15	10	7	20	12	9
Minimum:	2	1	1	7	4	2
Mean:	**8.49**	**5.21**	**3.28**	**12.43**	**7.98**	**4.45**
Std. Dev.:	2.97	1.85	1.56	3.44	2.11	1.56

Simon Reproduction Spans. The averaged results for both groups of subjects on the Simon Memory Game are displayed in Figure 11 separately for each of the three presentation conditions. The normal-hearing children are shown on the left; the children with cochlear implants are shown on the right. The dependent measure plotted here is the longest list length that the child could reproduce correctly at least once during a given condition. Examination of these data reveals several differences. First, the normal-hearing children have longer reproduction spans for all three conditions than the children with cochlear implants. Second, the normal-hearing children display a “redundancy gain” in the colornames + lights condition compared to the lights-only condition. These children were able to benefit and increase their memory spans when the colornames and lights were congruent and paired together simultaneously. In contrast, however, the hearing-impaired children with cochlear implants did not show this same pattern. There is no difference between the three presentation conditions for these children and they do not appear to be able to use the additional redundant auditory information to improve their reproductive spans in the colornames + lights condition. In addition, we also observed an unexpected finding in the lights-only conditions. Even in this condition that did not involve the presentation of any auditory information, the children with cochlear implants had significantly shorter reproduction spans than the normal-hearing children. This finding suggests that the differences in working memory span between these two groups are not directly related to encoding of auditory inputs via the cochlear implant but reflect some aspect of the rehearsal process or output routines used to generate a sequence of motor responses.

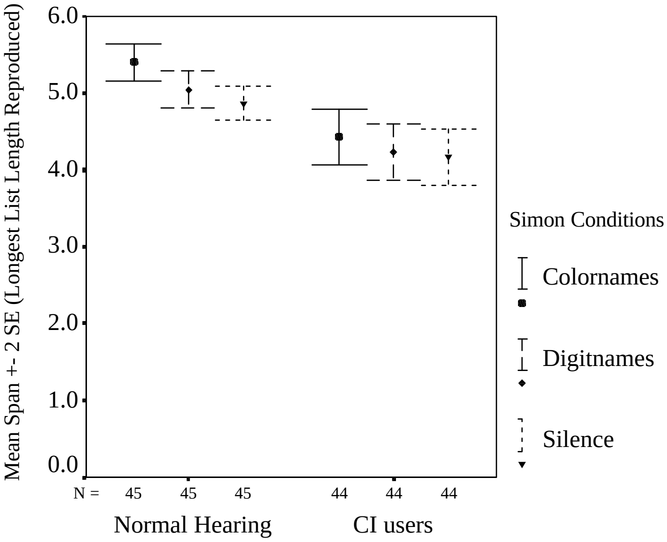

Figure 11. Mean Simon reproduction spans for three presentation formats (colornames, digitnames and lights-only) obtained from normal-hearing children (left) and deaf children with cochlear implants (right).

The absence of a redundancy gain in the colornames + lights condition and the shorter span length observed in the lights-only condition suggests that deaf children with cochlear implants may encode and process both auditory and visual information in ways that are fundamentally quite different from normal-hearing children who are able to make efficient use of cross-modal redundancies between correlated stimulus dimensions. Support for this hypothesis comes from an analysis of the WISC digit spans that were obtained from both groups. Not surprisingly, as we noted earlier, we found that the WISC forward and backward digit spans of the CI users were significantly shorter than the digit spans obtained from the normal-hearing children. Clearly, there are substantial differences in working memory span between these two groups even for highly familiar materials like digits that may reflect differences in encoding, working memory capacity or speed and/or efficiency of processing sensory information. These are all possible explanations of the differences found in digit spans between the two groups.

Of more interest, however, were the correlations between the WISC digit spans and the sequence reproduction spans obtained in the colornames + lights conditions. For the normal-hearing children the correlation between these two measures was positive and quite strong (r= +.58, p<.001), suggesting the operation and use of a common verbal rehearsal strategy in both memory tasks. However, the relationship between these two memory measures was quite different for the children with cochlear implants. There was no correlation at all between WISC digit span and colornames + lights (r= .09, NS), a finding that strongly suggests that the children with cochlear implants are carrying out the two memory tasks using different rehearsal strategies. For the colornames + lights memory game task, the CI children appeared to be using a visual-spatial rehearsal strategy based on encoding these multi-modal sequences as visual patterns. In contrast, in the WISC digit span task, they were forced to use a verbal rehearsal strategy because these items cannot be encoded or rehearsed using another alternative coding strategy.

An examination of the intercorrelations among the memory measures obtained from both tasks also showed a clear dissociation between the two groups of subjects in the pattern of correlations across these two tasks. The colornames + lights and lights-only and the digitnames + lights and lights-only were both highly correlated for the cochlear implant group (*r*= +.71, *p*<.001 and *r*= +.64, *p*<.001, respectively) but these same conditions were not correlated at all for the normal-hearing group (*r*= +.20, NS and *r*= +.09, NS, respectively). Taken together, the pattern of results obtained from these two memory tasks suggests that the children with cochlear implants were not encoding the stimulus input in the same way as the normal-hearing children did in this task. When there is an optimal way of encoding a multi-modal sequence, the cochlear implant children appear to prefer a visual-spatial rehearsal strategy while the normal-hearing children automatically use a verbal rehearsal strategy. It is possible that differences in encoding are related to processing speed as well as automaticity. Children with cochlear implants, even children who have used their implant for at least 5 years, may not be able to rapidly encode and maintain complex multi-dimensional inputs in working memory for short period of time. Normal-hearing children have developed very efficient strategies for verbal coding and rehearsal based on their experiences perceiving and using spoken language. It is quite possible that hearing-impaired children with cochlear implants have much less efficient and slower verbal rehearsal strategies which not only effect their working memory capacity as measured by WISC digit spans but also influence how they perceive and encode multi-modal inputs that could be perceived and coded in memory in an alternative manner using visual-spatial cues available in the stimulus display.

Although some children with cochlear implants can perceive speech and understand spoken language at reasonably high levels of performance as measured by standardized outcome measures, they may nevertheless encode and process speech signals in ways that are non-optimal given the high redundancy of human language. Traditional behavioral tests that are based on response accuracy may not be able to detect and measure some of these subtle differences in processing speed, efficiency and the use of stimulus redundancy, which are characteristic markers of normal-hearing listeners.

General Discussion

In 1995 the NIH published a Consensus Statement on Cochlear Implants in Adults and Children to provide clinicians and other health care providers with a current summary of the benefits and limitations of cochlear implants (NIH, 1995). The 14-member consensus panel consisted of experts representing the fields of otolaryngology, audiology, speech-language pathology, pediatrics, psychology and education. The panel concluded that while cochlear implants improve communication abilities in most postlingually deafened adults with severe to profound hearing loss, the outcomes of implantation are much more variable in children, especially prelingually deafened children. Among other findings related to the efficacy and effectiveness of cochlear implants, the report emphasized the wide variation in outcome measures among implant users and recommended that additional research be carried out on individual differences in both adults and children. The report also suggested that new methods and tools should be used to study how cochlear implants activate the central auditory system.

An examination of the literature on the effectiveness of cochlear implants in prelingually deaf children reveals several closely related findings which strongly suggest that “central” auditory, cognitive and linguistic factors may play an important role in accounting for the enormous variation and individual differences observed in traditional outcome measures. Although the NIH Consensus Statement mentioned “central” auditory factors, the panel was not specific about precisely what these factors might be, or what role higher-level cognitive processes might play in outcome measures. We can speculate that these would include, at the very least, processes such as perception, learning, memory, and language. We believe that the recommendations of the NIH panel are fundamentally correct in drawing attention to central auditory factors as another unexplored source of variance and recommending new research on cognitive processes and language development. Higher-level cognitive processes have not received much attention in the past and investigation of these factors may provide new insights into the underlying basis for the large individual differences as well as the specific effects of early experience on speech and language development in children with cochlear implants.

Five Key Findings

Five “key” empirical findings on cochlear implants in children were discussed earlier in the introduction to this report. In this final section, I first review these findings briefly because they provided the motivation for the new research we have carried out on process measures of performance. Then I attempt to tie several themes together and draw a few general conclusions that follow directly from our recent findings on working memory and coding strategies.

The existence of large individual differences in outcome is probably the most important issue in pediatric cochlear implantation at the present time. Until recently, we knew very little about the nature of these differences and the factors that were responsible for the variation in performance. In addition to the issue of individual differences, I described four other related findings that suggest a possible underlying basis for the wide variation among deaf children with cochlear implants. A careful examination of these findings also suggests that it might be fruitful to adopt a new and somewhat different research strategy in the future that focuses on “process” rather than the final “product” of perceptual analysis. The study of traditional audiological outcome measures and the effects of demographic variables have provided a great deal of valuable information about cochlear implants and changes in performance over time. However, these kinds of outcome measures are somewhat limited because they only assess the final product of what is generally regarded to be a complex set of interacting processes that draw on many different sources of knowledge.

As noted earlier, both age of implantation and length of deprivation have been shown to be very strong predictors of outcome performance in deaf children with cochlear implants. Children implanted at a younger age generally do better than children implanted at an older age and children who have been deaf for shorter periods of time generally do better than children who have been deaf for longer periods of time. How can we explain these related findings? Both results demonstrate the important contribution of “sensitive” or “critical” periods in development and both findings suggest close links between neural development, on the one hand, and behavior, on the other hand. This conclusion seems to be especially true for the skills and abilities that underlie the development and use of speech and language and the underlying biological component that drives the process of development.

It has been known for many years that language development in normal-hearing children has a strong biological basis and follows a genetically programmed maturational schedule (Lenneberg, 1967; Pinker, 1994). There is every reason to suspect that language development in deaf children who receive a cochlear implant also follows the same biologically based developmental schedule as well. As soon as these children begin to receive some auditory stimulation, novel interactions begin to emerge as the perceptual system and specialized phonetic module begins to detect, perceive and encode regularities in the input patterns. The actual time-course of language development in deaf children with cochlear implants may be delayed somewhat compared to normal-hearing children because of variable periods of sensory deprivation before implantation. However, there is also a wide range of variation in the onset and time-course of language development in the normal-hearing children too so it should not be surprising to see some variation in speech and language development in deaf children with cochlear implants.

Variation is an inherent part of the process of normal language development and small differences in normal-hearing children may simply be magnified and exaggerated in deaf children who have received cochlear implants. Once deaf children begin receiving auditory stimulation via their cochlear implant, even if this information is impoverished and degraded, it may be sufficient to get the neural mechanisms going, so to speak, and to start the "normal" process of language on a developmental trajectory. Without auditory stimulation to the nervous system during critical periods of development, it may never be possible for spoken language to develop fully or for the underlying sensory, perceptual and cognitive processes to reach their optimal states in a mature adult. Thus, the findings that age of implantation and length of deprivation affect outcome can be understood within a somewhat broader theoretical framework of critical periods for sensory-motor development and vocal learning which reflect the underlying neural specialization for speech and language (Pytte & Suthers, 1999; Suthers et al., 1999).

The second finding we touched on earlier concerned the effects of communication mode on outcome measures. Numerous studies have shown that communication mode affects outcome measures, especially outcome measures that rely heavily on the use of oral-language skills and phonological processing strategies in traditional assessment tasks used to measure outcome such as open-set word recognition, speech intelligibility, spoken language comprehension and even reading. The findings from several recent studies investigating the effects of communication mode strongly suggest that the specific language-learning environment that the child is exposed to and develops in may play a critical role in modulating, shaping and facilitating vocal learning and the process of language development. These conclusions seem to be especially relevant for spoken language development and the development oral skills and abilities that are used in receptive and expressive language processing tasks. These particular tasks make use of skills that rely heavily on phonological representations of spoken words and phonological processing strategies that transform highly variable sensory inputs into stable internal representations that encode the sound contrasts of the language and provide the basis for the motor programs used in speech production.

Once again, these are not particularly surprising findings for anyone who is familiar with the recent literature on speech and language development in normal-hearing infants and young children (see, Jusczyk, 1997; Hart & Risley, 1995). Young children learn language very quickly and are unusually sensitive and highly attuned to the regularities and frequencies of sound patterns in their language-learning environment (Jusczyk & Aslin, 1995; Saffran, Aslin & Newport, 1996). Numerous studies have shown that this "attunement" process closely tracks very subtle acoustic-phonetic differences in the input signals that children are exposed to during the first year or two after birth (Aslin & Pisoni, 1980; Aslin, Jusczyk & Pisoni, 1998). It is very likely that these early perceptual strategies play an important role in segmentation and word learning and form the basis for later syntactic and semantic development (Jusczyk, 1997). Past research on cochlear implants has generally failed to acknowledge the important contribution of learning and memory to performance although audiologists have shown that habituation and acclimatization effects do affect most outcome measures (Robinson & Summerfield, 1996; Tyler & Summerfield, 1996).

The third finding that we discussed in the introduction was the apparent lack of reliable preimplant predictors of success with a cochlear implant. From a theoretical perspective, we consider this to be a very important result because it suggests that basic underlying cognitive factors such as learning, memory and attention may be the kinds of outcome measures that should be used to assess performance in children with cochlear implants. One of the major assumptions of the information processing approach to cognition that guides our research program is that perception is not immediate but is a result of a series of processing stages that take place over time. Sensation, perception and memory are conceptualized within this framework as representing a continuum of processing activities that are organized in a hierarchical manner

(Haber, 1969). Very complex interactions exist in the language-learning environment that affect the way raw sensory information is perceived, encoded, stored and interpreted by the child. Investigation of these intermediate processes may provide valuable new insights into the wide variation observed in outcome performance. While the lack of preimplant predictors based on traditional outcome measures may be somewhat troubling for clinicians and researchers who would like to maximize the benefits of cochlear implants by modifying or adjusting intervention strategies soon after implantation, the findings reported in this paper suggest that other more basic measures of performance that are related to the information processing operations and skills such as working memory, coding and rehearsal strategies may be worth exploring in greater detail in addition to the traditional audiological outcome measures that have been used over the years.

It is very likely that earlier studies of preimplant predictors of outcome performance may not have succeeded in measuring the critical processing variables that reflect the encoding, perception and storage of sensory and perceptual information. All of the traditional outcome measures that have been used in the past are based on standardized assessment tests developed within the fields of clinical audiology and speech pathology. These tests use measures of performance that are “static” and reply exclusively on accuracy scores. More importantly, these tests assess the final “product” of performance not the intermediate “processes” and structures leading up to a final response. Thus, the lack of “true” process measures of performance in both adults and children with cochlear implants may be one of the primary reasons why the past efforts to find preimplant predictors have been so unsuccessful so far. Two recent studies have looked at this problem in greater depth and report encouraging findings that it may be possible to identify reliable preimplant predictors of outcome performance.

In a study of postingually deafened adults, Knutson et al. (1991) found that preimplant performance on a visual monitoring task predicted audiological outcome after 18 months of implant use. Strong and highly significant correlations were found between visual monitoring performance in a signal detection task and scores on four sound-only audiological measures, sentence perception, consonant and vowel perception and phoneme recognition in words. These results obtained with adult patients demonstrate that the cognitive processing operations and skills needed to rapidly extract information from sequentially arrayed visual stimuli may also be used in processing auditory signals and may underlie the successful use of a cochlear implant (see also Gantz et al., 1993). The findings obtained in Knutson et al.’s study support the hypothesis that higher-level cognitive factors related to perception, attention and working memory capacity play an important role in predicting outcome with an implant. More importantly, these results show that preimplant measures of information processing in the visual modality can be used to predict speech perception performance in the auditory modality.

More recently, Tait, Lutman and Robinson (submitted) reported moderate correlations between pre-verbal communication measures extracted from an analysis of videotapes and several outcome measures of speech perception obtained from prelingually deaf children three years after implantation. Video recording of 33 children were transcribed and scored for various turn-taking and autonomy behaviors before implantation. Outcome measures of sentence perception, discourse tracking and telephone use were obtained without the use of visual cues and correlations were computed with the behaviors obtained from the coded videotapes. Although positive correlations were found between each of the outcome measures and the pre-implant behaviors coded from the videotape analysis, none of the correlations with the turn-taking behaviors reached significance. However, the correlations with the autonomy behaviors were significant suggesting that some pre-verbal communicative behaviors that are present before implantation are associated with audiological outcome measures of speech perception and language processing obtained three years later.

Although somewhat limited in scope and generality at this point, the findings of Tait et al. are very intriguing and suggest that several important aspects of the development of spoken language are already present in infancy in these deaf children. These underlying pre-verbal communication skills may function as the "prerequisites" for speech and language and therefore may be quite general in nature reflecting multi-modal interactions between perception and action that are not tied to a specific sensory modality (see also Rizzolatti & Arbib, 1998 for recent findings on "mirror neurons" in monkeys that link actions of an observer and actor). The Tait et al. findings are, of course, correlational in nature and it will be necessary not only to attempt a replication of these findings but also try to specify more precisely the underlying neural and perceptual mechanisms that are responsible for these differences. It is possible that differences in imitation behaviors, gestures and perceptuo-motor links between perception and action are the fundamental processes that actually underlie the observations from the analysis of the videotapes.

Finally, and this is worth emphasizing strongly here, it is entirely possible that no preimplant measures will ever be found that will predict outcome performance in children with cochlear implants. The reason for this assertion is obvious if we consider the contribution of learning and memory processes to vocal development. If the underlying abilities for speech and language "emerge" after implantation and are the end product of a set of complex interactions between sensory, perceptual, cognitive and linguistic factors and sensory-motor learning processes that develop over time according to some built-in biological schedule, it may not be possible to find a unique signature or marker in only one measure of behavior that reflects all these different kinds of interactions. Because a substantial portion of the variance in outcome may be related to higher-level central auditory factors and vocal learning that reflect the way the initial sensory information is perceived, encoded and stored in long-term memory, it may be necessary to develop an entirely new set of outcome measures that can be used to assess these kinds of central auditory factors. Some of these new outcome measures might be behaviorally-based and "process-oriented" in nature like the measures of working memory span and the rehearsal strategies described earlier in this paper. Other outcome measures may use electrophysiological techniques to measure neural responses to sound more directly (see Kraus et al., 1996) or neural imaging (Naito et al., 1997; Wong, 1999) or measures of sensory-motor integration and vocal learning (Pytte & Suthers, 1999).

Analysis of the "Stars"

In the first section of this paper, we presented the results of a series of analyses that were carried out on two groups of prelingually deaf children who had received cochlear implants. An extreme groups design was used to identify differences in performance on a battery of speech and language measures that might provide new insights into the large individual differences observed on outcome measures with these children. One group consisted of children who were exceptionally good cochlear implant users-- the so-called "Stars." These were children who scored in the top 20% on the PBK test, a very difficult "open-set" test of spoken word recognition that has been used in the literature to identify exceptionally good implant users. A second group of children were selected as control subjects to draw comparisons. The children in this group scored in the bottom 20% on the PBK test and were unable to recognize any of the test words when they were presented in isolation using an open-set format. After the subjects were assigned to these two groups, scores on tests of speech perception, language comprehension, spoken word recognition, receptive vocabulary, receptive and expressive language development and speech intelligibility were obtained from an existing longitudinal database of 160 subjects. Descriptive analyses were carried out first to compare differences between the two groups on these different measures. Then a series of correlational analyses were computed for each group separately in order to study the relations among the dependent variables and to uncover patterns that might reflect common underlying sources of variance that could be used to predict outcome.

The results of our descriptive analyses after one year of implant use revealed several interesting findings about the exceptionally good users of cochlear implants. First, we found that although the “Stars” showed consistently better performance on some measures such as speech perception, language comprehension, spoken word recognition and speech intelligibility than the “control” group, the two groups did not differ from each other on measures of receptive vocabulary knowledge, non-verbal intelligence, visual-motor integration or visual attention. We also found that some measures of performance continued to improve over a time period of six years whereas other measures remained fairly stable and did not show changes with experience after the first year. These overall findings demonstrate that the “Stars” differ in selective ways from the “Control” subjects and whatever differences are revealed by other descriptive measures, it is clear that the results are not due to some global difference in overall performance between the two groups. More importantly, we found that the “Stars” displayed exceptionally good performance on another test of spoken word recognition, the LNT, which demonstrates that the superior skills and abilities of these children are not due to the specific items on the PBK test or the methods used to administer the test.

The results of correlational analyses carried out on the test scores for the “Stars” one year after implantation showed a consistent pattern of very strong and highly significant intercorrelations among several of the dependent variables, particularly for the measures of word recognition, language development and speech intelligibility, suggesting a common underlying source of variance. These patterns of correlations were not observed for the control group. The common source of variance found in the correlational analyses of the “Stars” seemed to be related in some way to the processing of spoken words and to the encoding, storage and retrieval of the phonological representations of words. Of particular interest was the finding of strong correlations with speech intelligibility scores for these children, suggesting transfer of knowledge and a common shared representational system for speech perception and speech production (see also Shadmehr & Holcomb, 1997). These analyses suggested that the exceptionally good performance of the “Stars” may be due to their superior skills and abilities to process spoken language, specifically, to perceive, encode and retrieve phonological representations of spoken words from lexical memory and use these representations in a variety of different language processing tasks, especially tasks that make use of vocal learning.

While the results of these correlational analyses were suggestive and point to several new directions for future research on individual differences, the data available on these children were confined to traditional outcome measures in our database that were collected as part of the annual assessments. All of the scores on these tests represent the final product of perceptual and linguistic analysis. Process measures of performance were not part of the standard research protocol and were never collected from these children so it was impossible to investigate differences in speed, fluency or capacity at this time. Differences in information processing including topics such as perceptual learning, categorization, attention, and memory may underlie the individual differences observed between the two groups of children in our initial study. However, traditional audiological assessments of hearing and speech perception performance especially those used in assessing performance of deaf children with cochlear implants have not typically measured these types of processing activities.

Working Memory Spans

In the second section of this paper, we described the results of a recent study carried out by Pisoni and Geers (1998) who obtained measures of working memory using the digit span subtests from the WISC. Memory span data were collected from 43 eight- and nine-year old prelingually deaf children with cochlear implants as part of a larger project on speech and language development that is being conducted at CID. All of the children included in this study had used their cochlear implants for a period of at least five years. This study of digit spans was the first investigation to obtain a measure of processing capacity, specifically, measures of working memory span from a large number of children. Correlations were carried out between digit span and four sets of outcome measures that assessed speech perception, speech production, language and reading. Moderate to high correlations were obtained between forward auditory digit span and each of the four outcome measures. The pattern of correlations suggested the presence of a common source of variance that is related in some way to working memory, specifically, the encoding and rehearsal of phonological representations of spoken words. Thus, differences observed on various outcome measures of performance using standardized assessment tests may actually reflect more fundamental differences in the way sensory information is processed by the nervous system and used in specific language processing tasks that make use of this information.

The findings from the study by Pisoni and Geers on working memory span in deaf children with cochlear implants are consistent with a large and growing body of recent data on working memory and language development in normal-hearing children. Gathercole and her colleagues have reported strong correlations between measures of working memory span and early word learning, vocabulary knowledge and non-word repetition abilities (Gathercole et al., 1997). Gupta and MacWhinney (1997) have suggested that the working memory system is the common processing mechanism and serves as the “interface” between speech perception and speech production and the phonological knowledge of words stored in the mental lexicon. Thus, language processing and working memory are closely linked together in a variety of tasks that require access to phonological information about words in the lexicon.

The correlations between working memory and several different measures of language processing found in our study demonstrate the important contribution of “processing variables” – fundamental information processing operations that are used in the encoding, storage, retrieval and rehearsal of the phonological representations of spoken words. These new findings on auditory digit span in children with cochlear implants help to identify the “locus” of precisely where differences in performance are located within the larger information processing system and how they operate in specific tasks. The differences in performance observed in the Pisoni and Geers study may be due to the operation of a subcomponent of working memory known as the “phonological loop.” The phonological loop is responsible for the rehearsal and maintenance of the phonological representations of spoken words in memory and plays a critical role in the learning of new words (Baddeley et al., 1998). The phonological loop is also assumed to play an important role in speech production as well by mediating access to retrieval of sensory-motor plans needed for speech motor control and articulation. Finally, the phonological loop is also used in reading, especially reading unfamiliar words or novel nonword patterns. All of these language processing tasks draw on the same common set of phonological representations of spoken words and all of them use the same processing resources in working memory, specifically, the phonological memory store and the articulatory subvocal rehearsal mechanism that serves as the primary interface between the initial sensory input and the representations of spoken words in the mental lexicon.

The correlations found between digit span and speech intelligibility and digit span and speaking rate suggest that rehearsal speed in working memory may be one of the factors that distinguishes good implant users from poorer ones. While these results are only correlational in nature, they do provide additional converging support for the proposal that differences in working memory are responsible for the enormous variation in outcome scores on standardized assessments used with these children. At the very least, these findings point to a specific processing mechanism and suggest several new directions to pursue in future studies. Additional support for the importance of working memory and rehearsal speed was observed in another analysis. In addition to the correlations between digit span and the four outcome measures reported earlier, Pisoni and Geers (1998) also observed a moderate but significant correlation between digit span and communication mode (r=+.38 p<.05). This correlation suggests that early auditory experience in oral-only programs may have very specific effects on working memory capacity and the elementary information processing operations that are used in language processing tasks. Not only was there a positive correlation between communication mode and auditory digit span but a subsequent analysis showed that the children from oral-only programs had significantly longer digit spans than the children from TC programs.

Children from oral-only programs are not only exposed to more speech and language (see Hart & Risley, 1995) but they also engage in more meaningful processing activities that require them to construct more robust phonological representations of the sound patterns of spoken words in their language. The study of working memory in these children provides us with a new approach to two long-standing research issues in the field of cochlear implants, the enormous individual differences observed among children with cochlear implants and the role of early auditory experience in the language-learning environment. Spoken language processing and working memory appear to be closely related in both normal-hearing children and deaf children with cochlear implants. The present findings suggest that early experience and exposure to oral language affects the underlying perceptual and sensory-motor mechanisms used to process and code the sensory information. Thus, working memory appears to be influenced and shaped by early auditory exposure and experience with spoken language in the language-learning environment. Again, this suggests that specific experience with spoken language and exposure to spoken words has an effect on a specific processing mechanism—working memory and a subcomponent of this system related to speed of rehearsal.

Coding and Rehearsal Strategies

In the third section of this paper, we presented some recent findings obtained by Cleary, Pisoni and Geers (this volume) using a new experimental methodology, the Simon memory game, to measure reproductive memory spans for sequences of stimuli. This memory game procedure was originally developed to obtain measures of working memory span without requiring the child to produce an explicit verbal-motor response as output. When digit spans are obtained using the WISC, the child simply repeats back or imitates the sequence of digits and the examiner records the child's verbal response. Using the Simon memory game procedure, children were presented with a sequence of stimuli, either visual-only or combined auditory+visual that were selected from an ensemble of four possible signals and were simply required to reproduce the stimulus pattern by pressing a sequence of buttons on a response panel. The difficulty of the Simon memory task and the amount of concurrent "processing load" was manipulated by increasing the length of the sequence to be reproduced using an adaptive testing program and then recording the longest list length that a child was able to reproduce correctly under a given stimulus condition. This sequence length was taken as a measure of the child's "reproductive" memory span in a given experimental condition.

WISC digit spans and Simon reproductive memory spans using the new procedures were obtained for two groups of age-matched children, 45 deaf children with cochlear implants and 45 normal-hearing children. Both groups were tested under several different presentation conditions. For sequences of colored lights and color names, we found that the normal-hearing children showed a "redundancy gain, " an advantage for the auditory plus visual condition (lights and sounds) compared to the visual-only (lights) when the color names matched the colors of the lights that were illuminated on the panel. The children with cochlear implants did more poorly overall than the normal-hearing group on all of the conditions we studied and they failed to show the same advantage under the combined simultaneous auditory+visual conditions. The difference in performance between the two groups on the visual-only sequences which was not originally anticipated suggested the possibility that the children with cochlear implants might be using a different coding strategy to carry out the task, a visual-spatial strategy that relied entirely on encoding and rehearsing visual patterns without phonological-verbal coding or mediation.

Correlations were then carried out separately for each group using the measures of working memory obtained from the digit span task and the measures of reproductive span from the Simon memory game. An examination of the patterns of correlations across these tasks revealed a very interesting dissociation between visual-spatial and verbal rehearsal strategies in the two groups. The normal-hearing children appeared to use verbal coding and verbal rehearsal strategies in both memory tasks. Strong correlations were observed between forward digit spans and the combined auditory+ visual presentation conditions in the Simon memory game. In contrast, the children with cochlear implants relied on visual-spatial cues to do the Simon memory game in both the visual-only and the combined auditory+visual conditions. The correlations within the Simon conditions were all positive and very strong for the implant children but were weak or non-existent for the normal-hearing children.

The low correlation observed between the Simon auditory+visual condition and WISC forward digit span suggested that the children with cochlear implants were not able to take advantage of the redundancy across stimulus dimensions in the combined auditory+visual condition of the Simon game and simply encoded these sequences using visual-spatial cues. The pattern of results across these two tasks suggests that fundamentally different modes of processing complex multi-dimensional stimuli are being used by these two groups of children to encode and reproduce these sequences. When the memory task can be performed by using either verbal coding or visual-spatial coding, the normal-hearing children rely on verbal coding and are able to take advantage of the cross-modal redundancies between stimulus dimensions while the deaf children with cochlear implants prefer to use the visual-spatial cues and seem to ignore the auditory signals that are presented simultaneously with the light patterns. Exactly why they have a preference to do this is not entirely clear right now but it may reflect differences in processing capacity, robustness of stimulus encoding or automaticity. We know from the data on speech feature discrimination obtained with the minimal pairs test, that children with cochlear implants do not encode fine phonetic details in speech the way normal-hearing children do. As a result, they may construct and use only partial under-specified representations of signals in their environment and they may not process redundant stimulus information especially when the redundancy requires integration of multi-modal inputs from separate sensory modalities.

Process Measures of Performance

It should be clear from the three sets of findings presented in this paper that new “process” measures of outcome performance will be needed to assess learning, memory, attention and categorization--the “central” cognitive processes that act on and use the initial sensory input provided by the cochlear implant. Traditional audiological outcome measures are simply not adequate to assess the underlying processes used in speech and language processing tasks. Instead, one can imagine the development of an entirely new battery of “process” measures of performance that could be used to assess the flow and content of information as it is processed and coded by the listener. These new measures would be designed to measure and quantify what the listener does with the limited sensory information he/she receives through the cochlear implant. Some of these new measures could be used to assess differences in processing speed, efficiency and capacity. Thus, measures of working memory span, coding and rehearsal strategies, selective and divided attention and automaticity of processing may be much more informative and useful than the traditional battery of audiological outcome measures that have been used in the past which assess the final product of perceptual analysis. By refocusing research to the study of the elementary cognitive processes that are assumed to underlie the observed behavior in specific tasks, it may also be possible to develop a new set of preimplant measures that are more successful in predicting outcome than the current procedures available now. Given the tools that are currently available and the theoretical framework of human information processing, we think these are reasonable goals that can be achieved in a relatively short period of time.

Some New Research Directions

The findings from the three studies summarized in this paper strongly suggest that "central" auditory factors and higher-level cognitive processes contribute to the variability in performance found in traditional assessment measures. Using a new theoretical framework based on concepts and methodologies from the information processing approach in cognitive psychology, we have been able to gain some new insights into the specific sensory, perceptual, and linguistic factors that are responsible for the enormous individual differences in performance on a wide range of audiological outcome measures. Although our initial analysis of the descriptive data from the "Stars" pointed to a common source of variance associated with the processing of spoken words and the use of phonological knowledge, this account was based entirely on patterns of correlations among variables using existing data that were originally collected for audiological assessment purposes not hypothesis testing. When this research was originally carried out as part of a longitudinal study of outcome performance, process measures of memory, attention and learning or the time course of early perceptual analysis were not obtained from any of these children. As a consequence, we do not know what these deaf children actually do with the limited sensory information they receive through their cochlear implant and how their perceptual processing differs from normal-hearing and normal-developing children.

Our recent investigations of working memory capacity have provided the first direct evidence that process variables related to verbal coding and rehearsal contribute to the variability in audiological outcome measures. Two findings from these studies are particularly noteworthy. First, we found that working memory span was strongly correlated with several traditional outcome measures. This finding suggests that working memory and capacity limitations of working memory may be the locus of the individual differences observed in performance on other language processing tasks that draw on this common mechanism. The findings on speaking rate suggest that these capacity limitations are related in some way to rehearsal speed and processing efficiency. Second, we found that deaf children with cochlear implants do not automatically encode and process sequences of multi-dimensional stimuli using verbal rehearsal but instead use a visual-spatial coding strategy to perform the task. This finding demonstrates important differences in modes of processing complex stimuli and suggests that even very elementary cognitive processes like automaticity, attention and the allocation of processing resources may be carried out in fundamentally different ways by deaf children who have received cochlear implants after a period of sensory deprivation. The use of verbal rehearsal strategies in sequence memory tasks like those studied here may be an important early diagnostic marker that predicts success with a cochlear implant on a variety of outcome measures that make use of phonological coding and phonological processing skills.

Although these two initial studies have provided new knowledge about the operation of working memory and the use of different modes of processing, we still do not have any data on basic processes of learning, attention, automaticity and categorization in this population of children. In order to obtain a complete picture of the information processing capabilities of these children and the possible differences in the way they process and encode sensory information because of the limitations of their cochlear implant, it will be necessary to carry out additional studies of perceptual learning, implicit and explicit memory and long-term retention of verbal and non-verbal materials. It is possible that the differences observed in our studies of working memory may actually reflect the contribution of long-term knowledge and exposure to spoken language. Differences in long-term memory and lexical knowledge may also affect the speed of rehearsal and the time-course of perceptual processing for familiar and unfamiliar words which, in turn, may affect measures of processing capacity in working memory tasks because of differences in the rate of scanning verbal materials in short-term memory. Other research should be carried out on automaticity and attention as well as categorization of novel stimulus materials in order to chart out the time-course of perceptual learning and study long-term retention of new knowledge gained under controlled laboratory conditions. Studies of episodic and semantic memory and incidental learning may provide some additional valuable insights into the extent to which instance-specific details of complex stimulus events are encoded and stored in long-term memory and later used in categorization and memory tasks.

The findings reported by Pisoni & Geers (1998) that children from oral-only environments have longer memory spans than children from total communication environments demonstrates that working memory capacity is not fixed or hard-wired at birth but is extremely flexible and reflects on-going learning processes and interactions between the sensory and perceptual environment and the real-time processing mechanisms used to encode, store and manipulate information. Recent findings on vocabulary acquisition and language development summarized by Hart & Risley (1995), suggest that frequency of exposure to language matters and that vocabulary knowledge is related to the number and frequency of words used by the parents in the child’s language-learning environment. Other recent evidence suggests that memory spans for lists of spoken words are related to lexical knowledge and competition among phonetically similar items in long-term memory (Goh & Pisoni, 1998).

Studies on early word learning and research on the organization of words in the mental lexicon will also provide new information about how spoken words are encoded and stored in long-term memory and how children with cochlear implants gain access to this information and use it in receptive and expressive language processing tasks. It has been reported that normal-hearing children show very rapid word learning at a certain point in language development, a process often referred to in the literature as “fast mapping.” These findings suggest that words are learned quickly and effortlessly in context with only a few exposures (see Carey, 1978; Carey & Bartlett, 1978; Dollaghan, 1985; 1987). The process of early word learning in normal-hearing children appears to be quite different from other forms of perceptual learning and development which often show a very slow and gradual process of acquisition (Woodward & Markman, 1997). At the present time, we have very little knowledge about how deaf children with cochlear implants learn novel words, how they organize spoken words in long-term memory or how they retrieve the phonological representations of spoken words from the mental lexicon in different types of language processing tasks, especially tasks that require them to reproduce and imitate actions and specific gestures. The close relations between working memory, measures of immediate serial recall and lexical development noted by Gupta and MacWhinney (1997) and discussed at some length in their recent theoretical papers, suggest that this particular topic may be a very important and fruitful area for future research on individual differences in these children. This topic seems to be especially attractive at this time given the importance of lexical processes that emerged from the correlations that were computed on the outcome measures obtained from the “Stars” in our first study and the role working memory plays in language development, specifically, phonological and lexical development (Gathercole, Hitch, Service & Martin, 1997).

Summary and Conclusions

Our long-term goal is to obtain new knowledge about the effectiveness of cochlear implants in adults and children. Along the way, we hope to gain a detailed understanding of the basis for the enormous individual differences in audiological outcomes that have been reported universally in the literature on prelingually deaf children with cochlear implants. To accomplish this task, we began our investigation of individual differences by studying the exceptionally good users of cochlear implants, the so-called "Stars," in order to narrow down the scope of the problem and formulate more specific testable hypotheses about the underlying processes that distinguish this group of children from the other deaf children who are not able to benefit as much from their cochlear implant. In our initial analyses, we found that the "Stars" differed in several theoretically interesting ways from a comparison group of children with cochlear implants. Correlational analyses revealed a common underlying source of variance associated with spoken word recognition in several different tasks that required lexical access and use of phonological processing skills. This pattern emerged in both receptive and expressive measures of language and was related to the language-learning environment, the communication mode that the child was exposed to after implantation. The correlational analyses of the "Stars" also suggested that working memory capacity might be one place to look for the locus of the individual differences and variation in performance on audiological outcome measures of performance.

To study working memory, we obtained auditory digit spans from a large group of deaf children with cochlear implants. We found that the working memory spans of deaf children with cochlear implants were highly correlated with a number of traditional audiological and language-based outcome measures, including measures of spoken language comprehension, speech intelligibility and reading. In another study using a new experimental methodology to measure working memory spans that did not require a verbal output response, we found that deaf children with cochlear implants do not automatically encode and integrate redundant stimulus dimensions for sequences that are presented cross-modally. Instead, they perceived and processed these patterns using visual-spatial coding and a rehearsal strategy that appears to be fundamentally different from the highly automatized verbal coding strategies that age-matched normal-hearing children employed in the same experimental task.

Taken together, the present findings support the hypothesis that central auditory processes related to perception, attention, memory, learning and language may underlie the large individual differences observed in traditional audiological outcome measures reported in the literature for this population of implant users. Knowledge and understanding of the processes and mechanisms responsible for differences in the effectiveness of cochlear implants and variation in audiological performance should be extremely valuable to both clinicians and researchers for several reasons. First, this new knowledge will provide a principled theoretical basis for the development of new intervention strategies for children who are not benefiting optimally from their cochlear implant at a time in their development of language when changes can still be made. Second, detailed knowledge of the underlying source of these individual differences may help in identifying new preimplant predictors of audiological outcome. These predictors can then be used to refine current criteria for candidacy based on direct behavioral measures of performance which are related in a straightforward way to a variety of outcome measures, particularly measures of speech perception, language processing and language development.

Finally, several new areas of research on individual differences were identified based on techniques and experimental procedures from cognitive psychology that are designed to measure the content and flow of information as it is processed by the central nervous system. These new research methods focus on the microstructure of cognition, processing speed, capacity limitations and modes of processing sensory information, the intermediate processes and structures that underlie behavior in a given task rather than the final product of perceptual analysis which has been the primary defining characteristic of the traditional approach to audiological outcome measures used in the past.

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