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Speech Perception in Deaf Children with Cochlear Implants[1]

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Abstract. Cochlear implants work well in many profoundly deaf adults and children. However, despite the success of cochlear implants in many deaf children, large individual differences have been reported on a wide range of speech and language outcome measures. This finding is observed in all research centers around the world. Some children do extremely well with their cochlear implant while others derive only minimal benefits after receiving their implant. Understanding the reasons for the variability in outcomes and the large individual differences following cochlear implantation is one of the most important problems in the field today. This chapter summarizes recent findings on the speech perception skills of deaf children following cochlear implantation. The results of these studies suggest that in addition to several demographic and medical variables, variation in children's success with cochlear implants reflects fundamental differences in rapid phonological coding and verbal rehearsal processes which are used in a wide range of clinical outcome measures used to measure benefit following implantation.

Introduction

Each week for the last 12 years I have traveled from my home in Bloomington to Riley Hospital for Children at the IU Medical Center in Indianapolis, a distance of some 60 miles each way, to work on an unusual clinical research project. I am part of a multidisciplinary team of basic and clinical researchers who are studying the development of speech perception and language skills of profoundly deaf children who have received cochlear implants. My colleague, Dr. Richard Miyamoto, a pediatric otologist and head and neck surgeon has been providing profoundly deaf adults and children with cochlear implants since the early 1980s when the first single-channel implants were undergoing clinical trials. Since the approval of cochlear implants by the FDA as a treatment for profound deafness, over 60,000 patients have received cochlear implants at centers all over the world (Clarke, 2003).

A cochlear implant is a surgically implanted electronic device that functions as an auditory prosthesis for a patient with a severe to profound sensorineural hearing loss. It provides electrical stimulation to the surviving spiral ganglion cells of the auditory nerve bypassing the damaged hair cells of the inner ear to restore hearing in both deaf adults and children. The device provides them with access to sound and sensory information from the auditory modality. The current generation of multichannel cochlear implants consist of an internal multiple electrode array and an external processing unit (see Figure 1). The external unit consists of a microphone that picks up sound energy from the environment and a signal processor that codes frequency, amplitude and time and compresses the signal to match the narrow dynamic range of the ear. Cochlear implants provide temporal and amplitude information. Depending on the manufacturer, several different place coding techniques are used to represent and transmit frequency information in the signal.

For postlingually profoundly deaf adults, a cochlear implant provides a transformed electrical signal to an already fully developed auditory system and intact mature language processing system. These patients have already acquired spoken language under normal listening conditions so we know their central auditory system and brain are functioning normally. In the case of a congenitally deaf child, however, a cochlear implant provides novel electrical stimulation through the auditory sensory modality and an opportunity to perceive speech sounds and develop spoken language for the first time after a period of auditory deprivation. Congenitally deaf children have not been exposed to speech and do not develop spoken language normally. Although their brain and nervous system continue to develop in the absence of normal auditory stimulation, there is now evidence to suggest that some cortical reorganization has already taken place during the period of sensory deprivation before implantation and that several aspects of speech and language skills after implant may develop in an atypical fashion. Both peripheral and central differences in neural function are likely to be responsible for the wide range of variability observed in outcome and benefit following implantation.

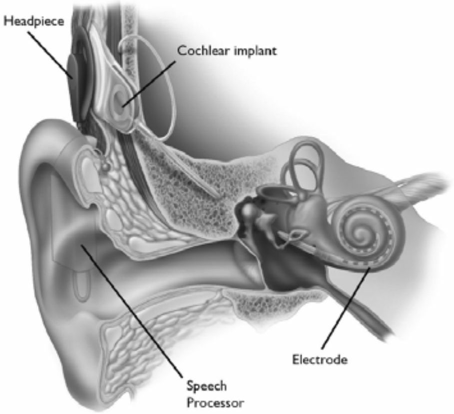

Figure 1. Simplified diagram of the internal and external components of a multichannel cochlear implant system. The external speech processor uses a transcutaneous radio-frequency (RF) transmitter to send electrical signals to an internal receiver which is connected directly to the implanted electrode array. (Courtesy of Cochlear Americas).

This chapter is concerned with congenitally deaf children who have received cochlear implants. These children are the most interesting and theoretically important clinical population to study because they have been deprived of sound and auditory stimulation at a very early point in neural and cognitive development. After implantation their hearing is restored with electrical stimulation that is designed to simulate the response of a healthy cochlea to speech and other auditory signals. Aside from the obvious clinical benefits of cochlear implantation as a method of treating profound prelingual deafness in children, this clinical population also provides a unique opportunity to study the effects of auditory deprivation on the development of speech perception and language processing skills. It also permits us to assess the effects of restoration of hearing via artificial electrical stimulation of the nervous system. In some sense, one can think of research on this clinical population as the modern-day analog of the so-called “forbidden experiment” in the field of language acquisition. In this case, after a period of sensory deprivation has occurred, hearing is restored via medical intervention and children receive exposure to sound and stimulation through the auditory modality. Under these conditions, it is possible to study both the consequences of a period of auditory deprivation on speech and language development as well as the effects of restoring hearing using artificial electrical stimulation of the auditory nerve.

While cochlear implants work and appear to work well for many profoundly deaf adults and children, they do not always provide benefits to all patients who receive them. Compared to other behavioral data I have seen in the field of speech perception and spoken word recognition over the years, the audiological outcomes and benefits following cochlear implantation were simply enormous and hard to fully understand at first glance. Some deaf adults and children do extremely well with their cochlear implants and display what initially appears to be near-typical speech perception and language skills on a wide range of traditional clinical speech and language tests when tested under quiet listening conditions in the laboratory. In contrast, other adults and children struggle for long periods of time after they receive their cochlear implant and often never achieve comparable levels of speech and language performance or verbal fluency.

Low-performing patients are unable to talk on the telephone and frequently have great difficulty in noisy environments or situations where more than one person is speaking at the same time. Almost all of these patients do derive some minimal benefits from their cochlear implants because they are able to recognize some nonspeech sounds and have an increased awareness of where they are in their environment in terms of space and time. But they have a great deal of difficulty perceiving speech and understanding spoken language in a robust fashion under a wide range of challenging listening conditions.

I began to wonder why this pattern of results occurred and I became curious about the underlying factors that were responsible for the enormous differences in audiological outcome. Seeing some of these deaf children and talking with them and their parents each week made a big difference in appreciating the magnitude of this problem and the consequences of the wide range of variability in outcome for the children and their families. In addition to the enormous variability observed in the speech and language outcome measures, several other findings have been consistently reported in the clinical literature on cochlear implants in deaf children. An examination of these findings provides some preliminary insights into the possible underlying cognitive and neural basis for the variability in outcome and benefit among deaf children with cochlear implants. A small handful of traditional demographic variables have been found to be strongly associated with outcome and benefit after implantation. When these contributing factors are considered together, it is possible to begin formulating some specific hypotheses about the reasons for the enormous variability in outcome and benefit.

Almost all of the clinical research on cochlear implants has focused on the effects of a small number of demographic variables using traditional outcome measures based on assessment tools developed by clinical audiologists and speech pathologists. Although rarely discussed explicitly in the literature, these behaviorally-based clinical outcome measures of performance are the final product of a large number of complex sensory, perceptual, cognitive and linguistic processes that contribute to the observed variation among cochlear implant users. Until recently, little if any research focused on the underlying information processing mechanisms used to perceive and produce spoken language in this clinical population. Our investigations of these fundamental neurocognitive and linguistic processes have provided some new insights into the basis of individual differences in profoundly deaf children with cochlear implants.

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

Early sensory and linguistic experience and language processing activities after implantation have also been shown to affect performance on a wide range of outcome measures. Implanted children who are immersed in “Oral-only” communication environments do much better on clinical tests of speech and language development than implanted children who are enrolled in “Total Communication” programs (Kirk, Pisoni, & Miyamoto, 2000). Oral communication approaches emphasize the use of speech and hearing skills and actively encourage children to produce spoken language to achieve optimal benefit from their implants. In contrast, total communication approaches employ the simultaneous use of some form of manual-coded English along with speech to help the child acquire language using both sign and spoken language inputs. The differences in performance between groups of children who are placed in oral communication and total communication education settings are observed most prominently in both receptive and expressive language tasks that involve the use of phonological coding and phonological processing skills such as open-set spoken word recognition, language comprehension and measures of speech production, especially measures of speech intelligibility and expressive language.

Until just recently, clinicians and researchers have been unable to find reliable preimplant predictors of outcome and success with a cochlear implant (see, however, Bergeson & Pisoni, 2004). The absence of preimplant predictors is a theoretically significant finding because it suggests that many complex interactions take place between the newly acquired sensory capabilities of a child after a period of auditory deprivation, properties of the language-learning environment and various interactions with parents and caregivers that the child is exposed to after receiving a cochlear implant. More importantly, however, the lack of preimplant predictors of outcome and benefit makes it difficult for clinicians to identify those children who are doing poorly with their cochlear implant at a time in development when changes can be made to modify and improve their language processing skills.

Finally, when all of the outcome and demographic measures are considered together, the available evidence strongly suggests that the underlying sensory and perceptual abilities for speech and language “emerge” after implantation. Performance with a cochlear implant improves over time for almost all children. Success with a cochlear implant therefore appears to be due, in part, to perceptual learning and exposure to a language model in the environment. Because outcome and benefit with a cochlear implant cannot be predicted reliably from traditional behavioral measures obtained before implantation, any improvements in performance observed after implantation must be due to sensory and cognitive processes that are linked to maturational changes in neural and cognitive development (see Sharma, Dorman & Spahr, 2002).

Our current hypothesis about the source of individual differences in outcome following cochlear implantation is that while some proportion of the variance in performance can be attributed directly to peripheral factors related to audibility and the initial sensory encoding of the speech signal into “information-bearing” sensory channels in the auditory nerve, several additional sources of variance also come from more central cognitive and linguistic factors that are related to psychological processes such as perception, attention, learning, memory and language. How a deaf child uses the initial sensory input from the cochlear implant and the way the environment modulates and shapes language development are fundamental research problems. These problems deal with perceptual encoding, verbal rehearsal, storage and retrieval of phonetic and phonological codes and the transformation and manipulation of phonological and neural representations of the initial sensory input in a range of language processing tasks.

To investigate individual differences and the sources of variation in outcome, we began by analyzing a set of data from a longitudinal project on cochlear implants in children (see Pisoni et al., 1997; 2000). Our first study was designed to study the “exceptionally” good users of cochlear implants—the so-called Stars. These are the children who did extremely well with their cochlear implants after only two years of implant use. The Stars are able to acquire spoken language quickly and easily and appear to be on a developmental trajectory that parallels normal-hearing children although delayed a little in time (see Svirsky et al., 2000). The theoretical motivation for studying the exceptionally good children was based on an extensive body of research on “expertise” and “expert systems” theory (Ericsson & Smith, 1991). Many important new insights have come from studying expert chess players, radiologists and other individuals who have highly developed skills in specific knowledge domains.

Analysis of the Stars

We analyzed scores obtained from several different outcome measures over a period of six years from the time of implantation to examine changes in speech perception, word recognition and comprehension over time (see Pisoni et al., 2000 for complete report). Before these results are presented, however, we describe how the Stars and a comparison group of lower-performing children were originally selected.

The criterion used to identify the Stars was based on scores obtained from one particular clinical test of speech perception, the Phonetically Balanced Kindergarten (PBK) Words test (Haskins, 1949). This PBK test is an open-set test of spoken word recognition (also see Meyer & Pisoni, 1999) and is very difficult for prelingually deaf children when compared to other closed-set speech perception tests routinely included in the standard clinical assessment battery (Zwolan, Zimmerman-Phillips, Asbaugh, Hieber, Kileny & Telian, 1997). Children who do reasonably well on the PBK test display ceiling levels of performance on other closed-set speech perception tests that measure speech pattern discrimination skills.

Open-set tests like the PBK test measure word recognition and lexical selection processes (Luce & Pisoni, 1998). To perform this test successfully, the child is required to search and retrieve the phonological representation of a test word from lexical memory and repeat it to the examiner. Open-set tests of word recognition are extremely difficult for hearing-impaired children with cochlear implants because the task requires that the child 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. A child must identify and then discriminate a unique phonological representation from a large number of lexical equivalence classes in memory (see Luce & Pisoni, 1998). It is important to emphasize here that although recognizing isolated spoken words in an open-set test format may seem like a simple task at first glance, it is very difficult for a hearing-impaired child who has a cochlear implant. Typically-developing children with normal hearing routinely display ceiling levels of performance under comparable testing conditions (Kluck et al., 1997).

To learn more about why the Stars do so well on open-set test of word recognition, we analyzed outcome data from children who scored exceptionally well on the PBK test two years after implantation. For comparison, we also obtained PBK scores from a group of low-performing children. The PBK score was used as the “criterial variable” to identify and select two groups of children for subsequent analysis using an “extreme groups” design. The Stars were children who scored in the upper 20% of all children tested on the PBK test two years post-implant. The low-performers consisted of children who scored in the bottom 20% on the PBK test two years post-implant. After the children were sorted into two groups, we examined their performance on a range of other clinical outcome measures that were available as part of large-scale longitudinal study at Indiana University. The speech perception data we discuss here include measures of speech feature discrimination, spoken word recognition and comprehension.

Scores for the two groups were obtained from a longitudinal database containing a variety of demographic and outcome measures from 160 deaf children (see Pisoni et al., 2000). Other measures of vocabulary knowledge, receptive and expressive language and speech intelligibility were also obtained (see Pisoni et al., 1997; 2000 for more details). All of the children in both groups were prelingually deafened. Each child received a cochlear implant because he/she was profoundly deaf and was unable to derive any benefit from conventional hearing aids. All children had used their cochlear implant for two years at the time when these analyses were completed. Using this selection procedure, the two groups turned out to be roughly similar in age at onset of deafness and length of implant use.

Speech Feature Discrimination

Measures of speech feature discrimination for both consonants and vowels were obtained for both groups of children using the Minimal Pairs Test (Robbins et al., 1988). This clinical test uses a two-alternative forced-choice picture pointing task. The child hears a single word spoken in isolation on each trial using live voice presentation by an examiner and is required to select one of the pictures that correspond to the test item. Examples of two test plates are shown in Figure 2.

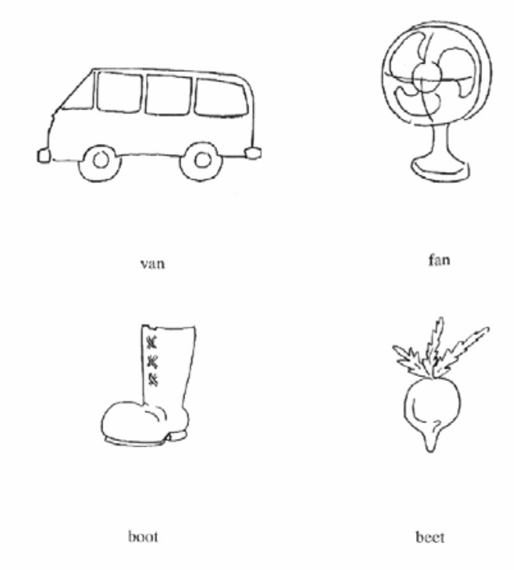

Figure 2. Examples of two test plates used to measure speech feature discrimination on the Minimal Pairs Test (from Robbins et al., 1988).

A summary of the consonant discrimination results for both groups of subjects is shown in Figure 3. Percent correct discrimination is displayed separately for 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 low-performers are shown by the open bars in this figure. Chance performance on this task is 50% correct as shown by a horizontal line. A second horizontal line is also displayed in this figure at 70% correct corresponding to scores that were significantly above chance using the binominal distribution.

Examination of the results for the Minimal Pairs Test obtained over a period of six years of implant use reveals several findings. First, performance of the Stars was consistently better than the control group for every comparison across all three consonant features. Second, discrimination performance improved over time with implant use for both groups. The increases were primarily due to improvements in discrimination of manner and voicing by the Stars. At no interval did the mean scores of the comparison group ever exceed chance performance on discrimination of voicing and place features. Although increases in minimal pair discrimination performance were observed over time for the controls, their 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.

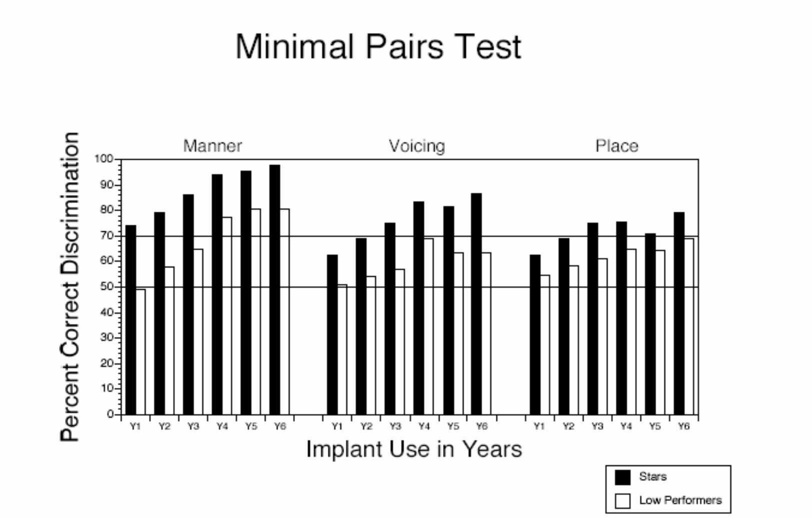

Figure 3. Percent correct discrimination on the Minimal Pairs Test (MPT) for manner, voicing and place as a function of implant use. The Stars are shown by filled bars, the Low-Performers are shown by open bars (from Pisoni et al., 2000).

The results of the Minimal Pairs Test demonstrate that both groups of children have difficulty perceiving, encoding and discriminating fine phonetic details of isolated spoken words in a simple two-alternative closed-set testing format. Although the Stars discriminated differences in manner of articulation after one year of implant use and showed consistent improvements in performance over time for both manner and voicing contrasts, they still had a great deal of difficulty reliably discriminating differences in place of articulation, even after five years of experience with their implants. In contrast, the low-performing children were just barely able to discriminate differences in manner of articulation above chance after four years of implant use. The lower-performing children also had a great deal of difficulty discriminating differences in voicing and place of articulation even after five or six years of use.

The pattern of speech feature discrimination results shown in Figure 3 suggests that both groups of children encode spoken words using "coarse" phonological representations. Their representations appear to be "underspecified" and contain much less fine-grained acoustic-phonetic detail than the lexical representations that normal hearing children typically use. The Stars were able to discriminate manner and to some extent voicing much sooner after implantation than the low-performers. In addition, the Stars also displayed consistent improvements in speech feature discrimination over time after implantation.

The speech feature discrimination data reveal several differences in the encoding of sensory information and the phonological representations that are used for subsequent word learning and lexical development. It is likely that if a child cannot reliably discriminate small phonetic differences between pairs of spoken words that are phonetically similar under these relatively easy forced-choice test conditions, they will also have difficulty recognizing words in isolation with no context or retrieving the phonological representations of highly familiar words from memory for use in simple speech production tasks that require immediate repetition. We would also expect them to display a great deal of difficulty in recognizing and imitating nonwords as well which have no lexical representations.

Spoken Word Recognition

Two additional word recognition tests were used to measure open-set word recognition. Both tests use words that are familiar to preschool age children. The Lexical Neighborhood Test (LNT) contains monosyllabic words; the Multi-syllabic Lexical Neighborhood test (MLNT) contains multisyllabic words (Kirk, Pisoni & Osberger, 1995). Both tests contain two different sets of words that are used to measure lexical discrimination and provide detailed information about how the lexical selection process is carried out. Half of the items in each test are lexically "easy" words and half are lexically "hard" words.

The differences in performance on the easy and hard words provide an index of how well a child is able to make fine phonetic discriminations among acoustically similar words. Differences in performance between the LNT and the MLNT provide a measure of the extent to which the child is able to make use of word length cues to recognize and access words from the lexicon. The test words are presented in isolation one at a time by the examiner using a live-voice auditory-only format. The child is required to imitate and immediately repeat a test word after it is presented by the examiner.

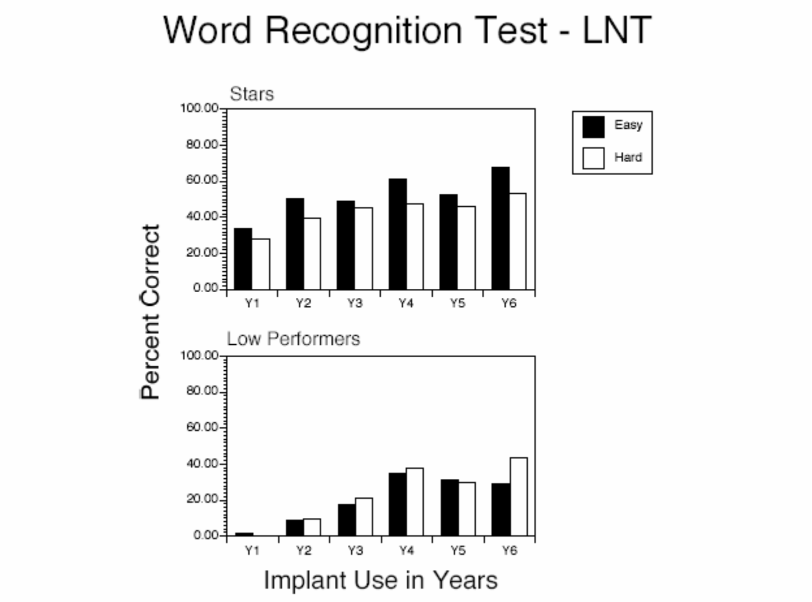

Figure 4. Percent correct word recognition performance for the Lexical Neighborhood Test (LNT) monosyllabic word lists as a function of implant use and lexical difficulty (from Pisoni et al., 2000).

Figures 4 and 5 show percent correct word recognition obtained on the LNT and the MLNT for both groups of children as a function of implant use. The data for the Stars are shown in the top panel of each figure; the data for the low-performers are shown in the bottom panels. Scores for the "easy" and "hard" words are shown separately within each panel.

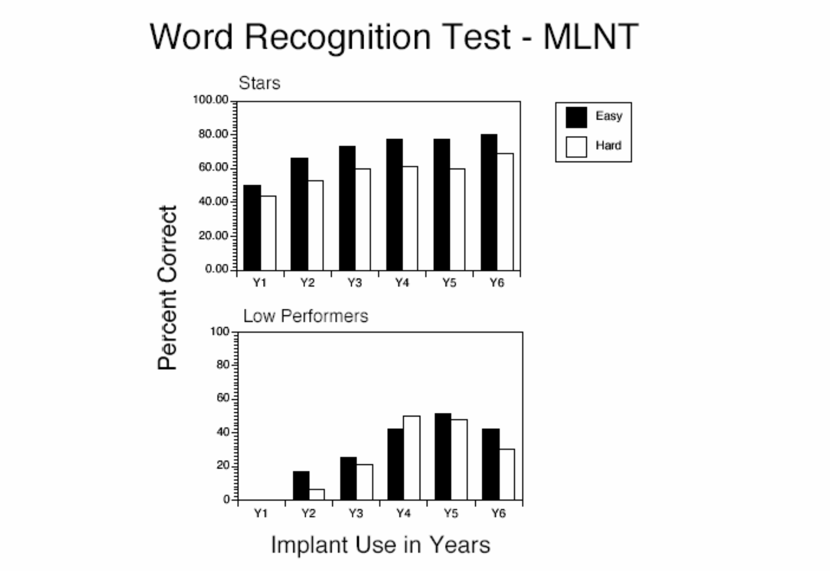

Figure 5. Percent correct word recognition performance for the Multi-syllabic Lexical Neighborhood Test (MLNT) word lists as a function of implant use and lexical difficulty (from Pisoni et al., 2000).

Several consistent differences in performance are shown in Figures 4 and 5. The pattern of these differences provides some insights into the task demands and processing operations used in open-set word recognition tests. First, the Stars consistently demonstrate higher levels of word recognition performance on both the LNT and the MLNT than the low-performers. 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 low-performers 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 test even after six years of implant use. Normal-hearing children typically display very high levels of performance on both of these tests by age 4 (Kluck et al., 1997).

The Stars also displayed a word length effect at each testing interval. Recognition was always better for long words on the MLNT than for short words on the LNT. This pattern is not present for the low-performers who were unable to do this open-set task at all during the first three years. The existence of a word length effect for the Stars suggests that these children are recognizing spoken words "relationally" in the context of other words they have in their lexicon (Luce & Pisoni, 1998). If these children were just recognizing words in isolation, either holistically as global temporal patterns or segment-by-segment without reference to the representations of words they already know, we would expect performance to be worse for longer words than shorter words because longer words contain more stimulus information. But this is not what we found.

The pattern of results for the Stars is exactly the opposite of this prediction and parallels earlier results obtained with normal-hearing adults and normal-hearing typically-developing children (Luce & Pisoni, 1998; Kirk et al., 1995; Kluck et al., 1997). Longer words are easier to recognize than shorter words because they are phonologically more distinctive and discriminable and therefore 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.

Additional support for role of the lexicon and the use of phonological knowledge in open-set word recognition is provided by another finding. The Stars also displayed a consistent effect of “lexical discrimination.” As shown in Figures 4 and 5, the Stars recognized 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 although it is larger and more consistent over time for the MLNT test. Once again, the lower-performing children did not display sensitivity to lexical competition among the test words.

The differences in performance observed between these two groups of children on both open-set word recognition tests were not at all surprising because the two extreme groups were initially created based on their PBK scores, another open-set word recognition test. However, the overall pattern of the results shown in Figures 4 and 5 is theoretically important because the findings demonstrate that the processes used in recognizing isolated spoken words are not specific to the particular test items on the PBK test or the experimental procedures used in open-set tests of word recognition. The differences between the two groups of children readily generalized to two other open-set word recognition tests that use completely different test words.

The pattern of results strongly suggests a common underlying set of linguistic processes that is employed in recognizing and imitating spoken words presented in isolation. Understanding the cognitive and linguistic processing mechanisms that are used in open-set word recognition tasks may provide new insights into the underlying basis of the individual differences observed in outcome measures in children with cochlear implants. It is probably no accident that the PBK test, which is considered the “gold standard” of performance, 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 measures fundamental language processing skills that generalize well beyond the specific word recognition task used in open-set tests. The important conceptual issue is to explain why this happens and identify the underlying cognitive and linguistic processing mechanisms used in open-set word recognition tasks as well as other language processing tasks. We will return to this issue again below.

Comprehension of Common Phrases

Language comprehension performance was also measured in these two groups of children using the Common Phrases Test (Osberger et al., 1991), an open-set test with three presentation formats: auditory-only (CPA), visual-only (CPV) and combined auditory plus visual (CPAV). Children are asked questions or given directions to follow under these three conditions. The results of the Common Phrases Test are shown in Figure 6 for both groups of subjects as a function of implant use for the three different presentation formats.

Figure 6 shows that the Stars performed consistently better than the low-performers 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 CPAV condition after five years of implant use. CPAV conditions were always better than either the CPA or CPV 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 CPA conditions. Even after three years of implant use, the lower-performing children were barely able to perform the common phrases task above 25% correct when they had to rely entirely on auditory cues in the speech signal to carry out the task.

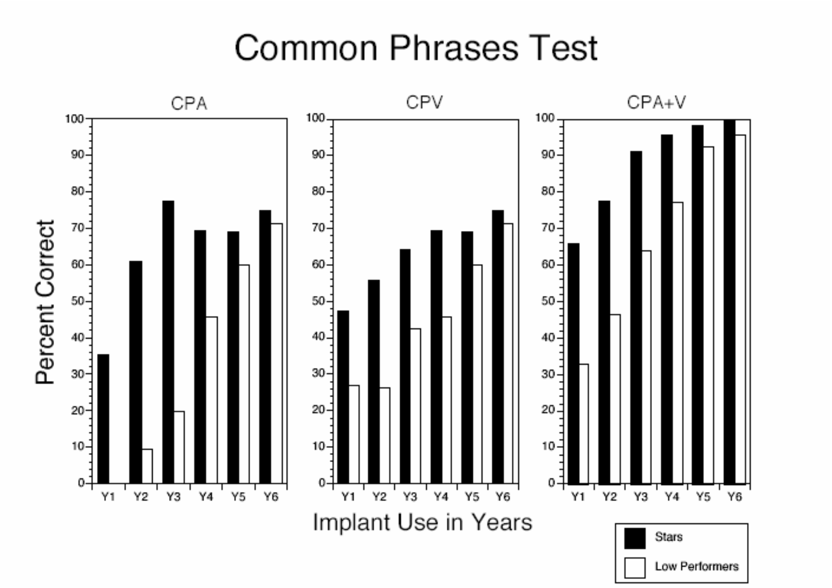

Figure 6. Percent correct performance on the Common Phrases Test (CPT) for auditory-only (CPA), visual-only (CPV) and combined auditory plus visual presentation modes (CPAV) as a function of implant use. The Stars are shown by filled bars, the low-performers are shown by open bars (from Pisoni et al., 2000).

Correlations among Measures of Speech Perception

These descriptive results show that the exceptionally good performers, the Stars, do well on measures of speech feature discrimination, spoken word recognition and language comprehension. They also do well on other tests of receptive and expressive language, vocabulary knowledge and speech intelligibility (see Pisoni et al., 1997; 2000). This pattern of findings suggests that a common source of variance may underlie the exceptionally good performance of the Stars on a range of different speech and language outcome measures. Until our investigation of the exceptionally good children, no one had studied individual differences in outcome in this clinical population or the underlying perceptual, cognitive and linguistic processes. The analyses of speech feature discrimination, spoken word recognition, and spoken language comprehension scores summarized here demonstrate that a child who displays exceptionally good performance on the PBK test also shows good scores on other speech perception tests. Analyses of the other outcome measures revealed a similar pattern of results.

To assess the relations between these different tests, we carried out a series of simple correlations on the speech perception scores and the other outcome measures. 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 comprehension? Is the good performance of the Stars restricted only to open-set word recognition tests or is it possible to identify a common underlying variable or process that can account for the relations observed among the other outcome measures?

Simple bivariate correlations were carried out separately for the Stars and low-performers using the test scores obtained after one year of implant use (see Pisoni et al., 1997; 2000 for the full report). The results of the correlational analyses on the outcome measures revealed a strong and consistent pattern of intercorrelations among all of the test scores for the Stars (see Pisoni et al. 1997, 2000). This pattern was observed for all three of the speech perception tests described here as well as vocabulary knowledge, receptive and expressive language and speech intelligibility. The outcome measures that correlated the most strongly and most consistently with the other tests were the open-set word recognition scores on the LNT and MLNT tests.

The finding that performance on open-set word recognition was strongly correlated with all of the other outcome measures was of special interest to us. The pattern of intercorrelations among all these dependent measures strongly suggests a shared common underlying source of variance. The extremely high correlations with the open-set word recognition scores on the LNT suggests that the common source of variance may be related to the processing of spoken words, specifically to the encoding, storage, retrieval and manipulation of the phonological representations of spoken words. The fundamental cognitive and linguistic processes used to recognize (decompose) and repeat (reassemble) spoken words in an open-set tests like the PBK or LNT are also used in other language processing tasks, such as comprehension and speech production and even nonword repetition, which draw on the same sources of phonological information about spoken words in the lexicon.

The results of the correlational analyses suggest several hypotheses about the source of the differences in performance between the Stars and the low-performers. Some proportion of the variation in outcome appears to be related to how the initial sensory information is processed and used in clinical tests that assess speech feature discrimination, word recognition, language comprehension and speech production. Unfortunately, the data available on these children were based on traditional audiological outcome measures that were collected as part of their annual clinical assessments. All of the scores on these behavioral tests are "endpoint measures" of performance that reflect the final product of perceptual and linguistic analysis. Process measures of performance that assess what a child does with the sensory information provided by his/her cochlear implant were not part of the standard research protocol used in our longitudinal study so it was impossible to examine differences in processing capacity and speed. It is very likely that fundamental differences in both information processing capacity and speed are responsible for the individual differences observed between these two groups of children.

For a variety of theoretical reasons, we refocused our research efforts to study "working memory." One reason is that working memory plays a central role in human information processing because it serves as the primary interface between sensory input and stored knowledge in long-term memory. Another is that working memory has also been shown to be a major source of individual differences in processing capacity across a wide range of domains from perception to memory to language (Ackerman, Kyllonen & Roberts, 1999; Carpenter, Miyake & Just, 1994; Baddeley, Gathercole, & Papagno, 1998; Gupta & MacWhinney, 1997).

Measures of Working Memory

To obtain some new measures of working memory capacity from a large group of deaf children following cochlear implantation, we began collaborating with Dr. Ann Geers and her colleagues at Central Institute for the Deaf (CID) in St. Louis where there was a large-scale clinical research project underway. They collected a wide range of different outcome measures of speech, language and reading skills from 8- and 9-year old children who had used their cochlear implants for at least three and one-half years. Thus, in this study, chronological age and length of implant use were controlled.

Using the test lists and procedures from the WISC III (Wechsler 1991), forward and backward auditory digit spans were obtained from 176 deaf children who were tested in separate groups during the summers of 1997, 1998, 1999 and 2000. Forward and backward digit spans were also collected from an additional group of 45 age-matched normal-hearing 8- and 9-year old children who were tested in Bloomington, Indiana, and served as a comparison group (see Pisoni & Cleary, 2003).

The WISC-III memory span task requires the child to repeat a list of digits that is spoken live-voice by an experimenter at a rate of approximately one digit per second (WISC-III Manual, Wechsler 1991). In the "digits-forward" condition, the child is required simply to repeat the list as heard. In the "digits-backward" condition, the child is told to "say the list backward." In both subtests, the lists begin with two items and increase in length until a child gets two lists incorrect at a given length, at which time testing stops. Points are awarded for each list correctly repeated with no partial credit.

A summary of the digit span results for all five groups of children is shown in Figure 7. Forward and backward digit spans are shown separately for each group. The children with cochlear implants are shown in the four panels on the left by year of testing; the normal-hearing children are shown on the right. Each child's digit span in points was calculated by summing the number of lists correctly recalled at each list length.

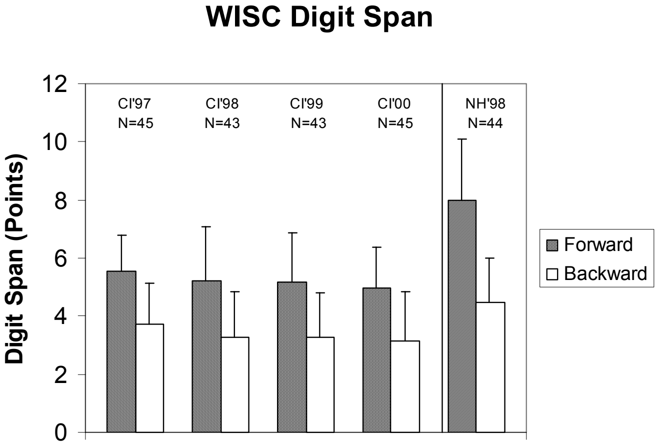

Figure 7. WISC digit spans scored by points for the four groups of 8- and 9-year old children with cochlear implants and for a comparison group of 8- and 9-year-old normal-hearing children. Forward digit spans are shown by the shaded bars, backwards digit spans by the open bars. Error bars indicate one standard deviation from the mean (from Pisoni & Cleary, 2003).

The results shown in Figure 7 reveal a systematic pattern of the forward and backward digit spans for the deaf children with cochlear implants. All four groups are quite similar to each other. In each group, the forward digit span is longer than the backward digit span. The pattern is quite stable over the four years of testing despite the fact that these scores were obtained from independent groups of children. The difference in span length between forward and backward report was highly significant for the entire group of 176 deaf children and for each group taken separately ($p < .001$).

The forward and backward digit spans obtained from the 44 age-matched normal-hearing children are shown in the right-hand panel of Figure 7. These results show that the digit spans for the normal-hearing children differ in several ways from the spans obtained from the children with cochlear implants. First, both digit spans are longer than the spans obtained from the children with cochlear implants. Second, the forward digit span for the normal-hearing children is much longer than the forward digit spans obtained from the children with cochlear implants. This latter finding is particularly important because it demonstrates atypical development of the deaf children's short-term memory capacity and suggests several possible differences in the underlying processing mechanisms that are used to encode and maintain sequences of spoken digits in immediate memory.

Numerous studies have suggested that forward digit spans reflect coding strategies related to phonological processing and verbal rehearsal mechanisms used to maintain information in short-term memory for brief periods of time before retrieval and output response. Differences in backward digit spans, on the other hand, are thought to reflect the contribution of controlled attention and operation of higher-level "executive" processes that are used to transform and manipulate verbal information for later processing operations (Rudel & Denckla, 1974; Rosen & Engle, 1997).

The digit spans for the normal-hearing children shown in Figure 7 are age-appropriate and fall within the published norms for the WISC III. However, the forward digit spans obtained from the children with cochlear implants are atypical and suggest possible differences in encoding and/or verbal rehearsal processes used in immediate memory. In particular, the forward digit spans reflect differences in processing capacity of immediate memory between the two groups of children. These differences may cascade and affect other information processing tasks that make use of working memory and verbal rehearsal processes. Because all of the clinical tests that are routinely used to assess speech and language outcomes rely heavily on component processes of working memory and verbal rehearsal, it seems reasonable to assume that these tasks will also reflect variability due to basic differences in immediate memory and processing capacity.

Correlations with Digit Spans

In order to learn more about the differences in auditory digit span and the limitations in processing capacity, we examined the correlations between forward and backward digit spans and several speech and language outcome measures also obtained from these children at CID (see Pisoni & Cleary, 2003). Of the various demographic measures available, the only one that correlated strongly and significantly with digit span was the child's communication mode. This measure is used to quantify the nature of the child's early sensory and linguistic experience after receiving a cochlear implant in terms of the degree of emphasis on auditory-oral language skills by teachers and therapists in the educational environment.

We found that forward digit span was positively correlated with communication mode ($r = +.34$, $p < .001$). Children who were in language learning environments that primarily emphasized oral skills displayed longer forward digit spans than children who were in total communication (TC) environments. However, the correlation between digit span and communication mode was highly selective in nature because it was restricted only to the forward digit span scores; the backward digit spans were not correlated with communication mode or any of the other demographic variables.

In order to examine the effects of early experience in more detail, a median split was carried out on the communication mode scores to create two subgroups. Figure 8 shows the digit spans plotted separately for the oral and total communication children for each of the four years of testing at CID. The oral group consistently displayed longer forward digit spans than the total communication group. While the differences in forward digit span between oral and total communication children were highly significant, the differences in backward digit span were not. This pattern suggests that the effects of early sensory and linguistic experience on immediate memory is related to coding and verbal rehearsal processes that affect only the forward digit span conditions in this task.

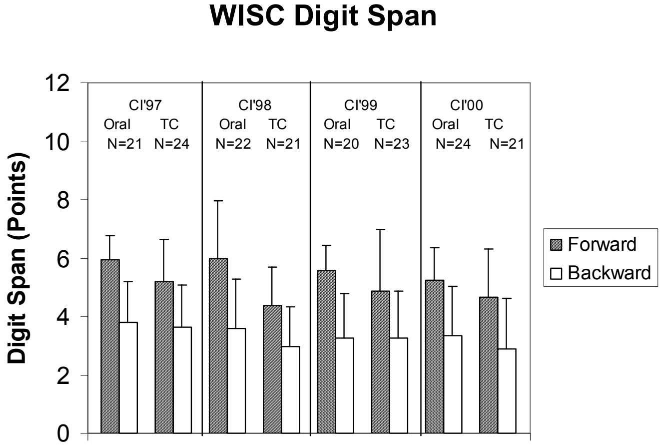

Figure 8. WISC digit spans scored by points for the four groups of 8- and 9-year old children with cochlear implants, separated by communication mode. For each year, scores for the oral group are shown to the left of those for the total communication group. Forward digit spans are shown by the shaded bars, backwards digit spans by the open bars. Error bars indicate one standard deviation from the mean (from Pisoni & Cleary, 2003).

The difference in forward digit span between oral and total communication children is present for each of the four groups. These differences could be due to several factors such as more efficient encoding of the initial stimulus patterns into stable phonological representations in working memory, speed and efficiency of the verbal rehearsal processes used to maintain phonological information in working memory or possibly even speed of retrieval and scanning of information in working memory after recognition has taken place. All three factors could influence measures of processing capacity and any one of these could affect the number of digits correctly recalled from immediate memory in this task.

Digit Spans and Word Recognition

Although these results indicate that early experience in an environment that emphasizes oral language skills is associated with longer forward digit spans and increased information processing capacities of working memory, without additional converging measures of performance, it is difficult to specify precisely what elementary processes and information processing mechanisms are actually affected by early experience and which ones are responsible for the increases in forward digit spans observed in these particular children. Recent studies of normal-hearing children have demonstrated close “links” between working memory and learning to recognize and understand new words (Gupta & MacWhinney, 1997; Gathercole et al., 1997). Other research has found that vocabulary development and several important milestones in speech and language acquisition are also associated with differences in measures of working memory, specifically, measures of digit span, which can be used as estimates of processing capacity of immediate memory (Gathercole & Baddeley, 1990).

To determine if immediate memory capacity is related to spoken word recognition, we correlated the WISC forward and backward digit span scores with three different measures of word recognition. A summary of the correlations between digit span and word recognition scores based on these 176 children is shown in Table I.

The WIPI test (Word Intelligibility by Picture Identification Test) is a closed-set test of word recognition in which the child selects a word from among six alternative pictures (Ross & Lerman, 1979). As described earlier, the LNT is an open-set test of word recognition and lexical discrimination that requires the child to imitate and reproduce an isolated word (Kirk, Pisoni & Osberger, 1995). Finally, the BKB is an open-set word recognition test in which key words are presented in sentences (Bench, Kowal & Bamford, 1979).

Table I
Correlations between WISC digit span and three measures of spoken word recognition (from Pisoni & Cleary, 2003).

	Simple Bivariate Correlations		Partial Correlations[a]	
	WISC Forward Digit Span	WISC Backward Digit Span	WISC Forward Digit Span	WISC Backward Digit Span
Closed Set Word Recognition (WIPI)	.42***	.28***	.25**	.12
Open Set Word Recognition (LNT-E)	.41***	.20**	.24**	.07
Open Set Word Recognition in Sentences (BKB)	.44***	.24**	.27***	.09

*** p <.011, ** p<.01

[a] Statistically Controlling for: Communication Mode Score, Age at Onset of Deafness, Duration of Deafness, Duration of Cochlear Implant Use, Number of Active Electrodes, VIDSPAC Total Segments Correct (Speech Feature Perception Measure), Age

Table I displays two sets of correlations. The left-hand portion of the table shows the simple bivariate correlations of the forward and backward digit spans with the three measures of word recognition. The correlations for both the forward and backward spans reveal that children who had longer WISC digit spans also had higher word recognition scores on all three word recognition tests. This finding is present for both forward and backward digit spans. The correlations are all positive and reached statistical significance.

The right-hand portion of Table I shows a summary of the partial correlations among these same measures after we statistically controlled for differences due to chronological age, communication mode, duration of deafness, duration of device use, age at onset of deafness, number of active electrodes and speech feature discrimination. When these "contributing variables" were removed from the correlational analyses, the partial correlations between digit span and word recognition scores became smaller in magnitude overall. However, the correlations of the forward digit span with the three word recognition scores were still positive and statistically significant while the correlations of the backward digit spans were weaker and no longer significant.

These results demonstrate that children who have longer forward WISC digit spans also show higher word recognition scores; this relationship was observed for all three word recognition tests even after the other sources of variance were removed. The present results suggest a common source of variance that is shared between forward digit span and measures of spoken word recognition that is independent of other mediating factors that have been found to contribute to the variation in these outcome measures.

Digit Spans and Speaking Rate

While the correlations of the digit span scores with communication mode and spoken word recognition suggest fundamental differences in encoding and rehearsal speed which are influenced by the nature of the early experience a child receives, these measures of immediate memory span and estimates of information processing capacity are not sufficient on their own to identify the underlying information processing mechanism responsible for the individual differences. Additional converging measures are needed to pinpoint the locus of these differences more precisely. Fortunately, an additional set of behavioral measures was obtained from these children for a different purpose and made available to us for several new analyses.

As part of the research project at CID, speech production samples were obtained from each child to assess speech intelligibility and measure changes in articulation and phonological development following implantation (see Tobey et al., 2000). The speech samples consisted of three sets of meaningful English sentences that were elicited using the stimulus materials and experimental procedures developed by McGarr (1983). All of the utterances produced by the children were originally recorded and stored digitally for playback to groups of naïve adult listeners who were asked to transcribe what they thought the children had said. In addition to the speech intelligibility scores, we measured the durations of the individual sentences in each set and used these to estimate each child's speaking rate.

The sentence durations provide a quantitative measure of a child's articulation speed which we knew from a large body of earlier research in the memory literature was closely related to speed of subvocal verbal rehearsal (Cowan et al., 1998). Numerous studies over the past 25 years have demonstrated strong relations between speaking rate and memory span for digits and words (for example Baddeley, Thompson & Buchanan, 1975). The results of these studies suggest that measures of an individual's speaking rate reflect articulation speed and this measure can be used as an index of rate of covert verbal rehearsal for phonological information in working memory. Individuals who speak more quickly have been found to have longer memory spans than individuals who speak more slowly.

The forward digit span scores for the 168 children are shown in Figure 9 along with estimates of their speaking rates obtained from measurements of their productions of meaningful English sentences. The digit spans are plotted on the ordinate; the average sentence durations are shown on the abscissa. The top panel shows mean sentence durations; the bottom panel shows the log sentence durations. The pattern of results in both figures is very clear; children who produce sentences with longer durations speak more slowly and, in turn, have shorter forward digit spans. The correlations between forward digit span and both measures of sentence duration were strongly negative and highly significant (r = -.63 and r = -.70; p <.001, respectively). It is important to emphasize once again, that the relations observed here between digit span and speaking rate were selective in nature and were found only for the forward digit spans. There was no correlation at all between backward digit span scores and sentence duration in any of our analyses.

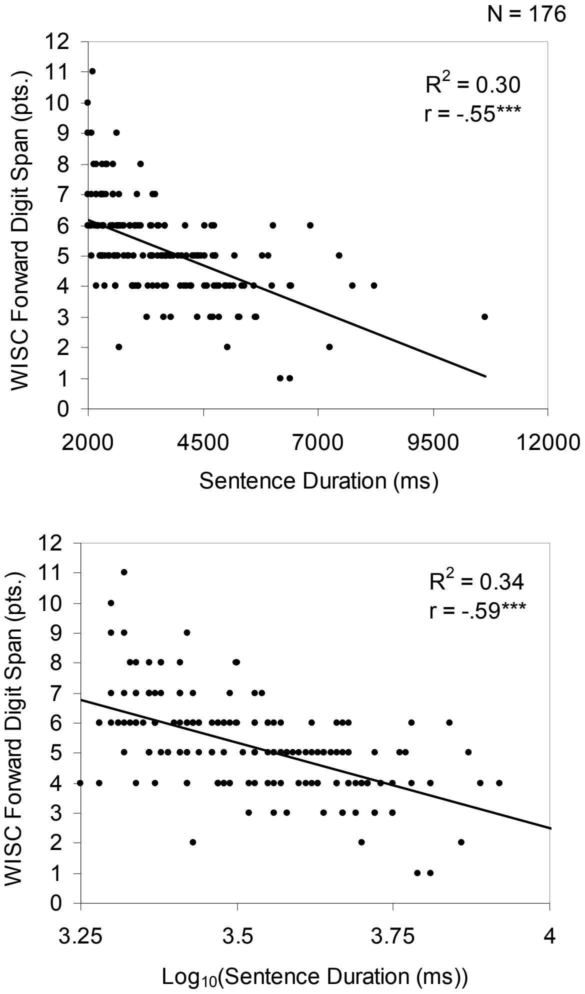

Figure 9. Scatterplots illustrating the relationship between average sentence duration for the seven-syllable McGarr Sentences (abscissa) and WISC forward digit span scored by points (ordinate). Each data-point represents an individual child. Non-transformed duration scores are shown in the top panel, log-transformed duration scores in the bottom panel. R-squared values indicate percent of variance accounted for by the linear relation (from Pisoni & Cleary, 2003).

The dissociation between forward and backward digit spans and the correlation of the forward spans with measures of speaking rate suggests that verbal rehearsal speed may be the primary underlying factor that is responsible for the variability and individual differences observed in deaf children with cochlear implants on a range of behavioral speech and language tasks. The common feature of each of these outcome measures is that they all make use of the storage and processing mechanisms of verbal working memory.

Speaking Rate and Word Recognition

To determine if verbal rehearsal speed is also related to individual differences in word recognition performance, we examined the correlations between sentence duration and the three different measures of spoken word recognition described earlier. All of these correlations are also positive and suggest once again that a common processing mechanism, verbal rehearsal speed, may be the factor that underlies the variability and individual differences observed in these word recognition tasks.

Our analysis of the digit span scores from these deaf children uncovered two important correlations linking forward digit span to both word recognition performance and speaking rate. Both of the correlations with forward digit span suggest a common underlying processing factor that is shared by each of these dependent measures. This factor appears to reflect the speed of verbal rehearsal processes in working memory. If this hypothesis is correct, then word recognition and speaking rate should also be correlated with each other because they make use of the same processing mechanism. This is exactly what we found. As in the earlier analyses, differences due to demographic factors and the contribution of other variables were statistically controlled for by using partial correlation techniques. In all cases, the correlations between speaking rate and word recognition were negative and highly significant. Thus, slower speaking rates are associated with poorer word recognition scores on all three word recognition tests. These findings linking speaking rate and word recognition suggest that all three measures, digit span, speaking rate and word recognition performance are closely related because they share a common underlying source of variance.

To determine if digit span and sentence duration share a common process and the same underlying source of variance which relates them both to word recognition performance, we re-analyzed the intercorrelations between each pair of variables with the same set of the demographic and mediating variables systematically partialled out. When sentence duration was partialled out of the analysis, the correlations between digit span and each of the three measures of word recognition essentially approached zero. However, the negative correlations between sentence duration and word recognition were still present even after digit span was partialled out of the analysis suggesting that processing speed is the common factor that is shared between these two measures.

The results of these analyses confirm that the underlying factor that is shared in common with speaking rate is related to the rate of information processing, specifically, the speed of the verbal rehearsal process in working memory. This processing component of verbal rehearsal could reflect either the articulatory speed used to maintain phonological patterns in working memory or the time to retrieve and scan phonological information already in working memory (see Cowan et al., 1998). In either case, the common factor that links word recognition and speaking rate appears to be related in some way to the speed of information processing operations used to store and maintain phonological representations in working memory (see Pisoni & Cleary, 2003).

Speech Timing and Working Memory

In addition to our recent studies on verbal rehearsal speed, we have also obtained several new measures of memory scanning during the digit recall task from a group of deaf children with cochlear implants and a group of typically-developing age-matched normal-hearing children (see Burkholder & Pisoni, 2003). Our interest in studying speech timing in these children was motivated by several recent findings reported by Cowan and his colleagues who have carefully measured the response latencies and interword durations during recall tasks in children of different ages.

In one study of immediate recall, Cowan et al. (1994) found that interword pause times provided a reliable measure of the dynamics of the memory scanning and retrieval process during development. Their results showed that children's interword pauses in immediate recall increased as list length increased. This finding supports Cowan's earlier (1992) proposal that serial scanning is carried out during the pauses. Recall of longer lists requires that more items have to be scanned serially, therefore prolonging interword pause time. Additional evidence showing that items in short-term memory are scanned during interword pauses was obtained in another study by Cowan et al. (1998) who found that children with shorter interword pauses also had longer immediate memory spans.

Cowan et al. (1998) also reported that older children have shorter pause durations in immediate recall than younger children. Taken together, their results on speech timing suggest that the memory span increases observed in older children might be associated with both shorter interword pauses during serial recall and faster speaking rates. Shorter interword pauses indicate that the scanning mechanisms used to retrieve items from short-term memory are executed faster and more efficiently in the older children. Combined with increases in articulation speed, this factor may enhance the ability to engage in efficient verbal recall strategies as children develop. These findings on speech timing in immediate memory tasks led Cowan and his colleagues to propose that two processing operations —serial scanning and retrieval of items from short-term memory and subvocal verbal rehearsal of phonological information are used by typically developing children in recall and both of these factors affect measures of working memory capacity (Cowan, 1999; Cowan et al., 1998).

Recently, we obtained several measures of speech-timing during immediate recall from a group of deaf children who use cochlear implants (see Burkholder & Pisoni, 2003). Measures of speaking rate and speech timing were also obtained from an age-matched control group of normal-hearing, typically developing children. Articulation rate and subvocal rehearsal speed were measured from sentence durations elicited using meaningful English sentences. Relations between articulation rate and working memory in each group of children were compared to determine how verbal rehearsal processes might differ between the two populations. To assess differences in speech timing during recall, response latencies, durations of the test items, and interword pauses were measured in both groups of children.

For the analysis of the speech-timing measures during recall, we analyzed only the responses from the digit span forward condition. Analysis of the speech-timing measures obtained during recall revealed no differences in the average duration of articulation of the individual digits or response latencies at any of the list lengths. There was no correlation between the average articulations taken from digit span forward and forward digit span scores when all children were considered together or when the children were evaluated in groups according to hearing ability or communication mode.

However, we found that interword pause durations in recall differed significantly among the groups of children. The average of individual pauses that occurred during recall in the forward condition was significantly longer in the deaf children with cochlear implants than in the normal-hearing children at list lengths three and four.

The results of this study replicated our previous findings showing that profoundly deaf children with cochlear implants have shorter digit spans than their normal-hearing peers. As expected, deaf children with cochlear implants also displayed longer sentence durations than normal-hearing children. Total communication users displayed slower speaking rates and shorter forward digit spans than the oral communication users. In addition to producing longer sentence durations than normal-hearing children, the deaf children with cochlear implants also had much longer interword pause durations during recall. Longer interword pauses are assumed to reflect slower serial scanning processes which may affect the retrieval of phonological information in short-term memory (Cowan, 1992; Cowan et al., 1994). Taken together, the pattern of results indicates that both slower subvocal rehearsal and serial scanning are associated with shorter digit spans in the deaf children with cochlear implants.

The overall pattern of speech-timing results found in both groups of children is quite similar to the findings reported by Cowan et al. (1998) with normal-hearing children. Their findings suggest that covert verbal rehearsal and the speed of serial scanning of items in short-term memory are two factors that affect immediate memory span in normal-hearing children. Cowan et al. also found that children who were faster at subvocal verbal rehearsal and serial scanning displayed longer immediate memory spans than children who executed these processes more slowly. However, his findings were obtained from typically developing normal-hearing children who differed only in chronological age.

Comparable results were observed in our study using children of similar chronological ages but with quite different developmental histories that reflect the absence of sound and early auditory experience during critical periods of perceptual and cognitive development. The effects of early auditory and linguistic experience found by Burkholder and Pisoni (2003) suggest that the development of subvocal verbal rehearsal and serial scanning processes may not only be related to maturationally-based milestones that are cognitively or metacognitively centered, such as the ability to effectively organize and utilize these two processes in tasks requiring immediate recall. Rather, efficient subvocal verbal rehearsal strategies and scanning abilities also appear to be experience- and activity-dependent reflecting the development of neural mechanisms used in speech perception and speech production.

Because the group of deaf children examined in the Burkholder and Pisoni (2003) study fell within a normal range of intelligence, the most likely developmental factor responsible for producing slower verbal rehearsal speeds, scanning rates, and shorter digit spans is an early period of auditory and linguistic deprivation prior to receiving a cochlear implant. Sensory deprivation may result in widespread developmental brain plasticity and neural reorganization, further differentiating deaf children's perceptual and cognitive development from the development of normal-hearing children (Kaas, Merzenich & Killackey, 1983; Shepard & Hardie, 2001). Brain plasticity affects not only the development of the peripheral and central auditory systems but other higher cortical areas as well, both before and after cochlear implantation (Ryugo, Limb, & Redd, 2000; Teoh, Pisoni & Miyamoto, in press a, b).

Discussion and Conclusions

Our recent findings on speech perception and working memory provide some new insights about the elementary information processing skills of deaf children with cochlear implants and the underlying cognitive and linguistic factors that affect the development of their speech and language skills on a range of outcome measures. These studies were specifically designed to obtain new process measures of performance that assessed the operation of verbal working memory in order to understand the nature of the capacity limitations in encoding and processing phonological information. Several important findings have emerged from our analysis of the memory span data suggesting that working memory capacity, verbal rehearsal speed and scanning processes in short-term memory contribute additional unique sources of variance to the outcome measures obtained with deaf children following cochlear implantation. The pattern of digit span scores, measures of speaking rate and speed of scanning of items in short-term memory clearly demonstrate the presence of atypical development of short-term working memory capacity in these deaf children. It also supports our initial hypothesis that cognitive processing variables contribute to the large individual differences observed in a range of outcome measures used to assess speech and language performance in these children.

The only demographic variable that was correlated with these cognitive processing measures was the child's communication mode. Deaf children who were immersed in oral-only environments displayed longer forward digit spans, faster speaking rates and more efficient scanning of short-term memory than the children who were in total communication environments. The presence of selective effects of early sensory experience on working memory suggests that the stimulus environment and the specific kinds of activities and experiences that children have with their parents and caretakers in the language learning environment operate in a highly selective manner on a specific information processing mechanism and subcomponent of the human memory system that is used for encoding, maintaining and retrieving phonological information in short-term memory. We suspect there may be something unique about the oral environment and the specific experiences and activities that the child engages in on a regular basis that produces selective effects on verbal rehearsal and phonological coding of speech signals.

Because children from total communication environments may simply have less exposure to speech and spoken language in their early linguistic environment after receiving their implant than oral children, they may display problems in both processing and actively rehearsing phonological information in short-term memory. In terms of initial encoding and recognition, the reduced exposure to speech and spoken language may affect the development of automatic attention and specifically the speed with which speech signals can be rapidly identified and encoded into stable phonological representations in short term memory. Thus, total communication children may have fundamental problems in scanning and retrieving phonological information in short-term memory. In terms of verbal rehearsal, total communication children may have slower and less efficient verbal rehearsal processes once information gets into short-term memory simply because they have had less experience than oral children in producing speech and actively generating phonological patterns.

Passive exposure to speech without explicit analysis and conscious manipulation of phonological representations may not be sufficient to develop robust lexical representations of spoken words and fluency in control of speech production. Deaf children who receive cochlear implants may need to be actively engaged in processing spoken language in order to develop automaticity and automatic attention strategies that can be carried out rapidly without conscious effort or processing resources. This may be one direct benefit of auditory-oral education programs. The excellent spoken language skills acquired by children in these programs may reflect the development of highly automatized phonological analysis skills which permit the child to engage in active processing strategies in perception that involve “decomposition” of a speech pattern into a sequence of discrete phonological units and then the “reassembly” of those individual units into sequences of gestures and sensory-motor patterns for use in speech production and articulation.

The development of automatized phonological processing skills may result in increases in the speed and efficiency of constructing phonological and lexical representations of spoken words in working memory. Recovering the internal structure of an input pattern in speech perception as a result of perceptual analysis and then reconstructing the same pattern in speech production may serve to establish permanent links between speech perception and production and may lead to further development of highly efficient sensory-motor articulatory programs for verbal rehearsal and coding of words in working memory. Thus, the development of phonological processing skills may simply be a byproduct of the primary emphasis on speech and oral language skills in oral-only educational environments and may account for why these children consistently display better performance on a wide range of outcome measures of speech and language.

The present set of findings permits us to identify a specific information processing mechanism, the verbal rehearsal process in working memory that is responsible for the limitations on processing capacity. Processing limitations are present in a wide range of clinical tests that make use of verbal rehearsal and phonological processing skills to encode, store, maintain and retrieve spoken words from working memory. These fundamental information processing operations are components of all of the current clinical outcome measures routinely used to assess receptive and expressive language functions. Our findings suggest that the variability in performance on the traditional clinical outcome measures used to assess speech and language processing skills in deaf children after cochlear implantation may simply reflect fundamental differences in the speed of information processing operations such as verbal rehearsal, scanning of items in short-term memory and the rate of encoding phonological and lexical information in working memory.

We believe these new results are clinically and theoretically significant because they suggest a motivated theoretically-based explanation for the enormous variability and individual differences observed in a range of speech and language processing tasks that make use of the same verbal rehearsal processes. As in normal-hearing typically-developing children, the present findings suggest that differences in verbal rehearsal speed may be the primary factor that is responsible for the large individual differences in speech and language development observed in deaf children following cochlear implantation.

References

Ackerman, P.L., Kyllonen, P.C. & Roberts, R.D. (1999). *Learning and individual differences*. American Psychological Association: Washington, DC.

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

Baddeley, A.D., Thomson, N. & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior, 14,* 575-589.

Ball, G.F. & Hulse, S.H. (1998). Birdsong. *American Psychologist, 53,* 37-58.

Bench, J., Kowal, A., & Bamford, J. (1979). The BKB (Bamford-Kowal-Bench) sentence lists for partially-hearing children. *British Journal of Audiology, 13,* 108-112.

Bergeson, T. & Pisoni, D.B. (2004). Audiovisual speech perception in deaf adults and children following cochlear implantation. In G. Calvert, C. Spence & B.E. Stein (Eds.), *Handbook of Multisensory Integration,* (pp. 749-772). Cambridge: MIT Press.

Burkholder, R. & Pisoni, D.B. (2003). Speech timing and working memory in profoundly deaf children after cochlear implantation. *Journal of Experimental Child Psychology, 85,* 63-88.

Carpenter, P.A., Miyake, A. & Just, M.A. (1994). Working memory constraints in comprehension. In M.A. Gernsbacher (Ed.) *Handbook of Psycholinguistics*, (pp. 1075-1122). San Diego: Academic Press.

Clarke, G. (2003). *Cochlear Implants: Fundamentals and Applications*. New York: Springer-Verlag.

Cowan, N. (1992). Verbal memory and the timing of spoken recall. *Journal of Memory and Language*, *31*, 668-684.

Cowan, N. (1999). The differential maturation of two processing rates related to digit span. *Journal of Experimental Child Psychology, 72*, 193-209.

Cowan, N., Keller, T., Hulme, C., Roodenrys, S., McDougall, S., & Rack, J. (1994). Verbal memory span in children: Speech timing clues to the mechanisms underlying age and word length effects. *Journal of Memory and Language, 33*, 234-250.

Cowan, N., Wood, N.L., Wood, P.K., Keller, T.A., Nugent, L.D. & Keller, C.V. (1998). Two separate verbal processing rates contributing to short-term memory span. *Journal of Experimental Psychology: General, 127,* 141-160.

Ericsson, K.A., & Smith, J. (1991). *Toward a general theory of expertise: Prospects and limits*. New York, NY: Cambridge University Press.

Gathercole, S., & Baddeley, A. (1990). Phonological memory deficits in language disordered children: Is there a causal connection? *Journal of Memory and Language, 29*, 336-360.

Gathercole, S.E., Hitch, G.J., Service, E. & Martin, A.J. (1997). Phonological short-term memory and new word learning in children. *Developmental Psychology, 33,* 966-979.

Gupta, P. & MacWhinney, B. (1997). Vocabulary acquisition and verbal short-term memory: Computational and neural bases. *Brain and Language, 59,* 267-333.

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

Kaas, J. H., Merzenich, M.M., & Killackey, H.P. (1983). The reorganization of somatosensory cortex following peripheral nerve damage in adult and developing mammals. *Annual Review of Neuroscience,* 6, 325-356.

Kirk, K.I., Pisoni, D.B., & Miyamoto, R.T. (2000). Lexical discrimination by children with cochlear implants: Effects of age at implantation and communication mode. In Waltzman, S.B., & Cohen, N.L. (Eds.), *Cochlear Implants,* (pp. 252-254). New York: Thieme.

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

Kluck, M., Pisoni, D.B. & Kirk, K.I. (1997). Performance of normal-hearing children on open-set speech perception tests. *Progress Report on Spoken Language Processing #21*, Indiana University, Department of Psychology, Bloomington, IN.

Konishi, M. (1985). Birdsong: From behavior to neuron. *Annual Review of Neuroscience, 8,* 125-170.

Konishi, M., & Nottebohm, R. (1969). Experimental studies in the ontogeny of avian vocalizations. In R.A. Hinde (Ed.), *Bird Vocalizations,* (pp. 29-48). New York: Cambridge University Press.

Luce, P.A., & Pisoni, D.B. (1998). Recognizing spoken words: The neighborhood activation model. *Ear and Hearing, 19,* 1-36.

Marler, P., & Peters, S. (1988). Sensitive periods for song acquisition from tape recordings and live tutors in the swamp sparrow, Meiosis georgiana. *Ethology, 77,* 76-84.

McGarr, N.S. (1983). The intelligibility of deaf speech to experienced and inexperienced listeners. *Journal of Speech and Hearing Research, 26,* 451-458.

Meyer, T.A. & Pisoni, D.B. (1999). Some computational analyses of the PBK Test: Effects of frequency and lexical density on spoken word recognition. *Ear & Hearing, 20,* 363-371.

Osberger, M.J., Miyamoto, R.T., Zimmerman-Phillips, S., et al. (1991). Independent evaluations of the speech perception abilities of children with the Nucleus 22-channel cochlear implant system. *Ear Hearing, 12,* 66-80.

Pisoni, D.B. & Cleary, M. (2003). Measures of working memory span and verbal rehearsal speed in deaf children after cochlear implantation. *Ear & Hearing, 24,* 106S-120S.

Pisoni, D.B., Cleary, M., Geers, A.E. & Tobey, E.A. (2000). Individual differences in effectiveness of cochlear implants in prelingually deaf children: Some new process measures of performance. *Volta Review, 101*, 111-164.

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

Robbins, A.M., Renshaw, J.J., Miyamoto, R.T., Osberger, M.J., & Pope, M.L. (1988). *Minimal pairs test.* Indianapolis, IN: Indiana University School of Medicine.

Rosen, V.M. & Engle, R.W. (1997). Forward and backward serial recall. *Intelligence, 25,* 37-47.

Ross, M., & Lerman, J. (1979). A picture identification test for hearing-impaired children. *Journal of Speech and Hearing Research, 13,* 44-53.

Rudel, R.G. & Denckla, M.B. (1974). Relation of forward and backward digit repetition to neurological impairment in children with learning disability. *Neuropsychologia, 12,* 109-118.

Ryugo, D., Limb, C., & Redd, E. (2000). Brain Plasticity: The impact of the environment on the brain as it relates to hearing and deafness. In J. Niparko (Ed.), *Cochlear Implants, Principles and Practices,* (pp. 33-56). Philadelphia: Lippincott Williams & Wilkins.

Sharma, A, Dorman, M.F. & Spahr, A.J. (2002) A sensitive period for the development of the central auditory system in children with cochlear implants: Implications for age of implantation. *Ear & Hearing, 23*, 532-539.

Shepard, R.K. & Hardie, N. (2001). Deafness-induced changes in the auditory pathway: Implications for cochlear implants. *Audiology and Neuro-Otology, 6*, 305-318.

Svirsky, M.A., Robbins, A.M., Kirk, K.I., Pisoni, D.B. & Miyamoto, R.T. (2000). Language development in profoundly deaf children with cochlear implants. *Psychological Science, 11,* 153-158.

Teoh, S.W., Pisoni, D.B. & Miyamoto, R.T. (In press, a). Cochlear implantation in adults with prelingual deafness: I. Clinical results. *Laryngoscope.*

Teoh, S.W., Pisoni, D.B. & Miyamoto, R.T. (In press, b). Cochlear implantation in adults with prelingual deafness: II. Underlying constraints that affect audiological outcomes. *Laryngoscope.*

Tobey, E. A., Geers. A. E., Morchower, B., Perrin, J., Skellett, R., Brenner, C., & Torretta, G. (2000). Factors associated with speech intelligibility in children with cochlear implants. *Annals of Otology, Rhinology and Laryngology Supplement, 185,* 28-30.

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

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