Some New Findings on Learning, Memory and Cognitive Processes in Deaf Children Following Cochlear Implantation[1]

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[1] This work was supported by NIH-NIDCD Training Grant T32 DC00012 and NIH-NIDCD Research Grants R01 DC00111, NIH NIDCD R01 DC00064 to Indiana University and NIH Research Grant R01 DC03100 to Central Institute for the Deaf. We would like to thank Tonya Bergeson, Steven Chin and Karen Iler Kirk for comments on an earlier version of this paper. This is a draft of a chapter to appear in F.G. Zeng, A.N. Popper & R.R. Fay (Eds.), *Handbook of Auditory Research: Auditory Prostheses*.

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Abstract. The present chapter reports new findings on learning, memory and cognitive processes in deaf children following cochlear implantation that attempt to account for the large individual differences in acquisition of aural/oral language skills in this clinical population. The role of known contributing demographic factors is briefly reviewed and the need for further process measures of performance is presented. Perception, attention, memory, and learning in normal language development are discussed. It is suggested that these specific cognitive processes should be studied in greater detail in this clinical population in order to explain the enormous variability in spoken language acquisition. Results from two new data sets are presented and discussed. In the first study, results from an investigation of the "Stars," deaf children who do exceptionally well with their implant is presented and discussed. The exceptionally good implant users differed from the poorer implant users in several ways related to their ability to rapidly encode sound patterns into phonological representations in working memory and coordinate receptive verbal abilities with expressive language skills. Using supporting literature on typically-developing children, it is argued that a cognitive processing factor having to do with fast and efficient encoding, maintenance, and retrieval of phonological information in short-term is what enables the better-performing implant users to take advantage of this coordinated linguistic system. The second set of studies involved implanted children who showed a more typical range of abilities. Results from a variety of new measures of information processing performance are reported along with data from age-matched normal-hearing children and normal-hearing adults. Within the group of deaf children who use cochlear implants, speaking rate, a measure shown in other populations to correlate well with an individual's rehearsal speed for items in immediate memory was found to be strongly correlated with measures of a child's short-term memory capacity as well as his auditory-only spoken word recognition performance. Finally, additional evidence is presented suggesting atypical short-term memory spans for auditory as well as visual sequences in at least some deaf children with cochlear implants. Data from a novel sequence-learning task revealed that deaf children with cochlear implants also show less than expected benefit from the repetition of familiarized sequences. These new findings on learning, memory and cognitive processes suggest that variation in children's success with cochlear implants may reflect differences in the operation of basic information processing skills used in a wide range of language processing tasks that draw on verbal rehearsal processes used in working memory.

Introduction

Cochlear implants work reasonably well in many profoundly deaf adults and children. For these patients, a cochlear implant is a form of intervention, an alternative way of providing access to sound via electrical stimulation of the auditory system. For the post-lingually deafened adult, a cochlear implant serves primarily as a sensory aid to restore lost hearing and regain contact with the world of sound as they knew it before the onset of deafness. In contrast, for the prelingually deaf child, the electrical stimulation provided by a cochlear implant represents the introduction of a new sensory modality and an additional way to acquire knowledge about sound, sound sources and the correlations between objects and events in the environment. Perhaps the most important benefit of a cochlear implant, however, is that it provides the prelingually deaf child with access to information about speech and spoken language. Because speech is a multi-modal event, the electrical stimulation provided by the cochlear implant also provides the child with a rich source of new information about the cross-modal relations between the auditory and optical correlates of speech that reflect the common underlying articulatory gestures of the talker. Finally, a cochlear implant provides the deaf child with auditory feedback about the consequences of his own vocal articulation in speech production that affects the development of speech and language acquisition after implantation.

Despite the success of cochlear implants in many deaf patients, enormous individual differences have been reported in adults and children on a wide range of outcome measures. This finding is observed in all research centers around the world. Some patients do extremely well with their cochlear implants while others derive only minimal benefits after receiving their implants. Understanding the reasons for the variability in outcomes and the large individual differences following cochlear implantation is one of the most important and challenging research problems in the field today. It is not immediately obvious why some patients do well while others struggle and achieve only small benefits after receiving a cochlear implant. Many factors may be responsible for these differences, and numerous complex interactions among these factors should be explored.

Our initial interest in studying individual differences in children following cochlear implantation came from several reports in the literature demonstrating that a small number of deaf children displayed exceptionally good performance with their cochlear implants. They appeared to acquire spoken language quickly and easily and seemed to be on a developmental trajectory that paralleled children with normal hearing. These children are often called “Stars,” and until recently their exceptionally good performance appeared to be an anomaly to many clinicians and researchers.

The finding that some deaf children with cochlear implants display exceptionally good performance can be taken, at first glance, as an “existence proof” for the efficacy of cochlear implants: cochlear implants work well with some children and they facilitate the processes of speech perception and language development. The major problem, however, is that cochlear implants do not work well with <u>all</u> children, and some children derive only minimal benefits from their implants. Why does this occur? What sensory, perceptual, cognitive and environmental factors are responsible for the differences in performance among deaf children with cochlear implants? These are the major questions that we have focused our research on over the last few years.

Our theoretical motivation for studying individual differences following cochlear implantation is based on an extensive body of research in the field of Cognitive Psychology over the last twenty-five years on “expertise” and “expert systems” theory (see Ericsson & Pennington, 1993). Many important new 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 reading, and even chicken-sexing (see Biederman & Shiffrar, 1987).

The rationale underlying our approach is quite straightforward. If we can learn more about the exceptionally good users of cochlear implants and the reasons why they do so well, perhaps we can use this information to develop new intervention techniques with children who are not benefiting from their implants. Knowledge and understanding of the exceptionally good users, the “Stars,” might also be useful for developing new pre-implant predictors of performance, modifying current criteria for candidacy and creating better methods of assessing performance and measuring outcome and benefit after implantation. Thus, there are many important clinical benefits that might result from research on individual differences in these particular children.

The variability in outcomes and the large individual differences following cochlear implantation also have implications for several important theoretical issues dealing with neural plasticity and development. Deaf children who receive cochlear implants have been deprived of sound input for some length of time after birth and their nervous systems have continued to develop in the absence of "normal" sensory stimulation during the critical period for language learning. These children represent a unique clinical population to study because they can provide important new information about the effects of early auditory deprivation on cognitive and linguistic development. What happens to the nervous system and brain of these children as a result of deafness and lack of auditory stimulation over this period of time? Can their atypical pattern of development be modified or reversed after the introduction of sound?

At the present, we know that a small number of demographic factors are strongly associated with a variety of speech and language development outcome measures in these children. However, the investigation of "higher-level" perceptual, cognitive and linguistic factors has not received very much attention until recently. One reason for our lack of knowledge about cognitive processes is that most of the clinical research on cochlear implants over the last 10-15 years has been carried out by audiologists and speech-language pathologists who have been concerned primarily with questions of device "efficacy" and assessment of outcome. Their primary interests have been focused on demonstrating that cochlear implants work and provide benefit to deaf patients. Historically, these researchers have had little if any interest in variation and individual differences in performance. Research on treatment efficacy requires well-defined assessment measures of outcome performance that are familiar to surgeons and clinicians who work with deaf patients. In contrast, research on variability and individual differences in performance deals with a somewhat different problem, namely the clinical "effectiveness" of cochlear implants, that is, explaining why cochlear implants do not work well in all patients who receive them.

Interest in individual differences following cochlear implantation has also become a high priority of the federal government, which funds basic and clinical research on hearing and deafness. In 1995, the National Institute of Health published a "Consensus Statement on Cochlear Implants in Adults and Children" to provide clinicians with an up-to-date summary of the benefits and limitations of cochlear implants (NIH, 1995). The NIH 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 panel focused on the wide variation in outcome measures in implant users and recommended that additional basic and clinical research be carried out on individual differences in both adults and children. The panel also suggested that new methods and tools should be developed 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 suggests that "central" auditory, cognitive and linguistic factors may be responsible for some of the variability and individual differences observed in traditional outcome measures (see Pisoni, 2000; Pisoni et al., 2000). Although the NIH Consensus Statement on cochlear implants mentioned "central" auditory factors, the report was not very specific about precisely what these factors might be or what role higher-level cognitive processes might play in outcome measures.

In this chapter, we present a summary of recent findings that suggest that the observed individual differences in outcome following implantation are related to central cognitive factors associated with perception, attention, memory, learning and language processing. These new findings are encouraging and suggest additional directions for future research on the effects of early sensory experience and language development in children following cochlear implantation. New process measures of performance have revealed the contribution of working memory, rehearsal and coding processes to several outcome measures of speech and language development (e.g., measures of open-set word recognition and tasks requiring the use of phonological processing skills). Recent findings also suggest that the particular form of learning that occurs following cochlear implantation may be "domain-specific" and may be related to processing sound sequences and coding speech signals into phonological representations in working memory. These phonological representations form the basic building blocks of spoken language processing that are used in word recognition, comprehension and speech production.

Effectiveness of Cochlear Implants: Five Key Findings

Five key findings have been consistently reported in the literature on cochlear implants in deaf children. These findings suggest that the investigation of central auditory factors may provide new insights into the enormous variability in outcome and benefits observed following cochlear implantation. Knowledge and understanding of the cognitive factors responsible for these individual differences should be useful in helping patients obtain optimal benefits from their cochlear implants. In this section, we briefly review the five key findings that serve as the starting point for the research presented in this chapter. Then we summarize the major assumptions of the information processing approach to cognition that has guided our research program on developing new process measures of performance.

Individual Differences in Outcome and Benefit

Large individual differences in outcome and benefit following implantation are well documented in the clinical literature. However, all current outcome measures of performance are the final end product of a large number of complex sensory, perceptual, cognitive and linguistic processes that contribute to the observed variation among cochlear implant users. Until our recent studies on working memory in pediatric implant users, no research had focused on "process" or examined the underlying psychological and cognitive processes used to perceive and produce spoken language. Understanding these central cognitive processes already has provided new insights into the basis of individual differences and may help in developing new intervention techniques that can be used with patients who are deriving only minimal benefits from their implants. Four other findings have also been consistently reported in the literature on cochlear implants in children. These findings place several additional constraints on the problem of individual differences following cochlear implantation.

Age of Implantation and Length of Deafness

Age of implantation and length of deafness have both been found to affect a range of outcome measures. Children who receive an implant at an early age do consistently better on all of the clinical outcome measures than children who are implanted at older ages. Moreover, children who have been deprived of sound stimulation for shorter periods of time also do much better on a variety of outcome measures than children who have been deaf for longer periods of time. Both findings – age of implantation and length of deafness -- demonstrate the role of sensitive periods in development and the close links between neural development and behavior, especially the sensory and cognitive processes underlying hearing, speech and language development (Ball & Hulse, 1998; Konishi, 1985; Konishi & Nottebohm, 1969; Marler & Peters, 1988).

Effects of Early Experience

The nature of the early sensory and linguistic experience after implantation also has been found to affect performance on a wide range of outcome measures. Implanted children in "Oral-only" communication environments do much better on standardized tests of speech, language and vocabulary development than implanted children in "Total Communication" programs (Kirk, Pisoni, & Miyamoto, 2000). The differences in performance between these two groups of children as a function of "communication mode" are seen most clearly in receptive and expressive language tasks that make use of phonological processing skills such as open-set word recognition, language comprehension and measures of speech production, especially measures of a child's speech intelligibility and expressive language development (Cullington et al., 2000; Hodges et al., 1999; Kirk et al., in press; Svirsky, Sloan, Caldwell & Miyamoto, 2000).

Lack of Preimplant Predictors of Outcome

Until recently, researchers have been unable to identify any reliable behavioral preimplant predictors of outcome and success in children with cochlear implants (see Tait, Lutman & Robinson, 2000). The lack of reliable preimplant predictors in children is an important finding because it suggests the operation of complex interactions between the newly acquired sensory and perceptual capabilities of a child after a period of sensory deprivation, properties of the language-learning environment and the interactions with parents and caregivers that the child is exposed to early on after receiving a cochlear implant. More importantly, the absence of reliable preimplant predictors of outcome makes it difficult to identify in a timely manner, those children who may benefit from specific interventions to improve their speech and language processing skills.

"Emergence" of Abilities After Implantation

When all of the outcome and demographic measures are considered together, the current evidence suggests that the underlying sensory and perceptual abilities for speech and language "emerge" after implantation and that performance with a cochlear implant improves over time. Because the outcome and benefit of cochlear implantation cannot be predicted reliably from current pre-implant behavioral measures, improvement in performance observed after implantation is assumed to be due to learning and memory processes that are related in complex ways to maturational changes in neural and perceptual development and exposure to the target language in the child's immediate environment.

Taken together, the effects of demographic variables on outcome measures after cochlear implantation suggest several general conclusions about how cochlear implants facilitate the acquisition and development of spoken language. The findings also point to several underlying factors that may account for individual differences on various outcome measures. Although some proportion of the total variance in outcome 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, additional sources of variance may also come from more central "cognitive" factors. These additional sources of variance have to do with information processing operations and cognitive demands—that is, how the child uses the initial sensory input that is received from the cochlear implant and how the language-learning environment modulates, shapes and facilitates this learning process. Investigation of the encoding, rehearsal, storage and retrieval of information may provide some new insights into the underlying basis of the large individual differences in outcome measures of speech and language development.

To gain a better understanding of what deaf children are learning via their cochlear implants and how they use sound input, we have adopted a different theoretical perspective which looks more closely at the content and flow of information within the nervous system and how it changes over time following implantation. Our research on cochlear implants in children focuses on the underlying psychological and linguistic processes that mediate speech perception and production (see Pisoni, 2000).

Little, if any, of the previous research on cochlear implants (CIs) has explored what the children learn after they receive their implants, how they go about the process of acquiring language or how they develop receptive and expressive language skills. Until recently, there have been very few attempts to study the process of language development in deaf children with CIs and compare their linguistic knowledge and performance with that of normal-hearing children or hearing-impaired children who use hearing aids (Miyamoto et al., 1997; Robbins & Kirk, 1996).

These are important new research directions that go beyond the basic questions of clinical assessment, device efficacy, and measuring benefit with traditional outcome measures; they are fundamental problems in speech and hearing sciences that deal with the "effectiveness" of cochlear implants outside the restricted conditions of the hearing clinic or the research laboratory. The exclusive reliance on assessment-based clinical research and prediction of outcome measures following cochlear implantation has changed over the last few years. Several recent papers have already reported new findings on some of these issues (Kirk et al., 1997; Pisoni, Svirsky, Kirk, & Miyamoto, 1997; Robbins et al., 1998; Zwolan et al., 1997) and other studies are currently underway at a number of research centers around the world.

Information Processing Approach to Cognition

In order to pursue these new research questions and to move beyond the study of demographics and issues surrounding clinical assessment and prediction of outcome measures, it has become necessary to look to other allied disciplines for guidance. New experimental methods and behavioral techniques are available to study individual differences and the emergence of fundamental underlying cognitive and neural processes and how these change over time after implantation. Many useful experimental procedures already have been developed by cognitive and developmental psychologists to study perception, attention, learning and memory in children within the framework of human information processing (Haber, 1969; Lachman et al., 1979; Neisser, 1967). More importantly, this theoretical approach has also provided a variety of conceptual tools for thinking about the structures and processes involved in cognitive activity and the underlying psychological phenomena (Lindsay & Norman, 1977; Reitman, 1965).

Learning, Memory and Cognition Viewed as Information Processing

Information Processing Approach

The foundational assumption of our approach to understanding and explaining the variation and individual differences in speech and language outcome measures has been to view the human nervous system as an information processor. An information processor is a system that encodes, stores and manipulates various types of symbolic representations. Information can exist in several different forms at a number of levels of representation in the system, ranging from early registration and encoding of the sensory input to permanent storage of symbolic representations in long-term memory.

By viewing human cognition and traditional areas of basic research such as sensation, perception, attention, memory and learning as information processing within a larger integrated framework, cognitive scientists have obtained several important benefits. These include the development of new tools and experimental methodologies to study the processes that underlie these behaviors as well as the availability of a new theoretical conceptualization that can be used to explain and predict variability in complex higher-level behaviors such as speech and language in different clinical populations. The information processing approach to human cognition has also provided the theoretical motivation for reformulating some long-standing problems as well as identifying new research questions that can be studied within this framework. These research efforts have provided new insights into human performance and the neural and cognitive processing mechanisms that underlie these different behaviors.

Although there are many good clinical reasons to study prelingually deaf children who have received cochlear implants and to understand the basis for the variability in outcome measures of their speech and language skills, there are also several additional reasons to carry out research with this unique population that touch on basic theoretical issues related to neural development and behavior. For a variety of moral and ethical reasons, it is not possible to carry out sensory deprivation experiments with young children and it is not possible to delay or withhold treatment for an illness or disability that has been identified and diagnosed. Thus, for studies of this kind which are concerned with investigating the effects of early sensory experience on neural and behavioral development, it is necessary to rely on clinical populations who are receiving interventions of various kinds and hope that appropriate experimental designs can be developed which will yield new scientific knowledge.

Among the broader theoretical questions on neural and cognitive development that this research addresses are the following: What effect does the absence of sound and auditory stimulation during the first few years of life have on the development of the basic neural information processing mechanisms and skills used in speech and language processing? What effect does the introduction of sound and auditory stimulation by means of electrical hearing via a cochlear implant have on the development of speech and language processing after a period of auditory deprivation? What kind of a linguistic system (i.e., grammar) does a deaf child develop after receiving a cochlear implant? Is a deaf child's language delayed but otherwise typical of normal-hearing children or is it disordered or impaired in some fundamental way relative to normal-hearing, typically-developing, age-matched peers? These are a few of the theoretical questions this work focuses on.

Looking at the "Stars" – Analysis of the Exceptionally Good Implant Users

Several years ago, we carried out an analysis of a data set from a longitudinal project on cochlear implants in children at the Indiana University School of Medicine to gain some new insights into the basis of individual differences and variation in outcome in this clinical population (see Pisoni et al., 1997). We began first 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 after only two years of implantation. The "Stars" appeared to acquire spoken language relatively quickly and easily and seemed to be on a developmental trajectory that paralleled normal-hearing children. At first glance, they look like normal hearing and normally developing children who simply have language delays (see Svirsky et al., 2000a, b).

To learn more about the "Stars," we analyzed outcome data from the children who scored exceptionally well on the PBK test two years after receiving their implant. The PBK test is an "open-set" test of spoken word recognition (see Meyer & Pisoni, 1999). Among clinicians, the PBK test is considered to be very difficult for prelingually deaf children compared to other, "closed-set" perceptual tests that are routinely used in standard assessment batteries (Kirk, Pisoni & Osberger, 1995; Zwolan, Zimmerman-Phillips, Asbaugh, Hieber, Kileny & Telian, 1997). Open-set tests of speech perception measure word recognition and lexical discrimination and require the child to search and retrieve the phonological representations of the test words from their lexical memory. These particular types of word recognition tests are extremely difficult for hearing-impaired children and adults with cochlear implants because the procedures 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. Basically, the listener is required to discriminate, select and then identify a unique phonological pattern from a very large number of equivalence classes in lexical memory (see Luce & Pisoni, 1998).

The PBK score was used as the “criterial variable” to initially identify and select two groups of children for subsequent analysis using an extreme groups design. 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 second set of children were selected as a comparison group. 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 these children were selected and sorted into two groups based on PBK scores, we examined their performance on a variety of other outcome measures already obtained from them as part of our large-scale longitudinal project. These outcome measures included tests of speech perception, language comprehension, word recognition, receptive vocabulary knowledge, receptive and expressive language development and speech intelligibility scores. Descriptive analyses were carried out first to compare differences between the two groups on these measures. Then correlations were computed among the various outcome measures to look at relationships and commonalities between the measures.

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 better performance on some outcome measures such as speech perception, language comprehension, spoken word recognition and speech intelligibility than the control group, the two groups of children did not differ from each other on measures of receptive vocabulary knowledge, non-verbal intelligence, visual-motor integration or visual attention (see Pisoni et al., 1997). We also found that some outcome measures of performance continued to improve over the course of six years, whereas other outcome measures remained fairly stable after the first year.

These findings demonstrate that the “Stars” differ in selective ways from the comparison group of control subjects. Whatever differences are revealed by other descriptive measures, it is clear that the results are not due to some global difference in overall performance levels between the two groups. More importantly, we found that the “Stars” also displayed exceptionally good performance on another test of spoken word recognition, the LNT (Kirk et al., 1995), demonstrates that the superior lexical discrimination skills of these children are not due to the specific words on the PBK test or the particular methods used to administer the test. Instead, the differences appear to be related to a common set of information processing operations and procedures that are used by these children to carry out open-set word recognition tasks. Among the component elementary information-processing skills needed for this task are encoding, storage, rehearsal, imitation and speech production. These are the same basic skills that are used in all of the traditional clinical outcome measures used to assess performance in these children after implantation.

The results of our correlational analyses of the test scores for the “Stars” one year after implantation revealed a consistent pattern of strong and significant intercorrelations among several of the dependent variables, particularly measures of word recognition, language development and speech intelligibility, suggesting a common underlying source of variance that is shared by these measures (see Pisoni et al., 1997). The same patterns of intercorrelations were not observed for the comparison group. One common source of variance found in the correlational analyses of the “Stars” was related to the processing of spoken words and to the encoding, storage and rehearsal of the phonological representations of words.

Of particular interest was the unexpected finding of strong correlations of several outcome measures with speech intelligibility scores obtained for these children, suggesting transfer of knowledge between speech perception and production and the use of a common shared representational system for receptive and expressive language functions (see also Shadmehr & Holcomb, 1997). The results suggested that the exceptionally good performance of the "Stars" may be due to their superior spoken language processing abilities, specifically, their ability to perceive, encode and retrieve phonological representations of spoken words from lexical memory and use these linguistic representations in a variety of different language processing tasks, especially tasks that depend on the decomposition and re-assembly of the sound patterns of spoken words such as lexical retrieval, rehearsal and speech production. Our working hypothesis was that this particular source of variance might reflect "modality-specific" elementary information processing operations that are involved in the phonological coding of sensory inputs and the construction of phonological representations of spoken language.

While the results of our initial correlational analyses point to several new directions for future research on individual differences, the data available on these children were based on traditional outcome measures that were collected as part of the annual assessments in our longitudinal study. All of the scores on these tests are "endpoint measures" of performance, and as such they reflect the final product of perceptual and linguistic analysis. Process measures of performance, that is, measures of what a child does with the sensory information provided by his cochlear implant, were not part of the standard research protocol so it was impossible to investigate differences in speed, fluency or processing capacity. It is very likely that fundamental differences in neural and cognitive information processing may underlie the individual differences observed between the two groups of children in our initial study.

The analyses we carried out on the speech perception, word recognition, spoken language comprehension, vocabulary knowledge and language development scores revealed that a child who displayed exceptionally good performance on the PBK test also showed very good scores on a variety of other speech and language measures as well. We consider these new results to be theoretically important. The differences in outcome measures observed between the two groups suggested that it may be possible to determine more precisely how the "Stars" differ from the minimal benefit cochlear implant users. 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," may be useful in helping the children who are not doing as well with their implants at an earlier point in development after implantation. Moreover, research on individual differences may have direct clinical relevance in terms of intervention in recommending specific changes to the child's language-learning environment and in modifying the nature of the interactions a child has with his parents, teachers and speech therapists, who provide the primary language model for the child. Research on individual differences may also help by 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.

The results of our analyses of the "Stars" suggested several hypotheses about the source of the individual differences in performance. The primary locus of the differences in performance on many of the speech and language-based outcome measures may be due to central rather than peripheral factors. That is, the source of the individual differences may be related to 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.

One of the key components that links these processes together and serves as the "interface" or "gateway" between the initial sensory input and stored knowledge in long-term memory is working memory. Investigations of the properties of working memory may provide new insights into the nature and locus of the individual differences observed among users of cochlear implants (see Baddeley, Gathercole, & Papagno, 1998; Carpenter, Miyake & Just, 1994; Gupta & MacWhinney, 1997). Unfortunately, at the time our analyses of the "Stars" were carried out, we did not have any memory data available to test this hypothesis. Since that time, however, several new studies have been carried out with our collaborators at the Central Institute for the Deaf (CID) in St. Louis to study working memory in children with cochlear implants (Pisoni & Geers, 2000). The results of these experiments are reported in the sections below.

At a superficial level, it seems reasonable to conclude that the children who "hear" better through their cochlear implants simply learn language better and, subsequently, recognize words better. This generalization might be appropriate as an explanation of the perceptual data obtained from outcome measures of receptive function, but it is much more difficult to explain the observed differences in speech intelligibility and expressive language simply on the basis of better hearing and language-processing skills without a more detailed description of the underlying linguistic skills and abilities used in speech production.

To account for the differences in speech intelligibility and expressive language development, it is necessary to assume that a given child has acquired an underlying linguistic system that mediates between speech perception and speech production. Without assuming a common linguistic system—a grammar—we would have no reason to expect a child's receptive and expressive language abilities to be as closed coordinated as they typically are in normal-hearing, normal-developing children. It is well known that reciprocal links exist between speech perception, production and a whole range of language-related abilities; these interconnections 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, independent of the child's developing linguistic system. Thus, explanations of the superior performance of the "Stars" framed in terms of hearing, audibility or sensory discrimination abilities cannot provide a satisfactory theoretical account of all of the results reported above or an adequate description of how early auditory experience affects speech perception and language development in these children. Some other non-sensory process must be responsible for the commonalities in speech perception and production observed across these diverse outcome measures.

In order to understand and explain the individual differences in these children, several additional performance measures are needed to assess how deaf children with cochlear implants process, code and represent the sensory, perceptual and linguistic information they receive through their implants, and how they use this information in a variety of behavioral tasks. The traditional endpoint outcome measures in our database were scores on behavioral tests used for assessment of specific speech and language skills thought to be important for measuring change and benefit after implantation. This battery of clinical tests was designed and constructed many years ago when theoretical issues about individual differences in performance were not high research priorities. As a result, no data were ever collected on cognitive processes such as memory, learning, attention, automaticity or modes of processing.

Some Measures of Information Processing Capacity

To obtain some initial measures of working memory capacity from a large number of deaf children following cochlear implantation, we were very fortunate to be able to collaborate with Ann Geers and her colleagues at CID, who already had an on-going large-scale research project underway. Their project was designed to obtain a wide range of outcome measures of speech, language and reading skills from 8 and 9 year old children who had all used their cochlear implants for at least three and one-half years. Thus, chronological age and length of implant use in the children were controlled in this study.

Using the test lists and procedures from the WISC III (Wechsler, 1991), forward and backward auditory digit spans were obtained from four groups of 8- and 9- year old deaf children with cochlear implants. A total of 176 children were tested in separate groups at CID 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. These children were tested in Bloomington, Indiana, and served as a comparison group.

The WISC-III memory span task requires the child to repeat back a list of digits as spoken live-voice by an experimenter at a rate of approximately one digit per second (WISC-III Manual, Wechsler 1991). In the "digits-forward" section of the task, the child is required to simply repeat back the list as heard. In the "digits-backward" section of the task, the child is told to "say the list backward." In both parts of the WISC task, the lists begin with two items, and are increased in length upon successful repetition until a child gets two lists incorrect at a given length, at which point testing stops. Points are awarded for each list correctly repeated with no partial credit. The task was administered using live-voice presentation with the face of the clinician visible to the child.

A summary of the digit span results for all five groups of children is shown in Figure 1. 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 separately by year of testing; the normal-hearing children are shown on the right. Each child's digit span in points is calculated by summing the number of lists correctly recalled at each list length. The points score for forward digit span can vary between zero and 16; the points score for backward digit span can vary between zero and 14.

Inspection of the data shown in Figure 1 reveals an orderly and 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 are based on separate independent groups of subjects. 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 ($p < .001$).

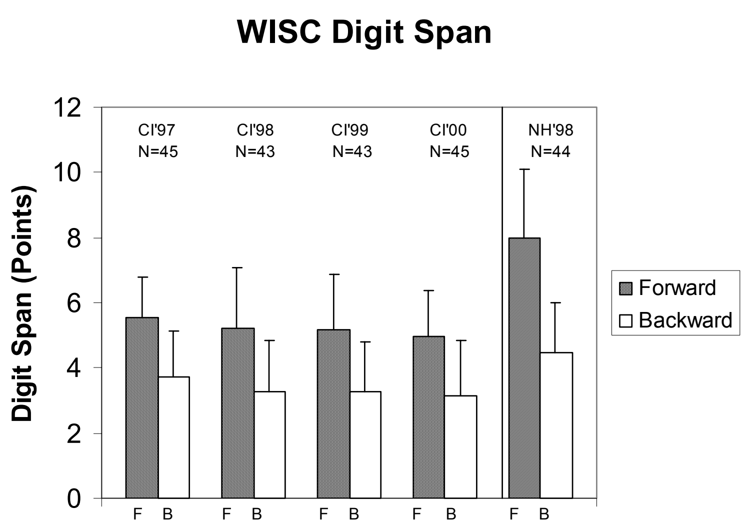


Figure 1. WISC digit spans scored by points for the four groups of 8- and 9-year old children with cochlear implants and for a comparison group of 8- and 9-year-old normal-hearing children. Forward digit spans are shown by the shaded bars, backwards digit spans by the open bars. Error bars indicate one standard deviation from the mean.

The forward and backward digit spans obtained from the 44 age-matched normal-hearing children are shown in the right-hand panel of the figure. Examination of these data shows that the digit spans for the normal-hearing children differ in several systematic ways from the digit 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 suggests atypical development of the deaf children's short-term memory capacity and points to several possible differences in the underlying processing mechanisms that are used to encode and maintain sequences of spoken digits in immediate memory.

Numerous studies over the years have suggested that forward digit spans can be used to index and assess initial 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. In contrast, differences in backward digit spans are thought to reflect the contribution of controlled attention and operation of "executive" processes used to recode, transform and manipulate verbal information for later processing operations (Rosen & Engle, 1997; Rudel & Denckla, 1974)

The digit spans for the normal-hearing children shown in Figure 1 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 rehearsal processes used in immediate memory. In particular, the forward digit spans reflect possible 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 rehearsal processes. Because all of the behavioral tasks typically used to assess clinical speech and language outcomes following implantation make use of the component processes of working memory and rehearsal, it seems reasonable to assume these tasks will also reflect variation due to individual differences in working memory and processing capacity.

Correlations with Digit Spans

In order to learn more about the observed differences in auditory digit span and the limitations in processing capacity in the children with cochlear implants, we examined the correlations between forward and backward digit spans and several speech and language outcome measures that were obtained from the same children at CID. Of the various demographic measures available, the only one that correlated strongly and significantly with digit span was a measure called "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 oral language skills by parents, teachers and therapists in the home and educational environments.

Each child's degree of exposure to Oral-only communication methods was quantified by determining the type of communication environment experienced by the child in the year just prior to implantation, each year over the first three years of CI use, and then in the year just prior to the current testing. A score was assigned to each year, ranging from a "1," corresponding to the use of "total communication" with a sign emphasis (that is, indicating extensive use of manual signs in addition to spoken language), to "6," indicating an auditory-verbal environment with a strong emphasis on auditory communication without the aid of lipreading (see Geers et al., 1999 for details). Communication methods intermediate between these two extremes were assigned intermediate scores ranging from 2 to 5. These scores were then averaged over the five points in time. The mean communication mode score for the group over the five intervals was approximately 3.9 on this 6-point scale. However, a wide range of communication mode backgrounds was present within the sample of 176 children (range of average communication mode scores = 1.0 to 6.0).

We found that forward digit span was positively correlated with Communication Mode (r= +.34, p < .001); children 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 other demographic variable.

In order to examine the effects of early experience in greater detail, a median split was carried out on the communication mode scores to create two subgroups, Oral children and TC children. Figure 2 shows the digit spans plotted separately for the Oral and TC children for each of the four years of testing at CID. Examination of the forward and backward digit spans for these two groups of children indicates that the Oral group consistently displayed longer forward digit spans than the TC group. While the differences in forward digit span between Oral and TC groups 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 selective in nature and appears to be restricted to coding and rehearsal processes that affect only the forward digit span task.

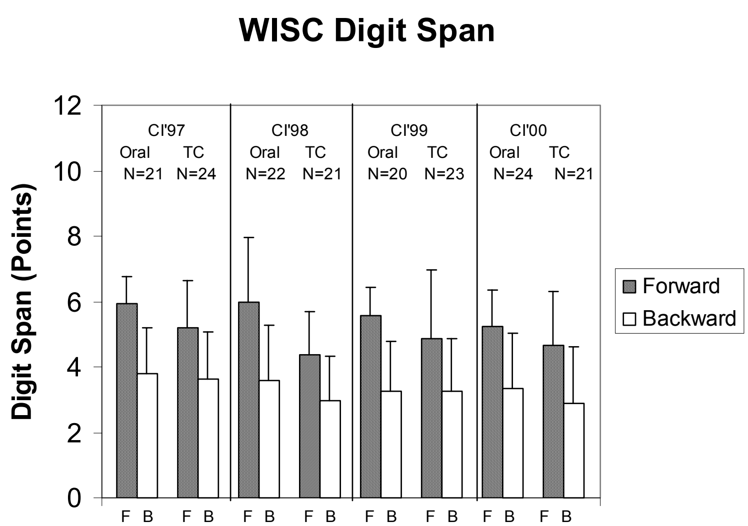


Figure 2. WISC digit spans scored by points for the four groups of 8- and 9-year old children with cochlear implants, separated by communication mode. For each year, scores for the oral group are shown to the left of those for the total communication group. Forward digit spans are shown by the shaded bars, backwards digit spans by the open bars. Error bars indicate one standard deviation from the mean.

The difference in forward digit span between Oral and TC children present for each of the four groups suggests that forward digit spans are sensitive to the nature of the early sensory and linguistic experience that the child receives immediately after cochlear implantation. The differences observed in the forward digit spans could be due to several factors, such as more efficient encoding of the initial stimulus patterns into more stable phonological representations in working memory, speed and efficiency of the rehearsal processes that are used to store and maintain information in working memory or possibly even speed of scanning and retrieval 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.

Regardless of which factor or factors are responsible for the differences observed above, these results demonstrate that forward digit span is sensitive to the effects of early sensory and linguistic experience and suggest that several specific mechanisms in the information processing system may be affected by the nature of the early experience the child receives after implantation. Although these results clearly demonstrate that early experience in an environment that emphasizes oral language skills is associated with longer digit spans and increased information processing capacities of working memory, without additional converging measures of performance, it is difficult to specify precisely what elementary 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.

Digit Spans and Word Recognition

As mentioned above in the summary of our findings on the “Stars,” the large individual differences we observed in a range of outcome measures of speech and language development appear to be related in some way to spoken word recognition skills and to tasks that make use of phonological representations of spoken words. At the time our research on the “Stars” was carried out, we did not have digit span data or any other process measures of performance from this group of deaf children. We assumed that the word recognition skills of the “Stars” would draw on the same basic component processes that are used in open-set tests of word recognition like the PBK test, which was used as the criterion variable to identify the exceptionally good implant users and sort our subject population into two extreme groups. While a number of demographic factors such as duration of deafness, length of device use and age at implantation have been shown to be related to variation in these outcome measures, these variables are only able to account for a small portion of the observed variance in performance. We reasoned that some other factor must be responsible for the wide range of performance observed in these deaf children.

Our current hypothesis is that a portion of the remaining unexplained variance can be accounted for in terms of individual differences in the elementary information processing operations that are related to the speed and efficiency with which phonological representations of spoken words are maintained and retrieved from memory after recognition and identification has taken place. Numerous studies of normal-hearing children over the past few years have demonstrated close links between verbal short-term memory and learning to recognize and understand new words (Baddeley, Gathercole, & Papagno, 1998; Gupta & MacWhinney, 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 verbal short-term working memory (e.g., specifically, measures of digit span), which can be used as estimates of processing capacity.

To determine if measures of digit span and capacity of immediate memory are related to spoken word recognition in deaf children following cochlear implantation, we examined the correlations between the WISC forward and backward digit span scores and three different measures of word recognition that were also obtained from the children tested at CID in 1997 and 1998. A summary of the correlations between digit span and word recognition scores based on these 88 children is shown in Table I for the WIPI, LNT and BKB word recognition tests.

Table I

	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)	.50***	.33**	.31**	.13
Open Set Word Recognition (LNT-E)	.54***	.31**	.33**	.10
Open Set Word Recognition in Sentences (BKB)	.56**	.37***	.35**	.12

*** $p < .001$, ** $p < .01$

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

The WIPI (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). The Lexical Neighborhood Test (LNT) is an open-set test of word recognition and lexical discrimination that requires the child to imitate and reproduce an isolated word (Kirk et al., 1995). This test is similar to the well-known PBK test, although the vocabulary on the LNT was designed to control for familiarity while lexical competition among the items was manipulated systematically to measure discrimination among phonetically similar words in the child's lexicon. Finally, the BKB test is an open-set word recognition test in which key words are presented in sentence contexts (Bench, Kowal & Bamford, 1979).

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. Examination of the correlations for both the forward and backward spans reveals that children who had longer WISC digit spans also displayed higher word recognition scores on all three tests. These correlations are all positive and reached statistical significance although the correlations of forward digit span with the word recognition scores are somewhat larger than the correlations found for the backward span.

The right-hand portion of the table shows a summary of the partial correlations among these same measures after statistically controlling for differences due to chronological age, communication mode, duration of deafness, duration of device use, age of onset of deafness, number of active electrodes and speech feature discrimination. When these seven other "contributing variables" were statistically removed from the correlational analyses, the partial correlations between digit span and word recognition scores became smaller in magnitude. However, the correlations of the forward digit span with the three word recognition scores are still positive and statistically significant while the correlations of the backward digit spans are weaker and no longer significant. These results demonstrate that children who have longer forward WISC digit spans show higher word recognition scores and that this relationship is observed for all three word recognition tests even after the other sources of variance are removed.

Forward digit span accounts for approximately 11% of the currently unexplained variance in the word recognition scores while the backward digit span accounts for only 1.4% of the variance in these scores. The present results suggest the presence of a common source of variance that is shared between forward digit span and measures of spoken word recognition that is independent of other obvious 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 scores 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 processing mechanism (or mechanisms) that are responsible for the individual differences. Additional converging measures are needed to pinpoint the locus of these processing differences. 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. These data consisted of a set of acoustic measurements of speech samples from each child. These speech samples provided a unique opportunity for us to use converging measures to understand and explain the digit span results.

As part of the on-going research project at CID, several speech production samples were obtained from each child in order 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) to assess the speech intelligibility and articulation of deaf children. 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 that were obtained for each child using these playback procedures, we analyzed the duration measurements of the individual sentences in each set and used these measures as estimates of each child's articulation rate.

We knew from a large body of research in the memory literature that a child's articulation rate is closely related to speed of subvocal rehearsal (Cowan et al., 1998). Numerous studies in the literature over the past 25 years have demonstrated strong relations between speaking rate and memory span for digits and words. The results of these studies have been replicated with several different populations and suggest that measures of an individual's speaking rate reflect articulation speed, which in turn, can be thought of as an index of rate of covert rehearsal for verbal (phonological) materials in working memory (Baddeley, Thompson & Buchanan, 1975). Individuals who speak more quickly have been found to have longer memory spans than individuals who speak more slowly. Measures of speaking rate are assumed to reflect articulation speed, which in turn, has been taken as an index of verbal rehearsal speed in working memory. Thus, individuals who have faster rehearsal speeds tend to show longer memory spans for sequences of digits and words.

Several different explanations of these findings have been proposed. One account assumes that more forgetting occurs from immediate memory at slower speaking rates because fewer words can be articulated and perceived within the same period of time. Another proposal assumes that the mechanism that controls speaking rate is the same one that regulates the speed of verbal rehearsal processes in immediate memory. Thus, more words can be maintained at faster rehearsal speeds. Regardless of which view is correct, the relation observed between measures of speaking rate and immediate memory span is a reliable and robust finding in the literature on working memory that has been observed in several different populations of subjects.

The forward digit span scores for the 88 children tested in 1998 and 1999 are shown in Figure 3 along with estimates of their speaking rates obtained from measurements of the seven syllable McGarr 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 logarithmic transformations of the sentence durations. The pattern of results in both figures is 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). The simple bivariate correlations between forward digit span and both the raw and transformed measures of sentence duration were also strongly negative and highly significant (r = -.55 and r = -.59; p < .001, respectively). For backwards digit span, the observed correlations were somewhat smaller, but still statistically significant (r = -.42 and r = -.42; p < .001).

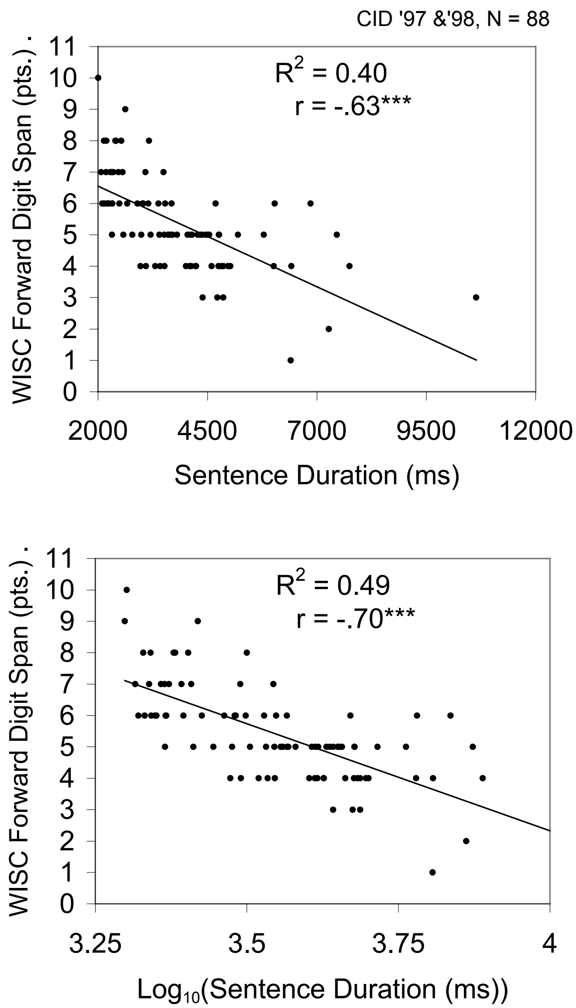


Figure 3. Scatterplots illustrating the relationship between average sentence duration for the seven-syllable McGarr Sentences (abscissa) and WISC forward digit span scored by points (ordinate). Each data-point represents an individual child. Non-transformed duration scores are shown in the top panel, log-transformed duration scores in the bottom panel. R-squared values indicate percent of variance accounted for by the linear relation.

These findings demonstrate that verbal digit span and articulation rate are correlated in this clinical population, as they are in normal-hearing school-age children and adults. That is, children who speak more quickly tend to have larger working memory capacities reflected by their longer digit spans. This result suggests the existence of a common information processing mechanism that is responsible for the individual differences observed within both tasks, namely, covert verbal rehearsal speed.

Speaking Rate and Word Recognition

To determine if rehearsal speed is also related to individual differences in word recognition performance, we examined the correlations between sentence durations and the three different measures of spoken word recognition described earlier. Table II shows the correlations between articulation rate and word recognition scores on the WIPI, LNT and BKB. All of these correlations are negative and strong, suggesting once again that a common processing mechanism, which we assume is related to verbal rehearsal speed, may be the primary factor that underlies the variation and individual differences observed in all three word recognition tasks.

Table II

	Simple Bivariate Correlations	
	Sentence Duration	Log (Sentence Duration)
Closed Set Word Recognition (WIPI)	-.65***	-.69***
Open Set Word Recognition (LNT-E)	-.59***	-.66***
Open Set Word Rec. in Sentences (BKB)	-.71***	-.78***

*** $p < .001$, ** $p < .01$

Our analysis of the digit span scores from these deaf children has uncovered two important correlations linking forward digit span to word recognition performance, on the one hand, and forward digit span to speaking rate (as indexed by measures of sentence duration), on the other hand. These correlations with forward digit span suggest the possibility of a common underlying processing factor that is shared by each of these dependent measures. This factor may 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.

Table III shows a summary of the partial correlations computed between the two measures of speaking rate based on the McGarr sentence durations and the three measures of spoken word recognition performance described earlier. As in the earlier analyses, differences due to demographic factors and the contribution of other variables were statistically controlled for by computing partial correlations. In all cases, the correlations between speaking rate and word recognition were negative and highly significant. Thus, slower speaking rates as measured by longer sentence durations are associated with poorer word recognition scores on all three word recognition tests. Sentence duration accounted for approximately 25% of the currently unexplained residual variance in the word recognition scores after the other mediating variables were removed. These findings linking speaking rate and word recognition suggest that all three measures (digit span, speaking rate and word recognition performance) are related because they share a common underlying source of variance.

Table III

	Partial Correlations[a]	
	Sentence Duration	Log (Sentence Duration)
Closed Set Word Recognition (WIPI)	-.50***	-.55***
Open Set Word Recognition (LNT-E)	-.38***	-.47***
Open Set Word Rec. in Sentences (BKB)	-.52***	-.64***

*** $p < .001$, ** $p < .01$

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

In order 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 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 pattern of results that emerges from these analyses suggests that the underlying process that is shared in common with sentence duration is related in some way to the rate of information processing, specifically, to the speed of verbal rehearsal in working memory. This processing component of verbal rehearsal could reflect either the actual articulatory speed used to recycle and maintain phonological patterns in working memory or the time to retrieve and scan items 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 to the speed of information processing operations used to maintain phonological information in working memory. Thus, variation in performance in these two tasks can be traced to a common elementary process that is shared by both measures of performance.

These new findings demonstrating a relation between speaking rate and digit span permit us to identify a specific information processing mechanism, the verbal rehearsal process, which appears to be responsible for the limitations on processing capacity. Processing limitations are present in a range of behavioral tasks that make use of verbal rehearsal and phonological processing skills to encode, store, maintain and retrieve spoken words from working memory. We suggest that these fundamental information-processing operations are common components of all current outcome measures that are routinely used to assess both receptive and expressive language functions. The present 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 reflect fundamental differences in the speed of information processing operations such as verbal rehearsal and the rate of encoding phonetic and lexical information in working memory.

Simon Reproductive Memory Spans

The traditional methods for measuring working memory using digit spans all require a subject to verbally imitate and repeat back a sequence of test items using an overt articulatory response. Because most deaf children with cochlear implants also have delays in speech development and display “atypical” articulation and speech motor control, it is possible that any differences observed in working memory using digit spans could be due to the nature of the response requirements during retrieval and output in addition to possible differences in encoding, storage and rehearsal processes.

To eliminate the use of an overt articulatory-verbal response, we developed a new experimental methodology to measure memory spans based on Milton Bradley’s Simon, a popular memory game. Figure 4 shows a display of the apparatus. In this procedure, a subject simply “reproduces” a stimulus pattern by manually depressing a sequence of colored response panels on a four-alternative response box. The Simon memory game procedure also permitted us to manipulate the stimulus presentation conditions in several ways while holding the response format constant. This particular property of the experimental procedure is quite useful in providing a way to measure how various perceptual dimensions of the visual and auditory modalities are analyzed and processed, alone and in combination. The Simon memory game apparatus and methodology also provided us with an opportunity to study learning, specifically, sequence learning and the relations between memory capacity and learning using the same experimental procedures and response demands.

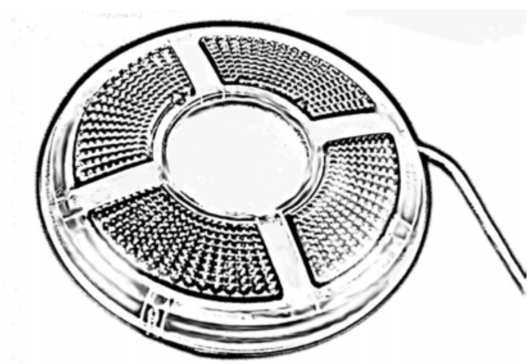
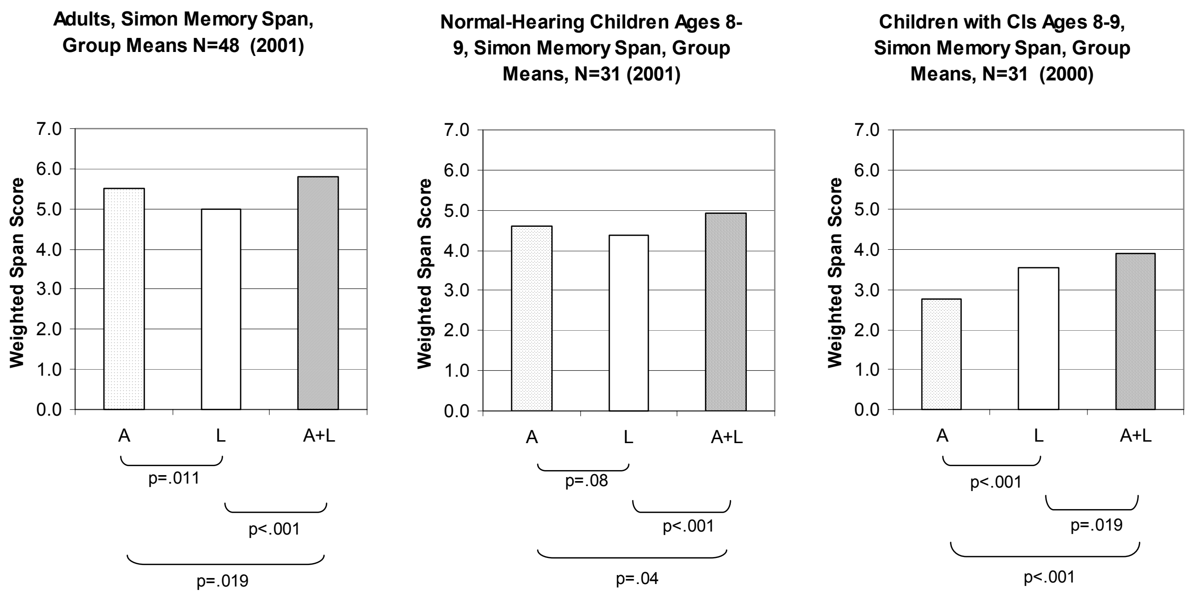


Figure 4. The Memory Game response box based on the popular Milton Bradley game “Simon.”

The lights on the Simon are arranged in temporal patterns that systematically increase in length as the subject progresses through successive finals in the experiment. An adaptive testing algorithm is used to control presentation. If the child reproduces a pattern correctly twice in a row, the pattern increases in length on the next trial until the child is no longer able to reproduce a sequence correctly. Before the memory game was administered, each child was asked to identify the recorded tokens of the color-names by pointing to the four large colored buttons on the response box.

Sequences used for the memory game task were generated pseudo-randomly by a computer program, with the stipulation that no single item would be repeated consecutively in a given list. Each subject started with a list length of one item. If two lists in a row at a given length were correctly reproduced, the next list presented was increased by one item in length. If on any trial the list was incorrectly reproduced, the next trial used a list one item shorter in length. This "adaptive tracking procedure" is similar to methods typically used in psychophysical testing (Levitt, 1970). We computed a "weighted" span score for each child by finding the proportion of lists correct at each list length and summing these proportions across all list lengths.

A summary of the results from the Simon reproduction memory task for the three groups of subjects is shown in Figure 5. The normal-hearing adults are shown in the left panel, the normal-hearing aged-matched children are shown in the middle panel and the children with cochlear implants are shown in the right panel. Within each panel, the scores for auditory-only presentation (A) are shown on the left, scores for lights-only presentation (L) are shown in the middle and scores for the combined auditory and lights presentation condition (A+L) are shown on the right.



p-values from multiple paired samples t-tests, p-values uncorrected

Figure 5. Mean working memory spans in each of the three conditions tested using the "Simon" response box. Scores for a group of normal-hearing adults are shown on the left, scores for normal-hearing 8- and 9-year-old children are shown in the center, and scores for a group of 8- and 9-year-old cochlear implant users are shown on the right. Speckled bars indicate mean spans in the auditory-only (A) condition, open bars indicate mean spans in the lights-only (L) condition, and shaded bars indicate mean spans in the auditory-plus-lights (A+L) condition.

Examination of weighted Simon memory span scores for the normal-hearing adults reveals several findings that can serve a useful benchmark for evaluating differences in performance of the other two groups of children. First, we found a "modality effect" in presentation format. Auditory presentation of sequences of color names produced longer memory spans than visual presentation of sequences of colored lights ($p< .01$). Second, we found a "redundancy gain." When information from separate auditory and visual modalities was combined together and presented simultaneously, the memory span scores increased compared to presentation using only one sensory modality ($p< .02$ for auditory-only and $p< .001$ for visual-only, respectively).

The modality effect and the redundancy gains demonstrate that the Simon memory game procedure is a valid methodology for measuring immediate memory span in normal-hearing adults because is able to assess subtle differences in the sensory modality used for presentation of the stimulus patterns. As in other studies of verbal short-term memory, longer Simon memory spans were found for auditory stimuli compared to visual stimuli, suggesting the use of phonological coding and verbal rehearsal strategies (Penny, 1989; Watkins, Watkins & Crowder, 1974). In addition, the Simon memory spans were sensitive to cross-modality redundancies between stimulus dimensions when the same information about a stimulus pattern was presented simultaneously to more than one sensory modality. This latter finding demonstrates that adults are not only able to combine and integrate redundant sources of information across different sensory modalities but they are also able to increase their working memory capacity when stimulus redundancies are present in both auditory and visual modalities simultaneously.

The middle panel of Figure 5 shows the results of the three presentation conditions for the group of normal-hearing 8-and 9-year old children who were age-matched to the group of deaf children who use cochlear implants. Overall, the pattern of the Simon weighted span scores is quite similar to the findings obtained with the normal-hearing adults (shown in the left-hand panel), although there are several differences worth pointing out. First, the absolute memory span scores for all three presentation conditions are lower than the scores obtained from the adults. Second, while the modality effect found with the adults is also present in these data, it is smaller in magnitude and marginally significant, suggesting possible developmental differences in the rate and efficiency of verbal rehearsal between adults and children in processing auditory and visual sequential patterns like those used in this task. The cross-modal "redundancy gain" observed with the adults was also found with the normal-hearing children, although it is also smaller in magnitude ($p < .04$ for auditory- only; $p < .001$ for visual-only, respectively). Again, these differences may simply be due to age, maturation and development.

The Simon memory span scores for the deaf children with cochlear implants are shown in the right-hand panel of Figure 5 for the same three presentation conditions. Examination of the pattern of these memory span scores reveals several important differences from the span scores obtained for the normal-hearing children. First, the memory spans for all three presentation conditions were consistently lower overall than the spans from the corresponding conditions obtained for the normal-hearing children. Second, the modality effect observed in both the normal-hearing adults and normal-hearing children is reversed for the deaf children with cochlear implants; the memory spans for visual-only presentation were longer than auditory-only presentation, and this difference was highly significant ($p < .001$). Third, although the cross-modal "redundancy gain" found for both the adults and normal-hearing children was also observed for the deaf children and was statistically significant for both conditions ($p < .001$ for auditory-only and $p < .02$ for visual-only), the size of the gain was much smaller. Moreover, the differences in the magnitude of the gain relative to performance in the auditory-only and visual-only conditions were also different because of the reversal of the modality effect in the deaf children.

The results shown in Figure 5 for the visual-only presentation conditions are of special theoretical interest because the deaf children with cochlear implants displayed shorter memory spans than the normal-hearing children. This was an unexpected finding that adds support to the hypothesis that recoding and verbal rehearsal processes in working memory may play an important role in perception, learning and memory in these children. Capacity limitations of working memory are closely tied to speed of processing information even for visual patterns which are rapidly recoded and represented in memory in a phonological or articulatory code for certain kinds of sequential processing tasks. Verbal coding strategies may be mandatory in memory tasks that require immediate serial recall of temporal patterns that preserve item and order information (Gupta & MacWhinney, 1997). Thus, although the visual patterns were presented using only sequences of lights, both groups of children may have attempted to recode the sequential patterns using verbal coding strategies to create stable phonological representations in working memory for maintenance and rehearsal prior to response output.

Although normal-hearing adults and normal-hearing children showed a similar pattern of memory span scores across the three presentation conditions, the deaf children may have used a different encoding strategy and different rehearsal processes for maintaining temporal sequences in working memory. Auditory deprivation and the resulting absence of sound stimulation due to deafness during early stages of development may affect not only early sensory processing and perception but also subsequent encoding and rehearsal processes in working memory. These deaf children showed a reduced capacity to maintain temporal information in working memory even when information that was initially presented through the visual sensory modality. These findings on working memory spans for auditory and visual patterns obtained with the Simon memory game, which did not require overt verbal articulatory-motor responses, are consistent with the earlier memory span results obtained using the WISC digit spans, which showed systematic differences between the deaf children with implants and normal-hearing children.

To our knowledge, these are the first memory span data collected from deaf children with cochlear implants demonstrating specific effects on working memory capacity and rehearsal processes without relying on an articulatory-based verbal response for output. Under all three presentation conditions, the children used the same manual responses to reproduce the stimulus sequences. The deaf children also showed much smaller redundancy gains in the multi-modal presentation conditions, which suggests that in addition to differences in working memory capacity and rate of verbal rehearsal, their information processing skills and abilities to perceive and encode multi-dimensional stimuli are atypical and somewhat compromised relative to age-matched normal-hearing children. The smaller redundancy gains observed in these deaf children may also be due to the reversal of the typical modality effect observed in studies of working memory that reflect verbal coding of the stimulus materials. The modality effect in short-term memory studies is generally thought to reflect phonological coding and verbal rehearsal strategies that actively maintain temporal order information of sequences of stimuli in immediate memory for short periods of time (see Watkins et al., 1974).

Simon Learning Spans

The first version of our Simon memory game used novel sequences of color names or colored lights. All of the sequences were generated randomly in order to prevent any learning from occurring, other than the routine adaptation that normally is observed in learning how to do a new task in a laboratory setting. Our primary goal was to obtain estimates of working memory capacity for temporal patterns that were not influenced by sequence repetition effects or idiosyncratic coding strategies that might increase memory capacity from trial to trial. Each test sequence was created on the fly by a random numbers generator so that the internal structure of a sequence of colors was always different and varied from trial to trial during the course of the experiment. If a subject correctly reproduced a pattern at a given length twice in a row, the adaptive testing algorithm in the experimental control program automatically increased the length of the sequence by one item on the next trial and then generated an entirely new temporal sequence of colors that was different from the sequence presented on the previous trial. This procedure was used throughout the entire experiment to obtain estimates of immediate memory capacity. Thus, there was no basis for learning to take place and the measures of Simon memory span can be used as estimates of capacity of immediate memory.

We have also used the same basic Simon memory game methodology to study sequence learning and to investigate the effects of long-term memory on coding and rehearsal strategies in working memory. To accomplish this goal and to be able to directly compare the gains in learning and the increases in working memory capacity to our earlier Simon memory span measures, we examined the effects of sequence repetition on immediate memory span by simply repeating the same pattern again if the subject correctly reproduced the sequence on a given trial. Thus, the same stimulus pattern was repeated over and over again on each trial for an individual subject and gradually increased in length by one item after each correct response until the subject was unable to reproduce the pattern correctly anymore. This provided an opportunity to study learning based on pattern repetition and to investigate how repetition affects the capacity of immediate memory.

Figure 6 displays a summary of the results obtained in the Simon learning conditions for the same three presentation formats used in the earlier conditions, that is, auditory-only (A), lights-only (L) and auditory+lights (A+L). The weighted memory span scores for the sequence learning conditions are shown on the right-hand side of each panel in this figure; the corresponding set of memory span scores obtained earlier under random presentation format for the same three presentation conditions are reproduced on the left-hand side of each panel. The data for the normal-hearing adults are shown in the left panel; the data for the normal-hearing 8-and 9-year old children are shown in the middle panel and the data for the deaf children with cochlear implants are shown in the right panel.

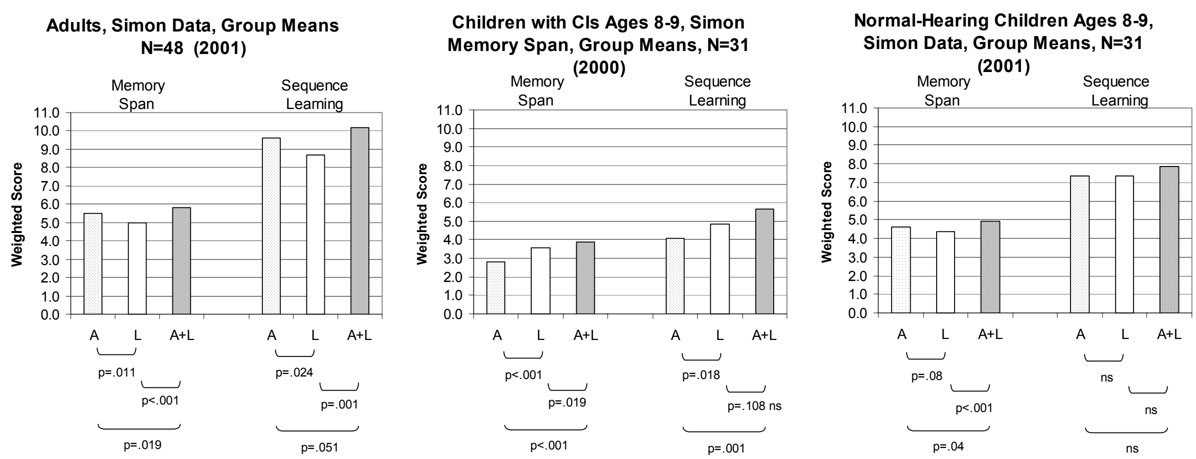


Figure 6. Mean working memory spans and mean sequence learning scores in each of the three conditions tested using the "Simon" response box. Scores for a group of normal-hearing adults are shown on the left, scores for normal-hearing 8- and 9-year-old children are shown in the center, and scores for a group of 8- and 9-year-old cochlear implant users are shown on the right. Speckled bars indicate mean scores in the auditory-only (A) condition, open bars indicate mean scores in the lights-only (L) condition, and shaded bars indicate mean scores in the auditory-plus-lights (A+L) condition. For each task, p-values for paired samples t-tests (uncorrected) between conditions are provided.

Examination of the two sets of memory span scores shown within each panel reveals several consistent findings. First, just repeating the same stimulus sequence again produced robust learning effects for all three groups of subjects. This repetition effect can be seen clearly by comparing the three scores on the right-hand side of each panel to the three scores on the left-hand side. In every case, the learning span scores are higher than the memory span scores; repetition of a pattern increased immediate memory span capacity, although the magnitude of the learning effects differed across the three groups of subjects. The memory spans observed for the adults in the learning condition are about twice the size of memory spans observed when the sequences were generated randomly from trial to trial. Although a repetition effect was also obtained with the deaf children who use implants, the size of their repetition effect was about half the size of the repetition effect found for the normal-hearing children shown in the middle panel.

Second, the rank ordering of the three presentation conditions in the sequence learning conditions was similar to the rank ordering observed in the memory span conditions for all three groups of subjects. The repetition effect was largest for the A+L conditions for all three groups. For both the normal-hearing adults and children, we also observed the same modality effect in learning that was found for memory span; auditory presentation was better than visual presentation. And, as before, the deaf children showed a reversal of this modality effect for learning. For these children, visual presentation was better than auditory presentation. Although none of the pair-wise differences in the sequence learning conditions reached statistical significance for the normal-hearing children, the overall pattern of their learning spans was similar to their earlier memory span results and to the pattern observed with the adults.

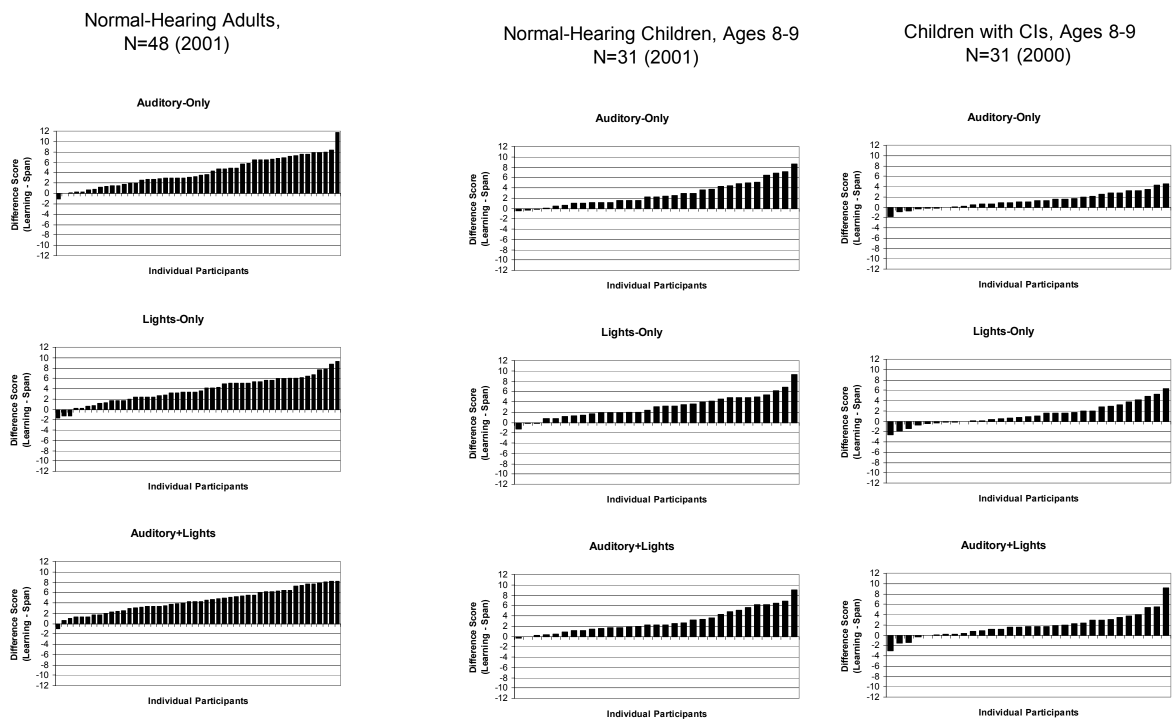


Figure 7. Difference scores for individual subjects showing sequence learning score minus his working memory span score. Data for the auditory-only (A) condition is shown on the top, lights-only (L) condition in the middle, and auditory-plus-lights (A+L) condition, on the bottom. Data from normal-hearing adults are shown on the left, scores for normal-hearing 8- and 9-year-old children in the center, and scores for 8- and 9-year-old cochlear implant users on the right.

To assess the magnitude of the repetition learning effects, we computed difference scores between the learning and memory conditions by subtracting the memory span scores from the learning span scores. The difference scores for the individual subjects in each group for the three presentation formats are displayed in Figure 7. Inspection of these distributions reveals a wide range of performance for all three groups of subjects. While most of the subjects in each group displayed some evidence of learning in terms of showing a positive repetition effect, there were a few subjects at the end of the distribution who either failed to show any learning at all or showed a small reversal of the predicted repetition effect. Although the number of these subjects was quite small in the adults and normal-hearing children, about one-third of the deaf children showed no repetition learning effect at all and no benefit from having the same stimulus sequence repeated on each trial.

Theoretical Significance

Taken together, the results of our recent experiments on working memory provide some new insights into the elementary information processing skills of deaf children with cochlear implants and the underlying cognitive factors that may affect their speech and language abilities. Our studies of working memory capacity using traditional digit span tests and the new Simon memory game were specifically designed to obtain process measures of performance that assessed specific subcomponents of working memory in order to understand the nature of the capacity limitations in encoding and processing sensory information. In this section, we briefly discuss the theoretical significance of our findings in light of the problems surrounding the enormous individual differences in the clinical outcome measures of speech and language that have been consistently reported in the literature.

Detailed analyses of the links between three different sets of measures—the digit span scores, the sentence durations and the word recognition scores using partial correlations, revealed that the common source of variance that was shared between all three of these tasks was processing speed, specifically, articulation speed and, by inference, speed of the verbal rehearsal process. This is a significant finding theoretically because it provides converging evidence from several different behavioral measures obtained on the same children for the existence and operation of a common information processing mechanism used for storage and maintenance of information in working memory and it suggests a principled explanation for the individual differences observed in a wide range of speech and language processing tasks. A task analysis of the traditional test battery used for assessment reveals that verbal rehearsal processes are a common component of every one of the outcome measures used to assess speech perception, spoken word recognition, vocabulary, comprehension and speech intelligibility.

We also found effects of early deafness and auditory deprivation on memory and learning of visual sequential patterns, a result that was initially unexpected when we began this research. The visual-only spans for the deaf children were shorter than the visual-only spans obtained from the age-matched normal-hearing children. This difference was observed in both the Simon memory span experiment, which used random sequences and the Simon learning experiment, which used repeated sequences.

The results of the visual-only conditions are of special theoretical interest to us because they demonstrate that differences observed in working memory are not necessarily restricted only to temporal patterns perceived via the auditory sensory modality; differences in memory span were also found in tasks when both item and order information in sequential visual patterns had to be preserved for a short period of time in immediate memory.

More detailed analyses of these results suggest that the deaf children may have used two different coding strategies to carry out the Simon sequence memory task, a visual-spatial coding strategy for the visual patterns and a verbal coding strategy for the auditory patterns. In contrast, the normal-hearing children may have used the same verbal coding and rehearsal strategy for both the visual and auditory patterns, a processing strategy that emerges, develops and becomes highly automatized over time and is routinely applied in a mandatory fashion for sequential patterns containing familiar linguistic stimuli like color names.

As we noted earlier in the section on redundancy gains under multi-modal presentation, the deaf children with cochlear implants did not use the informationally redundant auditory cues as well as the normal hearing children did to improve their immediate memory capacity. This finding was observed even when the deaf children could identify all of the auditory signals presented in isolation. To understand the basis for these differences and to obtain some further insights into the nature of the coding strategies used by the deaf children in carrying out the Simon memory game task, we first examined the intercorrelations between the multi-modal and the visual-only conditions of the Simon memory game for both groups of children (see also Cleary et al., 2001). We then examined the correlations between the WISC digit spans and the memory span scores obtained from the Simon memory game.

Table IV presents a summary of the intercorrelations among the two different sets of memory span scores, the forward and backward WISC digit span scores, and the Simon memory span scores for auditory, visual and auditory + visual presentation for both groups of children. The top section of this table displays the correlations among these memory span measures for the deaf children with cochlear implants, the bottom section displays the correlations for the normal-hearing children.

Examination of the intercorrelations of the Simon memory span scores for the deaf children in the top section of the table reveals a strong positive correlation between the multi-modal and the visual-only conditions ($r = +.71$, $p < .01$). If the deaf children were using the same visual-spatial coding strategy in both conditions of the Simon memory task, regardless of whether additional redundant auditory information were available, one would predict that these two measures of memory span would be strongly correlated. This is exactly the pattern we found. In contrast, examination of the intercorrelations for the normal-hearing children in the bottom section of the table reveals a different result. Here the correlation between the multi-modal and visual-only conditions is much lower and non-significant ($r = +.20$, NS). This pattern of results suggests that the normal-hearing children used two different coding strategies in the Simon memory game, a verbal-sequential strategy in the multi-modal condition and a visual-spatial strategy in the visual-only condition, while the deaf children used the same visual-spatial coding strategy in both tasks.

Additional support for this explanation comes from an analysis of the correlations between the WISC digit span scores and the Simon memory game scores. As shown in Table IV, a different pattern of correlations was observed between these two sets of measures in each group of children, suggesting again that different coding strategies were used to perform these two tasks. Although the WISC forward digit span scores were positively correlated with the memory game scores for the normal-hearing children, the correlation with forward span was only observed in the multi-modal Simon condition and not the visual-only Simon condition. This finding suggests that the normal-hearing children used the same verbal coding strategies in both the forward digit span task and the multi-modal Simon memory span task. In contrast, the WISC forward digit spans and the memory game conditions were not correlated at all for the deaf children in either of these conditions.

The dissociations observed between these two memory tasks would be expected if the deaf children used one coding strategy in the multi-modal condition of the Simon memory game and a different strategy in the WISC forward digit span task. The failure to find the same pattern of intercorrelations among the two different memory tasks in the deaf children with cochlear implants, taken together with the smaller redundancy gains observed in multi-modal Simon condition, suggests that the deaf children encoded and processed these temporal sequences in fundamentally different ways than the normal-hearing, typical-developing children. The deaf children apparently relied primarily on a visual-spatial coding strategy to perform the Simon memory game task even when additional redundant auditory cues were available to help them improve their performance on this memory task.

Table IV

Intercorrelations Obtained in Experiment 1 Between WISC Forward Digit Span, Memory Game Conditions, and WISC Backward Digit Span

Cochlear Implant Group, N = 43, (subgroup values in parentheses, N = 22)

	WISC Forward Digit Span	Memory Game Color-names-plus-Lights (A+L)	Memory Game Lights-only (L)
Memory Game Color-names-plus-Lights (A+L)	.09 (.14)		
Lights-Only (L)	-.02 (-.07)	.71** (.60**)	---
WISC Backwards Digit Span	.52** (.47*)	.46** (.50*)	.48** (.57**)

Normal-hearing Group, N = 44, (subgroup values in parentheses, N = 22)

	WISC Forward Digit Span	Memory Game Color-names-plus-Lights (A+L)	Memory Game Lights-only (L)
Memory Game Color-names-plus-Lights (A+L)	.58** (.54*)	---	
Lights-Only (L)	.01 (.03)	.20 (.30)	---
WISC Backwards Digit Span	.32* (.08)	.36* (.52*)	.19 (.22)

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

Final Remarks on Process Measures of Performance

The new findings summarized in this chapter suggest that additional processing measures of performance should be developed to study other aspects of cognition, such as attention, categorization, learning and memory—"central" cognitive processes that make use of the initial sensory input provided by a cochlear implant. One can imagine the construction of an entirely new battery of behavioral tests based on "process" measures of performance that could be used to assess the benefits of cochlear implantation and to study the time course of development of these basic information-processing skills. Some of these measures could be used to assess how well a listener is able to use the limited and impoverished sensory information conveyed through the cochlear implant. Other measures could be used to assess differences in processing speed, efficiency and processing capacity. Additional measures of working memory span, verbal and visual-spatial coding and rehearsal strategies, controlled and automatic attention and the development of automaticity may provide new knowledge about individual differences in the elementary cognitive processes that underlie the traditional endpoint measures of outcome performance. At some point in the future, it may also be possible to develop a set of pre-implant, performance-based measures of visual attention and memory for temporal sequences that could be used to predict outcome and benefit after implantation. Given the new tools and experimental methodologies that are currently available from research in cognitive science, we believe these goals can be achieved in the next few years as the age of implantation becomes lower and more profoundly deaf children become candidates for cochlear implantation.

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