Chapter 3

Efficacy and Effectiveness of Cochlear Implants in Deaf Children

David B. Pisoni, Christopher M. Conway, William G. Kronenberger, David L. Horn, Jennifer Karpicke, and Shirley C. Henning

One direction of our research program at the Indiana University School of Medicine has been concerned with understanding the large individual differences in speech and language outcomes in deaf children who have received cochlear implants (CIs). We are interested in explaining and predicting the enormous variability observed in a wide range of conventional measures of speech and language following cochlear implantation. The degree of variation in clinical outcome measures is enormous and is a robust finding observed universally at all implant centers around the world. The variability observed in outcome and benefit following cochlear implantation remains a significant problem for both clinicians and researchers alike. Why do some profoundly deaf children do so well with their CIs, and why do other children do more poorly? The problem of individual differences in outcome and benefit is a major clinical issue in the field, one which has been addressed repeatedly over the years by the two earlier National Institutes of Health (NIH) Consensus Conferences on Cochlear Implants (1988, 1995).

Despite the importance of understanding and explaining variability and individual differences following CI, very little solid progress has been made in identifying the neurobiologic substrates and neurocognitive factors that are responsible for individual variation in speech and language outcomes. Knowledge and understanding of these factors and the information processing subsystems that are affected by profound deafness and language delay is critical for diagnosis, prediction, and treatment and for explaining why some children do poorly with their CIs. Several reasons can be proposed for the unsatisfactory state of affairs concerning variability and individual differences.

First, most of the people who work in the field of hearing impairment and CIs are clinicians. The CI surgeons, audiologists, and speech-language pathologists are primarily interested in the medical care of the patient and documenting the efficacy of CIs as a medical treatment for profound deafness. For them, individual differences and variability in speech and language outcome are viewed as a source of undesirable noise, a "nuisance variable" so to speak, that must be reduced or eliminated in order to reveal the true underlying benefits of cochlear implantation. When a child does well with her CI, the family, clinical team, teachers, and other professionals are all delighted with the outcome. However, when a child does poorly with an implant, the clinical team is at a loss to explain the anomaly or suggest alternatives about what to do next. At present, given the nature of the clinical research carried out on CIs, it is unclear even how to approach the study of individual differences in this clinical population. What factors are responsible for the individual differences in outcome and benefit? What behavioral and neurocognitive domains should be investigated? What kinds of new measures should be obtained? What theoretical approach should be adopted to study this problem?

Second, the conventional battery of speech and language tests that is routinely administered to measure clinical outcome and benefit was developed by the CI manufacturers to establish efficacy as part of the clinical trials for U.S. Food and Drug Administration (FDA) approval. These behavioral tests were never designed to measure individual differences or assess variability in outcome. Moreover, and perhaps more importantly, the foundational assumptions and theoretical framework underlying the selection and use of the conventional speech and language outcome measures—the idea that speech perception and spoken language processing recruit formal rules and use context-free symbolic representations—is now being seriously questioned and undermined (see Gaskell, 2007). The formalist assumption that every child comes up with the same grammar of language despite vastly different individual developmental histories has been questioned in recent years in light of new knowledge about brain structure and function and the development of adaptive self-organizing systems like speech and language. The old static views of language as an idealized homogeneous context-free system of abstract linguistic knowledge are now being replaced by new conceptions linking mind, body, and world together in a complex interactive system (Clark, 1997).

Third, because the primary focus of most of the research on CIs has been clinical in nature—that is, demonstrating efficacy and safety and establishing that CIs work well under quiet testing conditions in the clinic or research laboratory—the typical battery of conventional behavioral tests only provides measures of the final "product" or "end-point" of a long series of neural and neurocognitive processes. All of the current outcome measures routinely used in the clinic and research laboratory rely on accuracy and percent-correct as the primary dependent variable to assess performance and document benefit following cochlear implantation. Unfortunately, end-point measures of performance, although they have strong face validity and have been used successfully to demonstrate efficacy of CIs, are fundamentally unable to measure and assess the basic underlying elementary information processing variables like speed, capacity, learning and memory, inhibition, attention, cognitive control, and the neurocognitive operations that are used in performing the specific individual behavioral tasks used to assess the benefits of CIs.

In addition, because the field of clinical audiology is an applied science drawing knowledge and methods from several different disciplines, no common integrated theoretical framework motivates the choice of specific outcome measures and tests, interprets the results and findings, provides explanations, or makes predictions. Without the benefit of a well-defined conceptual framework and additional theoretically motivated "process-based" measures of performance, it is impossible to gain any new knowledge about the underlying neural and neurocognitive factors that are responsible for the observed variability in the traditional audiologic outcome measures of performance. Without knowing what factors are responsible for the individual differences and understanding the basis for variation in performance, it is difficult to motivate and select a specific approach to habilitation and therapy after cochlear implantation. Moreover, all of the clinical research on CIs has been primarily descriptive in nature and not experimentally motivated by hypothesis-testing or specific predictions that would lead to understanding and explanation of process and mechanism. The bulk of CI research has focused on medical, demographic, and educational factors, not the underlying neurobiologic and neurocognitive processes that link brain and behavior.

Given what we know about population variability in biology, it is very likely that deaf children who are performing poorly with their CIs are a heterogeneous group that differ in numerous ways from each other, reflecting dysfunction of multiple processing systems associated with deafness and language delays (see Leigh, this volume). Adopting a common, uniform approach to assessment, therapy, and habilitation after cochlear implantation will be inadequate to accommodate a wide range of individual differences and subtypes in outcome and benefit. Without knowing how and why poorer performers differ from each other and from the exceptionally good performers, as well as typically developing hearing children, it is difficult to establish realistic goals and generate expectations for treatment and intervention following implantation. Moreover, it is unlikely that an individual child will be able to achieve optimal benefits from her implant without knowing about the problems and what specific neurocognitive domains are involved.

Deaf Children as a "Model System" for Development

Two reasons motivate our interest in studying deaf children with CIs. The first is clinical in nature. Cochlear implants provide a medical treatment for profound deafness and have been shown to facilitate the development of spoken language. Without some kind of medical or behavioral intervention, profoundly deaf children will not learn language normally from caretakers in their surrounding environment and will be unable to achieve their full intellectual potential as productive members of society. No one argues with this reason for studying deaf children. Sensory deprivation is a significant neurodevelopmental problem that has lasting and permanent effects on brain development and intellectual achievement (Riesen, 1975). A profound hearing loss at birth is viewed by hearing people as a clinically significant sensory disability, an impairment that affects cognitive, social, and intellectual development. Almost all of the clinical research on CIs has been concerned with device efficacy; that is, demonstrating that CIs work and provide benefit to profoundly deaf children and adults. In contrast, very little research has been devoted to effectiveness, specifically, to understanding the reasons for the enormous variability in outcome and benefit following implantation.

When considering the *efficacy* of a treatment or intervention, we mean the power to produce a desired effect in an individual; that is, does a CI work and provide benefit to a profoundly deaf person? In contrast, when considering the *effectiveness* of a treatment or intervention, we mean actually producing the expected effect; that is, does a CI work equally well and provide the desired benefit in everyone who is a candidate and receives a CI?

A second major reason for our interest in studying deaf children with CIs is more basic in nature, in terms of theoretical implications for gaining fundamental new knowledge about learning, development, and neural plasticity. Deaf children with CIs represent a unique and unusual clinical population, because they provide an opportunity to study brain plasticity and neural reorganization after a period of auditory deprivation and a delay in language development. In some sense, the current research efforts involving deaf children with CIs can be thought of as the modern equivalent of the so-called "forbidden experiment" in the field of language development, but with an unusual and somewhat unexpected and positive consequence. The forbidden experiment refers to the proposal of raising a child in isolation, without exposure to any language input, to investigate the effects of early experience and sensory deprivation on language development. These kinds of isolation experiments are not considered ethical with humans although they are a common experimental manipulation with animals to learn about brain development and neural reorganization in the absence of sensory input.

Following a period of auditory deprivation from birth, a medical intervention is now available that can be used to provide a form of "electrical" hearing to a congenitally deaf child. A CI provides electrical stimulation to the auditory system, the brain, and nervous system, therefore facilitating development of the underlying neurobiologic and neurocognitive systems used in speech and language processing as well as other domains of neuropsychological function.

The current population of deaf children who use CIs also provides an unusual opportunity for developmental scientists to study the effects of early experience and activity-dependent learning and to investigate how environmental stimulation and interactions with caretakers shapes the development of perception, attention, memory, and a broad range of other neurocognitive processes such as sensory–motor coordination, visual–spatial processing, and cognitive control. All of the latter may be "delayed" or "reorganized" as a consequence of a period of early auditory deprivation resulting from congenital or prelingual deafness prior to implantation and the associated delays in language development. When viewed in this somewhat broader context, the clinical and theoretical implications of research on deaf children with CIs are quite extensive. Research on this clinical population will contribute new knowledge and understanding about important contemporary problems in cognitive development and developmental cognitive neuroscience.

Perceptual Robustness of Speech

Research on deaf children who use CIs will also contribute new knowledge about perceptual learning and adaptation in speech perception and spoken language understanding. The most distinctive property of human speech perception is its perceptual robustness in the face of diverse physical stimulation over a wide range of environmental conditions that produce significant changes and perturbations in the acoustic signal. Hearing listeners adapt very quickly and effortlessly to changes in speaker, dialect, speaking rate, and speaking style and are able to adjust rapidly to acoustic degradations and transformations such as noise, filtering, and reverberation that introduce significant physical changes to the speech signal without apparent loss of performance (Pisoni, 1997). Investigating the perceptual, neurocognitive, and linguistic processes used by deaf listeners with CIs, and understanding how hearing listeners recognize spoken words so quickly and efficiently despite enormous variability in the physical signal and listening conditions, will provide fundamental new knowledge about the sources of variability in outcome and benefit in patients who use CIs.

What Is a Cochlear Implant?

A CI is a surgically implanted electronic device that functions as an auditory prosthesis for a patient with a severe to profound sensorineural hearing loss. The device provides electrical stimulation to the surviving spiral ganglion cells of the auditory nerve, bypassing the damaged hair cells of the inner ear to restore hearing in both deaf adults and children. This intervention/treatment provides patients with access to sound and sensory information via the auditory modality.

The current generation of multichannel CIs consist of an internal multiple-electrode array and an external processing unit. The external unit consists of a microphone that picks up sound energy from the environment and a signal processor that codes frequency, amplitude, and time and compresses the signal to match the narrow dynamic range of the ear. Cochlear implants provide temporal and amplitude information. Depending on the manufacturer, several different place-coding techniques are used to represent and transmit frequency information in the signal.

For postlingually profoundly deaf adults, a CI provides a transformed electrical signal to an already fully developed auditory system and an intact, mature language processing system. Postlingually deaf patients have already acquired spoken language under typical listening conditions, so it is more likely that their central auditory system and brain have developed normally (Luria, 1973). In the case of a congenitally deaf child, however, a CI provides novel electrical stimulation through the auditory sensory modality and an opportunity to perceive speech and develop spoken language for the first time after a period of auditory deprivation.

Congenitally deaf children have not been exposed to the auditory correlates speech and do not develop spoken language in a typical manner. Although the brain and nervous system continue to develop and mature in the absence of auditory stimulation, increasing evidence suggests that substantial cortical reorganization has already taken place during the period of sensory deprivation before implantation and that several aspects of speech and language, as well as other cognitive processes and neural systems, may be delayed and/or disturbed and develop in an atypical fashion after implantation. Although both peripheral and central differences in neural and cognitive function are likely to be responsible for the wide range of variability observed in outcomes following implantation, increasing evidence suggests that the enormous variability in outcome and benefit following cochlear implantation cannot be explained as a simple sensory impairment in detection and/or discrimination of auditory signals. Other more complex cognitive and neural processes are involved.

Cochlear Implants Do Not Restore Normal Hearing

Although CIs work reasonably well with a large number of profoundly deaf children and adults under quiet listening conditions, it is important to emphasize that CIs do not restore normal hearing, and they do not provide support for the highly adaptive robust speech perception and spoken language processing routinely observed in hearing listeners under a wide range of challenging listening conditions. The difficulties consistently reported by CI patients under difficult listening conditions are both theoretically and clinically important because they reflect fundamental differences in perceptual processing between acoustic hearing and electrical stimulation of the auditory system. These difficulties demonstrate that the rapid adaptation, tuning, and continuous adjustment of the perceptual processes that are the hallmarks of robust speech perception by hearing listeners have been significantly compromised by the processing and stimulation strategies used in the current generation of CIs and any neural reorganization that may have taken place before implantation.

Although everyone working in the field fully acknowledges the difficulties that CI patients have when listening in noisy environments, these problems are not explicitly discussed in the literature nor are they considered to be major research questions. Because of their fundamental design, CIs create highly degraded, "underspecified" neural representations of the phonetic content and indexical properties of speech that propagate and cascade to higher processing levels. Although the degraded electrical signal can often be interpreted by most deaf listeners as human speech and can support spoken word recognition and lexical access under quiet listening conditions, the fine episodic acoustic–phonetic details of the original speech waveform are not reliably reproduced or transmitted to the peripheral auditory nerve, central pathways, or higher cortical areas that are used for recognition, categorization, and lexical discrimination and selection. Moreover, the internal perceptual spaces that are used to code and represent linguistic contrasts are significantly warped and deformed in idiopathic ways by the unique pathology of each individual patient (Harnsberger et al., 2001). When confronted with different sources of variability that transform and degrade the speech signal, patients with CIs often have great difficulty perceiving speech and understanding the linguistic content of the talkers' intended message.

The speech perception and spoken word recognition problems experienced by patients with CIs also reflect impairments and disturbances in the neural circuits and categorization strategies that are routinely used to compensate and maintain perceptual constancy in the face of variability in the speech signal. Hearing listeners routinely have similar problems in noise under high cognitive load, but they can cope and overcome the variability and degradation. In some cases, such as listening in high levels of noise or against a background of multitalker babble, patients are unable to derive any benefits at all from their CI and often turn their device off because the speech signal is unpleasant or becomes an aversive stimulus to them.

Key Findings on Outcome and Benefit Following Cochlear Implantation

What do we know about outcome and benefit in deaf children with CIs? Table 3–1 lists seven key findings that have been observed universally at all implant centers around the world. These findings indicate that a small number of demographic, medical, and educational factors are associated with speech and language outcome and benefit following implantation. In addition to the enormous variability observed in these outcome measures, several other findings have been consistently reported in the clinical literature on CIs in deaf children. An examination of these findings provides some initial insights into the possible underlying cognitive and neural basis for the variability in outcome and benefit among deaf children with CIs. When these contributing factors are considered together, it is possible to begin formulating some more specific hypotheses about the reasons for the variability in outcome and benefit.

Much of the past research on CIs has been concerned with questions of assessment and device efficacy using outcome measures that were based on traditional audiological criteria. These clinical outcome measures included a variety of hearing tests, speech discrimination, word recognition, and comprehension tests, as well as some standardized vocabulary and language assessments and other assessments of speech production, articulation, and speech intelligibility. The major focus of most clinical research has been concerned with the study of demographic variables as predictors of these outcome measures. The available evidence suggests that age

Table 3–1. Key Findings on Outcome and Benefit Following Cochlear Implantation

Large individual differences in outcomes
Age of implantation (sensitive periods)
Effects of early experience (auditory–oral versus total communication)
No preimplant predictors of outcome
Abilities “emerge” after implantation (learning)
“Cross-modal plasticity” and “neural reorganization”
Links between speech perception, and production

at onset of deafness, length of deprivation, age at implantation, and early linguistic experience ("auditory–oral" versus "total communication") are all strongly associated with the traditional audiological outcome measures (Fryauf-Bertschy, Tyler, Kelsay, Gantz, & Woodworth, 1997; Kirk, Pisoni, & Miyamoto, 2000; Osberger, Robbins, Todd, & Riley, 1994; Staller, Pelter, Brimacombe, Mecklenberg, & Arndt, 1991; Waltzman et al., 1994, 1997).

Preimplant Predictors

Until recently, clinicians and researchers were unable to find reliable preimplant predictors of outcome and success with a CI (see, however, Bergeson & Pisoni, 2004; Horn, Davis, Pisoni, & Miyamoto, 2005a; Horn, Pisoni, Sanders, & Miyamoto, 2005; Tait, Lutman, & Robinson, 2000). The absence of preimplant predictors is a theoretically significant finding, because it suggests that many complex interactions take place between the newly acquired sensory capabilities of a child after a period of auditory deprivation, properties of the language-learning environment, and various interactions with parents and caregivers that the child is exposed to after implantation. More importantly, however, the lack of reliable preimplant predictors of outcome and benefit makes it difficult for clinicians to identify those children who may be at risk for poor outcomes at a time in perceptual and cognitive development when changes can be made to modify and improve their language-processing skills.

Learning, Memory, and Development

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

Our current working hypothesis about the source of individual differences in outcome following cochlear implantation is that, while some proportion of the variance in performance is associated with peripheral factors related to audibility and the initial sensory encoding of the speech signal into information-bearing sensory channels in the auditory nerve, several additional sources of variance are associated with more central cognitive and linguistic factors that are related to perception, attention, learning, memory, and cognitive control. As summarized in the following sections, several converging sources of evidence suggest that other neural systems and circuits secondary to deafness and hearing loss may also be disturbed by the absence of sound and auditory stimulation early in development before implantation takes place. Because of the rich interconnections of sensory and motor systems and auditory and visual signals in the brain, there are numerous reasons to suspect that the absence of sound and delays in language during early development produce effects on processes that are not necessarily related to the early sensory processes of hearing and audition (Luria, 1973). These processes are uniquely associated with the development of those neural circuits in the frontal cortex that are involved with executive function and cognitive control processes, such as allocation of conscious attention and control; self-regulation; monitoring of working memory; temporal coding of patterns, particularly memory, for sequences and temporal order information; inhibition; planning and problem solving; and the ability to act on and make use of prior knowledge and experiences in the service of perception, learning, memory, and action.

To investigate individual differences and the sources of variation in outcome, we began by analyzing a set of clinical data from a group of exceptionally good CI users (Pisoni, Cleary, Geers, & Tobey, 2000; Pisoni, Svirsky, Kirk, & Miyamoto, 1997). These deaf children, often referred to as the "Stars," acquire spoken language quickly and easily after implantation and show a developmental trajectory that parallels normal-hearing children (see Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). Clinical outcome measures of speech perception and language in these exceptionally good users were all found to be strongly intercorrelated with each other, suggesting the existence of a common underlying source of variance. These conventional clinical outcome measures of a child's speech and language skills reflect the final product or "end-point" of a long series of sensory, perceptual, cognitive, and linguistic analyses. "Process measures" of performance designed to assess how well a child uses the sensory information provided by a CI were not included in any of the standard clinical protocols at the time these data were collected, so it was impossible to assess information capacity, processing speed, memory and learning, inhibition, or organizational-integrative processes—neurocognitive factors that may be central for determining which children will become good CI users.

In light of these findings, our research program has explored process measures of performance that assess what a child does with the sensory information provided by a CI in terms of information processing (see Pisoni, 2000). We began by investigating working memory in deaf children with CIs. One reason for pursuing this particular research direction is that working memory has been shown to play a central role in human information processing (Cowan, 2005). Working memory serves as the primary "interface" between sensory input and stored knowledge and procedures in long-term memory. Another reason is that working memory has also been found to be a major source of individual differences in processing capacity across a wide range of information processing domains from perception to memory to language (Ackerman, Kyllonen, & Roberts, 1999; Baddeley, Gathercole, & Papagno, 1998; Carpenter, Miyake, & Just, 1994; Engle, Kane, & Tuholski, 1999; Gupta & MacWhinney, 1997; see Bavelier, Hauser, & Dye, this volume).

Process Measures of Performance

Immediate Memory Capacity

Measures of immediate memory capacity were obtained from a group of 176 deaf children following cochlear implantation in a study carried out in collaboration with Ann Geers and her colleagues at the Central Institute for the Deaf (CID) in St. Louis (Geers, Brenner, & Davidson, 2003; Pisoni & Geers, 2001). Geers and colleagues had a large-scale clinical research project already under way, and they collected a large number of different outcome measures of speech, language, and reading skills from 8- and 9-year-old children who had used their CIs for at least 3.5 years. Thus, chronological age and length of implant use were controlled in their 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 45 deaf children who were tested separately during the summers of 1997–2000. Forward and backward digit spans were also collected from an additional group of 45 age-matched hearing 8- and 9-year-old children who 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 spoken live-voice by an experimenter at a rate of approximately one digit per second. In the "digits-forward" condition, the child was required to repeat the list as heard. In the "digits-backward" condition, the child was told to "say the list backward." In both subtests, the lists begin with two items and increase in length until a child gets two lists incorrect at a given length, at which time testing stops. Points are awarded for each list correctly repeated with no partial credit for incorrect recall.

A summary of the digit span results for all five groups of children is shown in Figure 3–1. Forward and backward digit spans are shown separately for each group. The children with CIs are shown in the four panels on the left by year of testing; the hearing children are shown on the right.

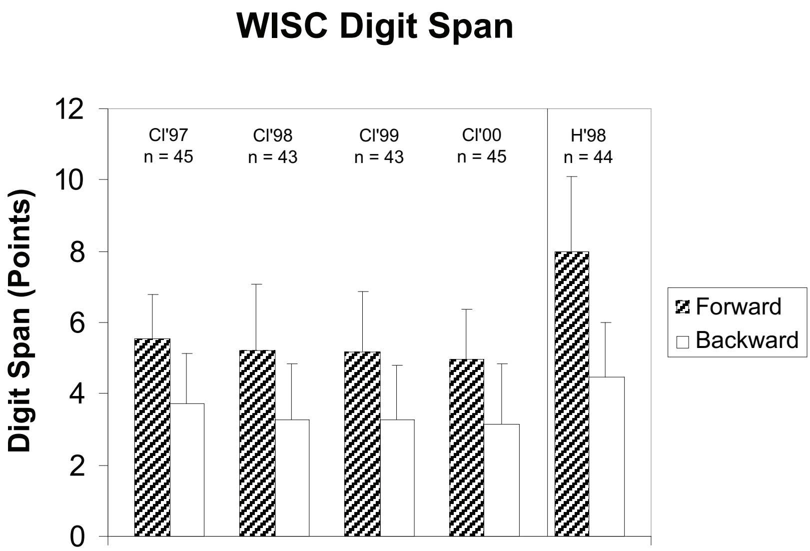

Figure 3–1. WISC digit spans scored by points for the four groups of 8- and 9-year-old children with cochlear implants and for a comparison group of 8- and 9-year-old hearing children. Forward digit spans are shown by the shaded bars, backwards digit spans by the open bars. Error bars indicate one standard deviation from the mean (adapted from Pisoni & Cleary, 2003).

Each child's digit span in points was calculated by summing the number of lists correctly recalled at each list length.

The forward and backward digit spans obtained from the group of age-matched hearing children are shown in the right-hand panel of Figure 3–1. These results show that the digit spans for the hearing children differ in several ways from the spans obtained from the children with CIs. First, whereas the digit spans for the hearing children are age-appropriate and fall within the published norms for the WISC III, those obtained from the children with CIs are atypical. That is, both forward and backward digit spans are longer for the hearing children than for the children with CIs. Second, the difference between the two groups is especially marked in the case of forward digit spans. The average difference between the forward and backward digit span scores was significantly larger in the normal-hearing group compared with the children with CIs.

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

These findings are important because they demonstrate for the first time that the short-term immediate memory capacity of deaf children with CIs is atypical and suggests several possible differences in the underlying processing mechanisms that are used to encode and maintain verbal information in immediate memory (Pisoni & Cleary, 2003; Pisoni & Geers, 2001). These differences may cascade and influence other information processing tasks that make use of working memory and verbal rehearsal processes. Because all of the clinical tests routinely used to assess speech and language outcomes in this clinical population rely heavily on component processes of working memory, verbal rehearsal, and cognitive control, it seems reasonable to assume that these tasks will also reflect variability due to basic differences in immediate memory and processing capacity.

Correlations with Digit Spans

Several studies of hearing children have demonstrated close links between working memory and learning to recognize and understand new words (Gathercole, Hitch, Service, & Martin, 1997; Gupta & MacWhinney, 1997). Other research has found that vocabulary development and several other important milestones in speech and language acquisition are also associated with differences in measures of working memory—specifically, measures of digit span, which are commonly used as estimates of processing capacity of immediate memory (Gathercole & Baddeley, 1990).

To determine if immediate memory capacity was related to spoken word recognition, we correlated the WISC forward and backward digit span scores with three different measures of spoken word recognition that were obtained from the same children. A summary of the correlations between digit span and the spoken word recognition scores based on these 176 children is shown in Table 3–2.

The Word Intelligibility by Picture Identification Test (WIPI) is a closed-set test of word recognition in which the child selects a word's referent from among six alternative pictures (Ross & Lerman, 1979). The LNT is an open-set test of word recognition and lexical discrimination that requires the child to imitate and reproduce an isolated word (Kirk, Pisoni, & Osberger, 1995). Finally, the BKB is an open-set word recognition test in which key words are presented in short meaningful sentences (Bench, Kowal, & Bamford, 1979). The correlations for both the forward and backward spans reveal that children who had longer WISC digit spans also had higher word recognition scores on all three word recognition tests. This

Table 3–2. Correlations Between WISC Digit Span and Three Measures of Spoken Word Recognition

	Simple Bivariate Correlations	
	WISC Forward Digit Span	WISC Backward Digit Span
Closed-set word recognition (WIPI)	.42***	.28***
Open-set word recognition (LNT-E)	.41***	.20**
Open-set word recognition in sentences (BKB)	.44***	.24**

*** $p < 0.001$, ** $p < 0.01$
Adapted from Pisoni & Cleary, 2003.

finding was observed for both forward and backward digit spans. The correlations were all positive and reached statistical significance.

In addition, partial correlations were obtained after statistically controlling for differences due to seven other contributing variables, including chronological age, communication mode, and duration of deafness. Even after these other sources of variance were removed, forward digit span scores were still positively and significantly correlated with the three word recognition scores; however, the correlations with backward digit span scores were much weaker and no longer reached significance. These results demonstrate that children who have longer forward WISC digit spans also show higher spoken word recognition scores. The present results suggest a common source of variance, shared between forward digit span and measures of spoken word recognition, and independent of other mediating factors that have been found to contribute to the variation in these outcome measures.

Digit Spans and Verbal Rehearsal Speed

As part of the research project, speech production samples were obtained from each child to assess her 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 originally developed by McGarr (1983) to measure intelligibility of "deaf speech." 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, the durations of the individual sentences in each set were measured and used to estimate each child's speaking rate.

The sentence durations provided a quantitative measure of a child's articulation speed, which we knew from a large body of earlier research in the memory literature was closely related to speed of subvocal verbal rehearsal (Cowan et al., 1998). Numerous studies over the past 30 years have demonstrated strong relations between speaking rate and memory span for digits and words (for example, Baddeley, Thompson, & Buchanan, 1975). The results of these studies with hearing children and adults suggest that measures of an individual's speaking rate reflect articulation speed, and this measure can be used as an index of rate of covert verbal rehearsal for phonological information in working memory. Individuals who speak more quickly have been found to have longer memory spans than individuals who speak more slowly (see Baddeley et al., 1975).

A scatterplot of the forward digit span scores for the 168 children are shown in Figure 3–2 along with estimates of their speaking rates obtained from measurements of their productions of meaningful English sentences. The digit spans are plotted on the ordinate; the average sentence durations are shown on the abscissa. The top panel shows mean sentence durations; the bottom panel shows the log sentence durations. The pattern of results in both figures is very clear: children who produce sentences with longer durations speak more slowly and, in turn, have shorter forward digit spans. The correlations between forward digit span and both measures of sentence duration were strongly negative and highly significant. It is important to emphasize once again that the relations observed here between digit span and speaking rate were selective in nature and were found only for the forward digit spans. No correlation was observed between backward digit span scores and sentence duration in any of these analyses.

The dissociation between forward and backward digit spans and the correlation of the forward spans with measures of speaking rate suggests that verbal rehearsal speed is the primary underlying factor responsible for the variability and individual differences observed in deaf children with CIs on a range of behavioral speech and language tasks. The common feature of each of these clinical outcome measures is that they all make use of the storage and processing mechanisms of verbal working memory (Archibald & Gathercole, 2007).

Verbal Rehearsal Speed and Word Recognition

To determine if digit span and sentence duration share a common process and the same underlying source of variance that relates them both to word recognition performance, we 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

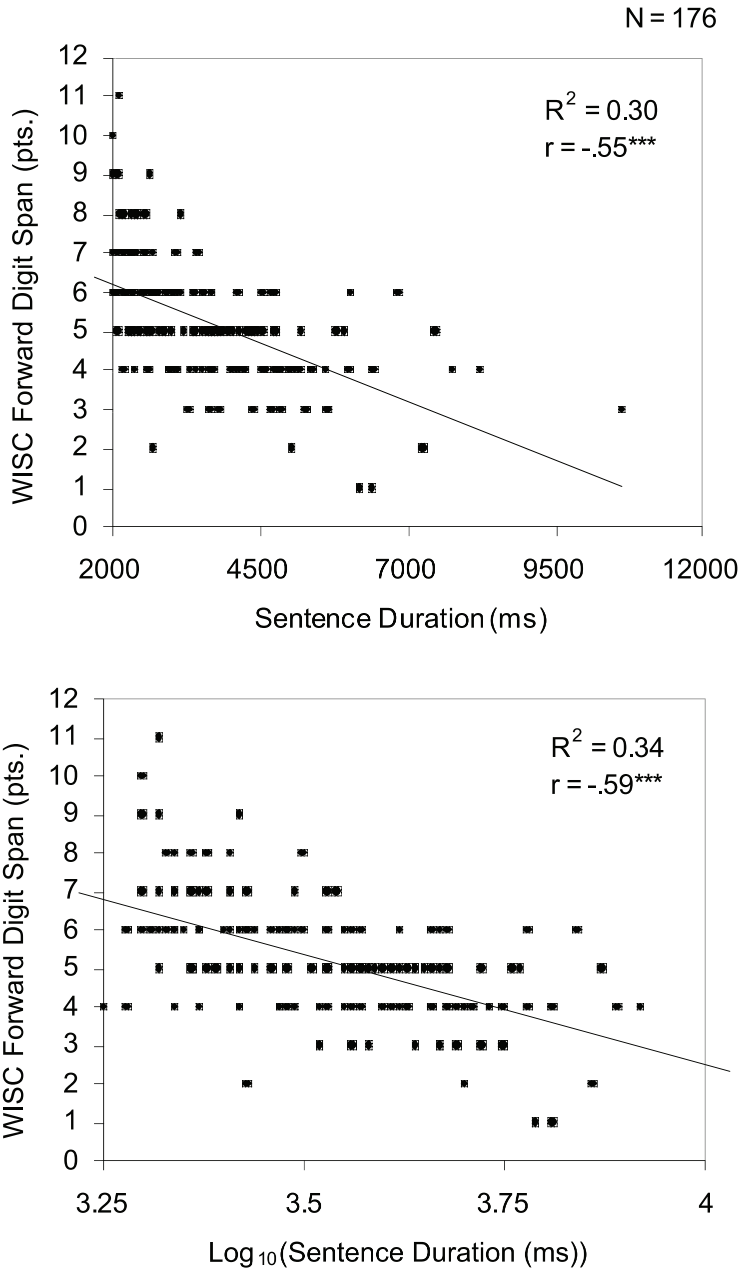

Figure 3–2. Scatterplots illustrating the relationship between average sentence duration for the seven-syllable McGarr Sentences (*abscissa*) and WISC forward digit span scored by points (*ordinate*). Each data-point represents an individual child. Measured duration scores are shown in the top panel, log-transformed duration scores in the bottom panel. R-squared values indicate percent of variance accounted for by the linear relation (adapted from Pisoni & Cleary, 2003).

three measures of word recognition essentially approached zero. However, sentence duration and word recognition were significantly negatively correlated even after digit span was partialled out of the analysis, suggesting that processing speed is the common factor shared between these two measures.

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

Scanning of Information in Immediate Memory

In addition to our studies on verbal rehearsal speed, we also obtained measures of memory scanning during the digit recall task from a group of deaf children with CIs and a comparison group of typically developing age-matched hearing children (see Burkholder & Pisoni, 2003; 2006). Our interest in studying scanning of verbal information in short-term memory in these children was motivated by several earlier findings reported by Cowan and his colleagues, who have carefully measured the response latencies and interword pause durations during recall tasks in children of different ages (Cowan, 1992; Cowan et al., 1994; 1998). Articulation rate and subvocal rehearsal speed were measured using sentence durations elicited with meaningful English sentences. To assess differences in speech timing during recall, the response latencies, durations of the test items, and interword pauses were also measured in both groups of children.

Our findings showed that interword pause durations in recall differed significantly between the two groups of children. The average of individual pauses that occurred during digit recall in the forward condition was significantly longer in the deaf children with CIs than in the hearing children at list lengths three and four. Although the deaf children with CIs correctly recalled all the items from the three- and four-digit lists, their scanning and retrieval speeds were *three times slower* than the average retrieval speed of age-matched hearing children (Burkholder & Pisoni, 2003). Longer interword pauses reflect slower serial scanning processes, which affects the retrieval of phonological information in short-term memory (Cowan, 1992; Cowan et al., 1994). Taken together, the pattern of results indicates that both slower subvocal verbal rehearsal and slower serial scanning of short-term memory are associated with shorter digit spans in the deaf children with CIs.

The effects of early auditory and linguistic experience found by Burkholder and Pisoni (2003) suggest that the development of subvocal verbal rehearsal and serial scanning processes may be related to developmental milestones in cognitive control processes, such as the ability to effectively organize and utilize these two processes in tasks requiring immediate recall. Efficient subvocal verbal rehearsal strategies and scanning abilities also appear to be experience- and activity-dependent, reflecting the development of basic sensory-motor circuits used in speech perception and speech production.

Because the group of deaf children examined in the Burkholder and Pisoni (2003) study fell within a normal range of intelligence, the most likely developmental factor responsible for producing slower verbal rehearsal speeds, scanning rates, and shorter digit spans is an early period of auditory deprivation and associated delay in language development prior to receiving a CI. Sensory deprivation results in widespread developmental brain plasticity and neural reorganization, further differentiating deaf children's perceptual and cognitive development from the development of hearing children (Kaas, Merzenich, & Killackey, 1983; Riesen, 1975; Shepard & Hardie, 2001). Brain plasticity affects not only the development of the peripheral and central auditory systems but other higher cortical areas as well, both before and after cochlear implantation (Ryugo, Limb, & Redd, 2000; Teoh, Pisoni, & Miyamoto, 2004a, b).

Sequence Memory and Learning

All of the traditional methods for measuring memory span and estimating the capacity of immediate memory use recall tasks that require a subject to explicitly repeat a sequence of test items using an overt articulatory–verbal motor response (Dempster, 1981). Because deaf children may also have disturbances and delays in other neural circuits that are used in speech motor control and phonological development, it is possible that any differences observed in performance between deaf children with CIs and age-matched hearing children using traditional full-report memory span tasks could be due to the nature of the motor response requirements used during retrieval and output. Differences in articulation speed and speech motor control could magnify other differences in encoding, storage, rehearsal, or retrieval processes.

To eliminate the use of an overt articulatory–verbal response, we developed a new experimental methodology to measure immediate memory span in deaf children with CIs based on the Simon memory game developed by Milton-Bradley. Figure 3–3 shows a display of the apparatus, which we

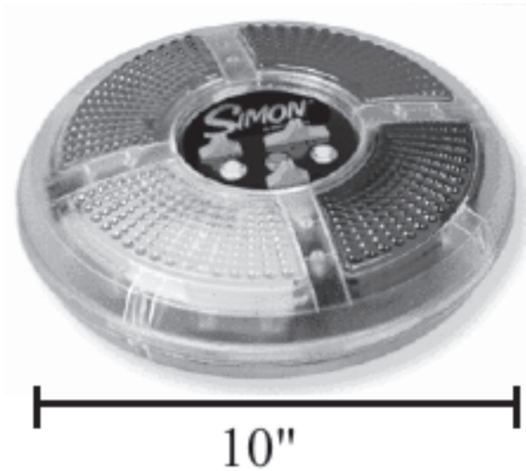

Figure 3–3. The memory game response box based on the popular Milton Bradley game "Simon."

modified so it could be controlled by a PC. In carrying out the experimental procedure, a child is asked to simply "reproduce" a stimulus pattern by manually pressing a sequence of colored panels on the four-alternative response box.

In addition to eliminating the need for an overt verbal response, the sequence memory task methodology permitted us to manipulate the stimulus presentation conditions in several systematic ways while holding the response format constant. This particular property of the experimental procedure was important, because it provided us with a novel way of measuring how auditory and visual stimulus dimensions are analyzed and processed alone and in combination, and how these stimulus manipulations affected measures of sequence memory span. This methodology also offered us an opportunity to study learning processes—specifically, sequence learning and the relationships between working memory and learning—using the identical experimental procedures and response demands (see Conway, Karpicke, & Pisoni, 2007; Karpicke & Pisoni, 2004).

Simon Sequence Memory Spans

In our initial studies with the Simon apparatus, three different stimulus presentation formats were employed (Cleary, Pisoni, & Geers, 2001; Cleary, Pisoni, & Kirk, 2002; Pisoni & Cleary, 2004). In the first condition, the sequences consisted only of spoken color names (A). In the second condition, sequences of colored lights (L) were presented in the visual modality. In the third presentation condition, the spoken color names were presented simultaneously with correlated colored lights (A+L). Thirty-one deaf children with CIs were tested using the Simon memory game apparatus; 31 hearing children who were matched in terms of age and gender with the group of children with CIs were also tested. Finally, 48 hearing adults were recruited to serve as an additional comparison group (see Pisoni & Cleary, 2004).

Sequences used for the Simon memory game task were generated pseudorandomly by a computer program, with the stipulation that no single item would be repeated consecutively in a given list. A memory span score was computed for each subject by finding the proportion of lists correctly reproduced at each list length and averaging these proportions across all list lengths.

A summary of the results from the Simon immediate memory task for the three groups of subjects is shown in Figure 3–4, presented on the left-hand side of each graph (called "memory span"). Examination of these memory span scores for the hearing adults reveals several findings that can serve as benchmarks for comparing and evaluating differences in the performance of the two groups of children. First, as in other studies of verbal short-term memory (Penny, 1989; Watkins, Watkins, & Crowder, 1974), we found a "modality effect" for presentation format. Auditory presentation (A) of sequences of color names produced longer immediate memory spans than did visual presentation (L) of sequences of colored lights. Second, we found a "redundancy gain." When information from the auditory and visual modalities was combined together and presented simultaneously (A+L), the memory spans were longer compared to presentation using only one sensory modality, reflecting the efficient use of cross-modal redundancies between stimulus dimensions (Garner, 1974).

Overall, the pattern of the Simon memory span scores for the group of hearing 8- and 9-year-old children is similar to the findings obtained with the hearing adults. However, the absolute memory spans for all three presentation conditions were lower for the hearing children; furthermore, both the modality effect and the cross-modal "redundancy gain" were smaller in magnitude, suggesting possible developmental differences in processing sequential patterns.

Examination of the pattern of the memory spans for the deaf children with CIs reveals several striking differences from the memory spans obtained from the hearing children and adults. First, the memory spans for all three presentation conditions were consistently lower overall than were the spans from the corresponding conditions obtained for the age-matched hearing children. Second, the modality effect observed in both the hearing adults and hearing children was reversed for the deaf children with CIs. The memory spans for the deaf children were longer for visual-only sequences than for auditory-only sequences. Third, although the cross-modal "redundancy gain" found for both the adults and hearing children was also

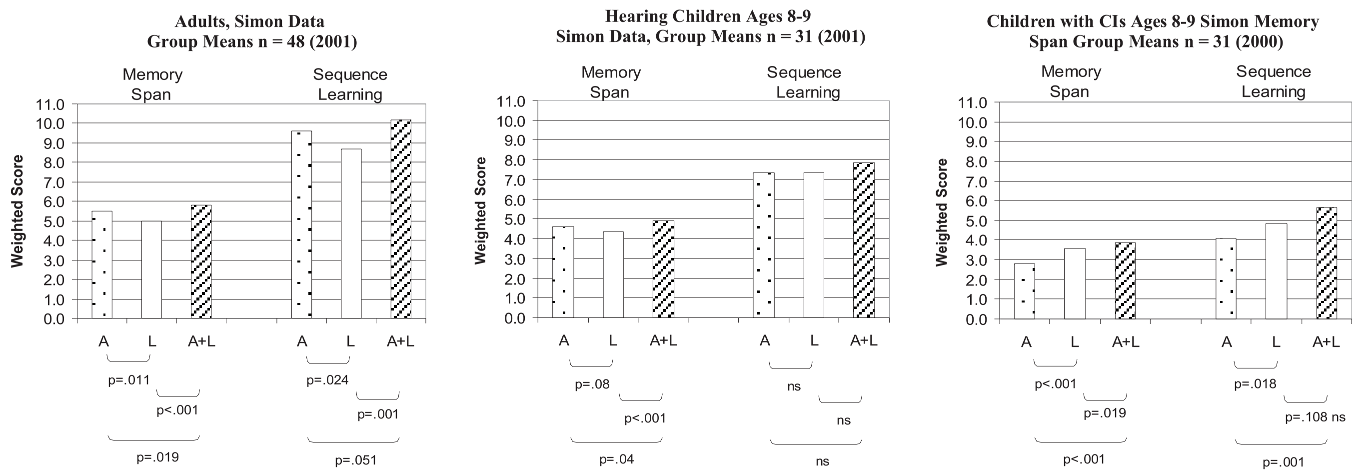

Figure 3–4. Mean immediate memory spans and sequence learning scores in each of the three conditions tested using the "Simon" memory game (adapted from Pisoni & Cleary, 2004). A, Auditory-only; L, Lights-only; AL, Auditory+Lights.

observed for the deaf children and was statistically significant for both conditions, the absolute size of the redundancy gain was smaller in magnitude than the auditory–visual gain observed with the hearing children.

The results obtained for the visual-only presentation conditions are of particular theoretical interest, because the deaf children with CIs displayed shorter memory spans for visual sequences than did the hearing children. This finding adds additional support to the hypothesis that phonological recoding and verbal rehearsal processes in working memory play important roles in perception, learning, and memory in these children (Pisoni & Cleary, 2004). Capacity limitations of working memory are closely tied to speed of information processing even for visual patterns that can be 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). Although the visual patterns were presented using only sequences of colored lights, both groups of children appeared to recode these sequential patterns using verbal coding strategies to create stable phonological representations in working memory for maintenance and rehearsal prior to response output.

The deaf children with CIs also showed much smaller redundancy gains under the multimodal presentation conditions (A+V), which suggests that, in addition to differences in working memory and verbal rehearsal, automatic attention processes used to perceive and encode complex multimodal stimuli are atypical and disturbed relative to age-matched hearing children. The smaller redundancy gains observed in these deaf children may also be due to the reversal of the typical modality effects observed in studies of working memory that reflect the dominance of 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 the temporal order information of stimuli sequences in immediate memory for short periods of time (Watkins et al., 1974). Taken together, the present findings demonstrate important differences in both automatic attention and working memory processes in this population. These basic differences in information processing skills may be responsible for the wide variation in the traditional clinical speech and language outcome measures observed in deaf children following cochlear implantation (Cleary, Pisoni, & Kirk, 2002).

Simon Sequence Learning Spans

In addition to measuring immediate memory capacity, we have also used the Simon memory game procedure to study sequence learning and investigate the effects of long-term memory on coding and rehearsal strategies in working memory (Cleary & Pisoni, 2001; Conway, Karpicke et al., 2007; Karpicke & Pisoni, 2004). To accomplish this goal and 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 over again if the subject correctly reproduced the sequence on a given trial. In the sequence learning conditions, the same stimulus pattern was repeated on each trial for an individual subject and the sequences gradually increased in length by one item after each correct response until the subject was unable to correctly reproduce the pattern. This change in the methodology provided an opportunity to study nondeclarative learning processes based on simple repetition and to investigate how repetition of the same pattern affects the capacity of immediate memory (see Hebb, 1961; Melton, 1963).

Figure 3–4 also displays a summary of the results obtained from the Simon learning conditions that investigated the effects of sequence repetition on memory span for the same three presentation formats used in the earlier conditions, auditory-only (A), lights-only (L), and auditory+lights (A+L). Examination of the two sets of memory span scores shown within each panel reveals several consistent findings. First, repetition of the same stimulus sequence produced large learning effects for all three groups of subjects. The sequence repetition effects can be seen clearly by comparing the three scores on the right-hand side of each panel of Figure 3–4 to the three scores on the left-hand side. For each of the three groups of subjects, the learning span scores on the right were higher than the memory span scores on the left. Although a repetition effect was also obtained with the deaf children who use CIs (shown in the right panel), the size of their repetition effect was about half the size of the repetition effect found for the hearing children.

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 hearing adults and hearing children, we also observed the same modality effect in learning that was found for immediate memory span. Auditory presentation was better than visual presentation. And, as before, the deaf children also showed a reversal of this modality effect for learning. Visual presentation was better than auditory presentation.

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 for each subject. The data for individual subjects in each group for the three presentation formats are displayed in Figure 3–5, which reveals a wide range of

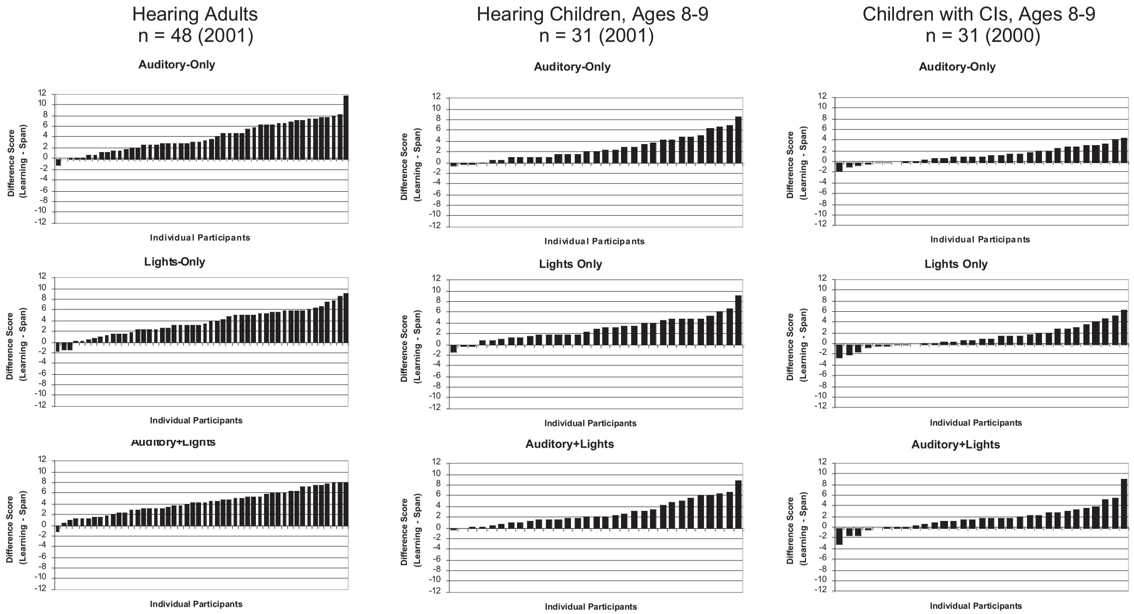

Figure 3–5. Difference scores for individual subjects showing sequence learning score minus memory span score. Data for the auditory-only (A) condition is shown on the top, lights-only (L) condition in the middle, and auditory-plus-lights (A+L) condition on the bottom. Data from hearing adults are shown on the left, scores for hearing 8- and 9-year-old children in the center, and scores for 8- and 9-year-old cochlear implant users on the right (adapted from Pisoni & Cleary, 2004).

performance for all three groups of subjects. Although most of the subjects in each group displayed some evidence of learning in terms of showing a positive repetition effect, a few subjects in the tails of the distributions either failed to show any learning at all or showed a small reversal of the predicted repetition effect. Although the number of subjects who failed to show a repetition effect was quite small in the adults and hearing children, about one-third of the deaf children with CIs showed no evidence of a repetition learning effect at all and failed to benefit from having the same stimulus sequence repeated on each trial.

Sequence Learning and Outcome Measures

To study the relations between sequence learning and speech and language development in these children, Cleary and Pisoni (2001) computed a series of correlations between the three learning scores obtained from the Simon learning task and several of the traditional audiological outcome measures of benefit that were obtained from these children as part of the larger CID project (see Geers, Nicholas, & Sedey, 2003). None of the demographic variables was found to be correlated with any of the Simon sequence learning scores. However, moderate positive correlations were obtained for three measures of spoken word recognition, the WIPI, BKB sentences, and the LNT and the auditory-only Simon learning condition. Moreover, the auditory-only Simon learning span was also found to be correlated with the Test for Auditory Comprehension of Language-Revised (TACL-R), a measure of receptive language, as well as the backward WISC digit span.

Thus, sequence learning in the auditory-only condition was positively correlated with outcome measures that involve more complex neurocognitive processing activities that reflect executive functions and controlled attention (Engle et al., 1999; Miller & Cohen, 2001). In a follow-up study, Pisoni and Davis (2003) assessed two additional sequence learning measures in a different group of deaf children who use CIs: a redundancy gain score that assessed how much gain the child received from the addition of redundant auditory information to a visual pattern, and a sequence learning gain score that assessed changes in the rate of sequence learning over time. These measures were found to be significantly correlated with several traditional speech and language outcome measures, including Common Phrases (auditory-alone) scores and vocabulary knowledge as assessed by the Peabody Picture Vocabulary Test-III (PPVT; Dunn & Dunn, 1997). These results show that measures of sequence learning in deaf children with CIs are associated with changes over time in several traditional clinical outcome measures of speech and language.

Together with the other Simon memory and learning results, these findings are of interest both clinically and theoretically, because they suggest that the individual differences in outcome of deaf children who receive CIs may reflect fundamental learning processes that affect the encoding and retention of temporal information in both short- and long-term memory. These findings suggest that differences in the development of basic sequence learning mechanisms in this population may contribute an additional unique source of variance to the overall variation observed in a range of different outcome measures following cochlear implantation. Additional studies of sequence learning and memory in hearing children and adults and deaf children with CIs have been carried out recently and are reported elsewhere (Conway, Karpicke et al., 2007; Conway, Pisoni, Anaya, Karpicke, & Henning, 2008).

Neurocognitive Measures

Examination of the findings described thus far on immediate memory capacity, speed of verbal rehearsal, and scanning of items correctly retrieved from short-term memory, suggests that the verbal coding strategies and automatized phonological processing skills of deaf children with CIs are atypical and differ in several significant ways from age-matched, typically developing hearing children. Deaf children with CIs demonstrated shorter digit spans, slower verbal rehearsal speeds and significant processing delays in scanning and retrieval of verbal information from short-term memory even for items that were successfully retrieved and correctly recalled. Disturbances were also found in visual sequence memory and learning. In particular, deaf children with CIs showed significant declines in sensitivity to sequence repetition effects in the Simon learning conditions, which suggests fundamental differences in repetition priming, procedural learning, and processes involved in encoding and retention of temporal sequences in long-term memory. Furthermore, the memory and learning results obtained with the Simon task suggest that the effects of deafness and delay in language development, the cognitive and behavioral sequelae following a period of auditory deprivation before implantation, are not modality-specific nor are they restricted to only the perception and processing of auditory signals. The effects of deafness appear to be much broader and more global in scope, involving the processing of sequences and temporal patterns independently of input modality and the allocation of attentional resources to perceptual dimensions of complex multidimensional stimuli (see Marschark & Wauters, this volume; Pelz, Marschark, & Convertino, this volume).

The present findings suggest that multiple information processing systems and the neural circuits underlying their operation are affected by a period of deafness and associated delay in language development prior to implantation. The memory, attention, and sequence learning effects observed in these studies are not directly related to the peripheral coding and sensory aspects of hearing or the perception of auditory signals, although these factors contribute to establishing and maintaining distinctiveness and discriminability of phonological information at the time of initial encoding and registration in sensory and short-term memory.

It is very likely that many of the deaf children with CIs tested in our studies have comorbid disturbances and delays in the development of neural circuits that underlie other information processing systems that are secondary to their profound hearing loss and delay in language development. The absence of sound and auditory experience during early development prior to implantation affects neurocognitive development in a wide variety of ways. Differences resulting from deafness and language delays and subsequent neural reorganization of multiple brain systems may be responsible for the enormous variability observed in speech and language outcome measures following implantation.

To explore these findings further, we shifted our research efforts in two new directions. First, we began searching for preimplant predictors of outcome and benefit that did not involve any direct measures of speech or language processing or perception of auditory signals. Second, adopting a broader integrated functional systems approach to brain, behavior, and development (Luria, 1973), we collected several new sets of data using several standardized neuropsychological measures of visual–motor integration and sensory–motor processes, as well as executive function and cognitive control, so that age-equivalent comparisons can be made based on normative data. Finally, we have recently obtained some preliminary data using the Behavior Rating Inventory of Executive Functions (BRIEF) (Gioia, Isquith, Guy, & Kenworthy, 2000), a behavioral rating inventory filled out by a parent or caretaker to study behavioral regulation, metacognition, and executive function in real-world environments outside the clinic and research laboratory. We have also obtained several additional measures of learning, memory, and attention using the Learning, Executive, and Attention Functioning (LEAF) (Kronenberger, 2006) and the Conduct-Hyperactive-Attention Problem-Opposition Scale (CHAOS) (Kronenberger, Dunn, & Giauque, 1998) rating scales that were developed in our attention deficit-hyperactivity disorder (ADHD) clinic to assess learning, executive function, and attention-hyperactivity. We present a summary of these new findings in the sections below.

Development of Motor Skills

In our research center, as part of the process for determining candidacy prior to implantation, a battery of standardized psychological tests is administered to each child by a clinical psychologist who has extensive experience working with deaf children. Historically, these tests were not considered as research data because they were administered prior to implantation and were designed primarily to rule out mental retardation and other developmental disorders that were thought to be possible risks for cochlear implantation. One of the parental reports used in our psychological assessments is the Vineland Adaptive Behavior Scales (VABS) (Sparrow, Balla, & Cicchetti, 1984), which we use to obtain information about the child's adaptive functioning in three functional domains: daily living skills, socialization, and motor skills. These three domains on the VABS provide valuable normative information about the child's adaptive behaviors prior to implantation and offered an opportunity to assess whether a period of profound deafness and language delay prior to cochlear implantation affects adaptive behaviors in these areas.

We examined data for 43 deaf children from the VABS for the motor development, daily living, and socialization scales as a function of duration of deafness prior to implantation (Horn et al., 2005). All of the children subsequently received a CI at our center, and all of them also provided scores on a range of traditional speech and language outcome measures obtained at several test intervals following implantation. Because the children in this study received their CIs at different ages, we were able to assess the effects of length of deprivation (i.e., duration of deafness) prior to implantation on these three adaptive behaviors to determine whether these skills developed in an age-appropriate fashion before cochlear implantation.

For each of the three VABS domains, children were divided into two groups based on a median split. Using this design, spoken language outcomes were compared for each group. If a given VABS domain is predictive of spoken language outcomes after implantation, children in the high group should show higher scores on spoken language measures than children in the low group.

When compared to the results obtained from the daily living skills and socialization domains, the effect of the median split on spoken language outcomes was more robust for the motor domain. Children in the high motor domain group demonstrated significantly better performance on all spoken language measures than did children in the low motor domain group. For the Grammatical Analysis of Elicited Language-Presentence Level (GAEL-P), a closed-set test of spoken word recognition, the estimated mean score of children in the high motor domain group was 60.5% words correct compared with 34.1% for children in the low motor domain group. Children in the high motor domain group also demonstrated language and vocabulary skills that were closer to their chronological age peers than did children in the low motor domain group, as shown by the differences between the two groups on several other outcome measures.

We also found that the average motor domain score was age-appropriate and within the typical range of variability compared to the other two domains of the VABS. This finding differs from earlier studies that have reported delays in motor skills of deaf children compared with hearing children. The earlier studies of motor development used children attending residential schools for the deaf who used American Sign Language rather than oral or manual English (Wiegersma & Van der Velde, 1983). Moreover, these studies did not report or control for etiology of deafness or other potential confounding variables such as neurological impairment or age at diagnosis. These findings suggest that deaf children who present for a CI in infancy or early childhood do not display evidence of general motor impairments, as measured by the VABS.

Multivariate analyses also revealed that nonmotor VABS scores were negatively related to chronological age at testing. Children who were older at the time the VABS data were obtained showed greater delays in socialization and daily living skills than did children who were younger. These results suggest that motor development proceeds more typically in these children than do the other two developmental domains. Because age at testing and duration of auditory deprivation are highly correlated in this population of infants and children, the relations observed between age at testing and VABS domain scores can be recast in terms of duration of auditory deprivation; longer periods of profound deafness before cochlear implantation are associated with greater delays in socialization and daily living skills, but not motor development.

This pattern of results indicates that not all VABS domains were related to the development of spoken language skills. Motor development was related to performance on spoken word recognition, receptive language, expressive language, and vocabulary knowledge tests obtained over a 3-year period after implantation. Links between motor development and perceptual and linguistic skills have been widely reported in the developmental literature on both hearing and deaf children. In hearing children, motor development assessed in infancy has been shown to be strongly associated with language outcomes in later childhood. The study carried out by Horn et al. (2005) was the first to demonstrate that preimplant measures of motor development can be used to predict post-implant language outcomes in profoundly deaf infants and young children who have received a CI.

One explanation of the relationships observed between motor development and spoken language acquisition in deaf children with CIs is that motor and language systems are closely coupled in development and share common cortical processing resources that reflect the organization and operations of an integrated functional system used in language processing. This hypothesis is not new. Eric Lenneberg (1967), one of the first theorists to propose a biological explanation for the links between motor and language development, argued strongly that correlations between motor and language milestones in development reflected common underlying rates in brain maturation. Recently, a number of studies have explored the basic neural mechanisms behind these links in greater depth (Iverson & Fagan, 2004). These findings suggest an articulatory or motor-based representation of speech in which brain areas traditionally known to be involved in regulating motor behavior are also recruited during language processing tasks (Teuber, 1964; Wilson, 2002).

Divergence of Fine Versus Gross Motor Skills

In a follow-up study, Horn, Pisoni, and Miyamoto (2006) assessed whether gross or fine motor skills on the VABS showed any evidence of a developmental divergence. Horn et al. also investigated whether preimplant measures of fine or gross motor skills predict spoken language outcomes in prelingually deaf children with CIs. In the earlier VABS paper, we found that preimplant motor development scores were significantly correlated with postimplant scores on tests of word recognition, receptive and expressive language, and vocabulary knowledge. In the second study, fine and gross motor skills were analyzed separately using correlational analyses with several different postimplant spoken language scores.

As in the earlier study, three spoken language outcome measures were collected longitudinally at various times after implantation. The first test assessed closed-set spoken word recognition, the second assessed both receptive and expressive language skills, and the third assessed vocabulary knowledge. Correlations between gross motor scores and the three outcome measures were weakly positive, whereas correlations between fine motor scores and the three language outcome measures were more strongly positive. The only correlations to reach significance were between fine motor scores and expressive language quotients obtained at the 1- and 2-year postimplant intervals. In contrast, the correlations between gross motor scores and expressive language scores were all lower and nonsignificant. That is, preimplant fine motor skills predict postimplant expressive language acquisition. Infants and children with more advanced fine motor behaviors on the VABS prior to implantation demonstrated higher expressive language scores after 1 or 2 years of CI use than did children with less advanced fine motor behaviors. In contrast, gross motor skills measured prior to implantation were not related to postimplant expressive language skills.

An additional dissociation in development between gross and fine motor skills in prelingually deaf children was also found. Although the average differences for fine and gross motor skills did not differ, the two motor subdomains showed a developmental divergence as a function of chronological age. For gross motor skills, a positive relationship between age and motor development was observed: older deaf children tended to show more advanced gross motor behaviors compared with younger deaf children. In contrast, the opposite trend was observed for fine motor skills: older deaf children tended to show less advanced fine motor behaviors than did younger deaf children. Although these findings are correlational, they are consistent with the hypothesis that a period of auditory deprivation and associated language delay affects the development of fine motor skills in a way different from gross motor skills.

In sum, these results provide new evidence that fine motor development and spoken language acquisition are closely coupled processes in deaf infants and children with CIs. Our findings suggest that a common set of cortical mechanisms may underlie both the control of fine manual motor behaviors and spoken language processing, especially the development of expressive language skills in this population.

Links Between Visual–Motor Integration and Language

Numerous researchers have recognized that perceptual–motor development and language acquisition are closely linked and develop together in a predictable fashion with several behavioral milestones correlated across systems (Lenneberg, 1967; Locke, Bekken, McMinn-Larson, & Wein, 1995; Siegel et al., 1982). In addition to motor development, visual–motor integration skills have also been found to be closely linked to spoken language development in numerous studies. Traditionally, visual-motor integration is measured using design-copying and construction tasks in which adults and children are asked to copy a series of increasingly complex geometric figures (Beery, 1989). Performance on design copying tasks has been shown to be correlated with language development, reading ability, and general academic achievement in hearing children (Taylor, 1999) as well as deaf children who use American Sign Language (Bachara & Phelan, 1980; Spencer & Delk, 1985).

In addition, several studies have reported that deaf children display atypical performance on visual–motor integration tasks as well as other perceptual–motor tasks involving balance, running, throwing, and figure drawing (Erden, Otman, & Tunay, 2004; Savelsbergh, Netelenbos, & Whiting, 1991; Wiegersma & Van der Velde, 1983). In fact, more than 50 years ago, Myklebust and Brutten (1953) carried out one of the earliest studies investigating the visual perception skills of deaf children. They found that performance on the marbleboard test, which required children to reproduce visual patterns using marbles on a 10 × 10 grid was significantly lower for deaf children than for hearing age-matched controls. They concluded that deafness disturbs the visual perceptual processes required for constructing continuous figures from models consisting of discrete elements and causes an alteration in the normal response modes of the organism, including disruptions in visual perceptual organization. Myklebust and Brutten (1953) argued further that deafness should not be viewed as an isolated autonomous sensory-perceptual impairment but rather as a modification of the total reactivity of the organism.

Many of these early studies included deaf children who had other neurological and cognitive sequelae. And, all of the earlier studies were conducted before deaf children could be identified at birth through universal newborn hearing screening (NIH, 1993). Other studies tested deaf children who were immersed in a manual language environment in which auditory–oral spoken language skills were not emphasized. Thus, the results from these earlier studies cannot be generalized easily to the current population of prelingually deaf children who present for a CI. Two recent studies carried out in our center (Horn, Davis, Pisoni, &, Miyamoto, 2004; Horn, Fagan, Dillon, Pisoni, & Miyamoto, 2007) addressed several questions about the development of visual–motor integration skills.

In the first study, the Beery Test of Visual Motor Integration (VMI; Beery, 1989), was administered prior to implantation to children who were identified from the large cohort of pediatric CI patients followed longitudinally at our center. The Beery VMI test contains a sequence of 24 geometric forms of increasing complexity, ranging from a simple vertical line to a complex three-dimensional star. Children are asked to copy each item as accurately as they can. Several clinical spoken language measures were also obtained at 6-month intervals in this longitudinal study. Open-set word recognition was measured using the Phonetically Based Kindergarten (PBK) test. Sentence comprehension was assessed with the Common Phrases (CP) test (Osberger et al., 1994), using auditory-only, live voice presentation. Speech intelligibility scores were obtained using the Beginner's Intelligibility Test (BIT). Vocabulary knowledge was assessed with the PPVT. Finally, the Reynell Developmental Language Scales (RDLS) was administered to assess receptive and expressive language skills. The receptive scales (RDLS-r) measured 10 skills, including spoken word recognition, sentence comprehension, and verbal comprehension of ideational content. The expressive language scales (RDLS-e) assessed skills such as spontaneous expression of speech and picture description.

The speech and language measures were obtained during the preimplant period, within 6 months before implantation, and then at 6-month intervals after implantation. Scores were collapsed into one of five intervals of CI use: preimplant, 1-year post, 2-years post, 3-years post, and 4-years post. The mean preimplant VMI score for the 40 deaf children was 0.98, which did not differ significantly from the expected mean of 1.0 for hearing children. For all of the language outcome measures, the scores increased significantly as a function of CI use. Moreover, children with higher preimplant VMI showed higher percent correct scores on the postimplantation word recognition, comprehension, and intelligibility tests.

Several new findings were obtained in this study. First, the preimplant visual–motor integration scores of the deaf children in this study were age-appropriate when compared with the normative data. This result contrasts with earlier reports showing delays in deaf children compared with hearing children (Erden, Otman, & Tunay, 2004; Tiber, 1985). The differences may be due to several factors. First, the sample of deaf children used in our studies was likely to have been diagnosed earlier and received earlier audiological and speech-language intervention than the children used in the earlier studies. Second, children with gross cognitive or motor delays were excluded from the present study.

Third, the longitudinal analyses revealed that VMI scores were robust predictors of postimplant outcomes of speech perception, sentence comprehension, and speech intelligibility. Children with higher preimplant VMI scores displayed better performance on all of the outcome measures following CI. Higher VMI scores were also associated with larger increases in speech intelligibility scores over time than were lower VMI scores. Thus, preimplant VMI not only predicts overall performance, but it also predicts rate of improvement with CI experience.

One limitation of the first VMI study reported by Horn et al. (2004) was that the children were only tested at early ages before implantation as part of their initial preimplant psychological assessment. Variability of visual–motor integration skills in prelingually deaf children and the associations observed with spoken language outcomes might not be fully realized until children are a little older and have had more experience using their CI. To pursue these questions further, a second study was carried out with prelingually deaf children who had used their implants for longer periods of time. The Design Copying and Visual–Motor Precision tests from the NEPSY (Korkman, Kirk, & Kemp, 1998), a standardized battery of neuropsychological tests widely used in clinical settings to assess neurocognitive functions of children between 3 and 12 years of age, were administered to determine if the preimplant findings obtained in the first study would generalize to other visual–motor tasks obtained postimplantation. The measures reported here were collected as part of a larger study investigating neuropsychological functioning, phonological processing, and reading skills in prelingually deaf children with CIs (Dillon, 2005; Fagan, Pisoni, Horn, & Dillon, 2007; Horn et al., 2007).

Design Copying is very similar to the Beery VMI test used in our first study. This test is a pencil-and-paper test that measures a child's ability to copy two-dimensional geometrical figures of increasing complexity, under no time limits. Visual–Motor Precision is a timed maze-tracing task containing two mazes, a Simple Maze and a Complex Maze. Children were instructed to draw a line down the track as fast as they could without crossing the lines or rotating the paper. Composite raw scores for each maze reflected number of errors (number of times the line crossed the track) and speed (time to complete the task). Fewer errors and faster speed contributed to higher raw scores.

Several conventional speech and language outcome measures were also obtained from each child. Open-set word recognition was assessed with the PBK test. The PPVT was administered to assess receptive vocabulary knowledge. The Forward Digit Span and Backward Digit Span subtests of the WISC-III were also administered to measure information processing capacity. Test sentences developed by McGarr (1983) were used to estimate verbal rehearsal speed (Baddeley et al., 1975; Pisoni & Cleary, 2003). The children were asked to repeat the sentences aloud, and their utterances were recorded and then later measured for length of utterance in seconds.

The results of the Design Copying performance showed that, although most children fell within normal limits, the mean performance on Design Copying was lower than would be expected from a sample of age-matched hearing peers. The same pattern was observed for the Visual–Motor Precision scores. In addition, correlations were carried out on both sets of visual–motor scores. The only demographic factor found to correlate significantly with these scores was age at implantation. Children who received a CI at an earlier age tended to show higher Design Copying and Visual–Motor Precision scores than did children implanted at later ages. Several correlations were also carried out on the language measures. For the correlations that were significant, partial correlations were conducted to control for the effect of age at implantation. Design Copying showed significant correlations with PPVT, PBK, and backward digit-span scores. Each of these relationships remained significant after partial correlations were carried out to control for age at implantation. Visual–Motor Precision scores were also significantly correlated with PBK scores.

Overall, performance on both Design Copying and Visual–Motor Precision tasks was below the scores reported for hearing peers based on the NEPSY norms. Unlike the first study, in which preimplant VMI scores were not significantly below normative data, the present results replicate earlier findings showing that visual–motor integration skills of deaf children are delayed compared to hearing children (Erden, Otman, & Tunay, 2004; Tiber, 1985). When administered prior to implantation, it is possible that VMI and design copying tests are not sensitive enough to pick up differences between prelingually deaf children and hearing peers. It is also possible that visual–motor integration skills display a slower developmental trajectory in prelingually deaf children compared with hearing children and, thus, delays in visual–spatial processing skills may only become apparent at later ages.

As in the first VMI study, longer periods of deafness prior to implantation were associated with greater delays on the Design Copying and Visual–Motor Precision. Children implanted at later ages showed lower Design Copying and Visual–Motor Precision standard scores than did children implanted at earlier ages. Although the above correlations are not causal, they suggest that a period of auditory deprivation and language delay may lead to atypical development of nonverbal, visual–spatial skills such as those assessed in the VMI tests. Although recent neuroimaging work has begun to reveal mechanisms of auditory cortical plasticity underlying speech perception and production outcomes (Lee, D. et al., 2001; Sharma, Dorman, & Spahr, 2002), little is currently known about how nonverbal processes such as visual–spatial coding and sensory–motor processes are affected by a period of profound deafness and delay in language. In a recent paper by H. Lee et al. (2005), increased preimplant positron emission tomography activity in the frontal and parietal cortex, brain areas involved in behavioral control and visual–spatial processing, was found to be a predictor of postimplant speech perception scores.

These findings suggest that early auditory experience not only affects speech perception and language processing skills but also affects the development of attentional and behavioral inhibition systems. Several investigators have reported that deaf children with CIs show more age-typical performance on visual-only tests of sustained attention than do deaf children without CIs who use hearing aids (Quittner, Smith, Osberger, Mitchell, & Katz, 1994; Smith, Quittner, Osberger, & Miyamoto, 1998). Sustained attention has also been shown to improve with length of CI use (Horn, Davis, Pisoni, & Miyamoto, 2005b). Furthermore, the ability of prelingually deaf children with CIs to regulate and delay premature behavioral responses has been shown to increase with CI use and to be related to performance on several spoken language measures (Horn et al., 2005a). The findings obtained with the Visual Motor Precision task provide additional converging support for these earlier findings on the development of attention and behavioral regulation, processes that reflect the operation of cognitive control and executive function.

The studies by Horn et al. demonstrate that visual–motor integration skills in prelingually deaf children are influenced by early auditory and linguistic experience. The findings suggest that early experience and activity affects the development of several basic elementary information processing operations that are independent of the sensory domain. Although the precise underlying neurobiological mechanisms behind these findings are still unclear, the results suggest that working memory, subvocal verbal rehearsal, and behavioral inhibition, neurocognitive processes typically associated with frontal lobe executive function, may play important roles in cognitive control and self-regulation used in a wide range of behavioral tasks commonly used to assess speech and language outcomes in both hearing children and deaf children with CIs (see Hauser, Lukomski, & Hillman, this volume).

The results reported by Horn et al. also demonstrate that several visual–motor integration tests, such as the Beery VMI, the NEPSY, and the Design Copying and Visual–Motor Precision tests, can be used clinically to predict outcomes following implantation. These standardized neuropsychological tests, which can be easily administered to deaf children because they do not require auditory processing skills, should be considered as potential additions to assessment batteries used with this clinical population both pre- and postimplantation.

Cognitive Control and Executive Function

When compared with findings obtained on behavioral tests of hearing children, our findings suggest that several aspects of executive function and frontal lobe activity may be disrupted or delayed and may underlie the differences we have observed in traditional outcome measures. "Executive function" is an umbrella term in neuropsychology and cognitive neuroscience that includes several different processing domains such as attention, cognitive control, working memory, and inhibition (see Hauser et al., this volume).

Many cognitive neuroscientists believe that executive function involves using prior knowledge and experience to predict future events and modulate the current contents of immediate memory (Goldman-Rakic, 1988). There is general agreement that several different aspects of executive function play important roles in receptive and expressive language processes via top-down feedback and control of information processing activities in a wide range of behavioral tasks. The study of executive function and frontal lobe processes may provide new insights into the neurobiological and neurocognitive basis of individual differences following cochlear implantation.

BRIEF, LEAF, and CHAOS Rating Scales of Executive Function

We are now engaged in a series of new studies to assess the contribution of executive function and self-regulation in the development of speech and language processes in deaf children following cochlear implantation. To obtain measures of executive function as they are realized in the real-world home, school, or preschool settings, outside the highly controlled conditions of the audiology clinic or research laboratory, we have been using a neuropsychological instrument called the BRIEF (Behavior Rating Inventory of Executive Function; Psychological Assessment Resources, Inc., 1996). The BRIEF consists of rating scales that are filled out by parents, teachers, and daycare providers to assess a child's executive functions and self-regulation. These rating scales measure specific aspects of executive function related to inhibition, shifting of attention, emotional control, working memory, planning, and organization among others. Scores from these clinical subscales are then used to construct several aggregate indexes of behavioral regulation, inhibitory self-control, flexibility, and metacognition. Each rating inventory also provides a global executive composite score.

The BRIEF has been shown in a number of recent studies to be useful in evaluating children with a wide spectrum of developmental and acquired neurocognitive conditions, although it has not been used yet with deaf children who use CIs (Gioia, Isquith, Kenworthy, & Barton, 2002). From our preliminary work so far, we believe that this instrument may provide new measures of executive function and behavior regulation that are associated with conventional speech and language measures of outcome and benefit in this clinical population. Some of these measures can be obtained preimplant and therefore may be useful as behavioral predictors of outcome and benefit after implantation.

Our initial analysis of recent data obtained on the BRIEF from 15 hearing 5- to 8-year-old children and 12 deaf 5- to 10-year-old children with CIs revealed elevated scores in the CI group on several subscales (see Conway, Pisoni, Geers, Kronenberger, & Anaya, 2007). The group means on the Behavioral Regulation Index (BRI), Metacognition Index (MCI), and the Global Executive Composite (GEC) scores were all higher for deaf children with CIs than for hearing children, although none of them fell within the clinically significant range.

Examination of the eight individual clinical subscales showed significant differences in shifting, emotional control, and working memory. The elevated scores on the BRI suggest that a period of profound deafness and associated language delay before cochlear implantation not only affects basic domain-specific speech and language processes but also affects self-regulation and emotional control, metacognitive processes not typically considered to be sequela of deafness and sensory deprivation in this population (see Schorr, 2005). The BRIEF scores from this new study provide additional converging evidence that multiple processing systems are linked together in development and that disturbances resulting from deafness are not domain-specific and restricted only to hearing and auditory signal processing by the peripheral auditory system (Conway, Pisoni et al., 2007).

Analysis of the scores obtained on both the Learning Executive Attention Functioning (LEAF), which was developed to measure executive function in the context of learning environments, and the Conduct-Hyperactive-Attention Problem-Oppositional Scale (CHAOS), which was designed to screen for ADHD and disruptive behavior symptoms, also revealed elevated scores on the clinical subscales for the children with CIs compared with the hearing comparison group. In particular, significant differences were observed in learning, memory, attention, speed of processing, sequential processing, complex information processing, and novel problem-solving subscales on the LEAF; and attention, hyperactivity, and opposition problems on the CHAOS. No differences were observed on the conduct disorder subscale of the CHAOS.

These additional results reflecting real-world behaviors demonstrate the involvement of several parallel information processing systems and neural circuits involved in learning, memory, attention, and processing of complex sequential information. Deaf children with CIs show evidence of disturbances in cognitive and emotional control, monitoring behavior, self-regulation, planning, and organization. These differences are not isolated domain-specific symptoms but reflect domain-general properties of an integrated system used in language and cognition, linking brain function and behavior with the executive control processes that monitor and regulate ongoing behavior and social functioning in novel environments where highly robust adaptive behaviors are routinely required (Luria, 1973).

Summary and Implications

The results from a large number of studies covering a range of information processing domains have been presented. In this section, we provide a brief overview and summary of the major findings of these studies and suggest several conclusions about what these findings mean. We then offer several suggestions for how to understand and interpret these diverse findings in terms of both their direct clinical significance and more basic theoretical relevance.

What do all of these diverse behavioral measures have in common? At first glance, the diverse pattern of differences observed across these tasks may seem unrelated and anomalous. However, more careful examination reveals they have links in common and show several important similarities with the extensive clinical literature on frontal lobe disturbances and executive dysfunction in other clinical populations. These frontal lobe disturbances are associated with differences in controlled attention, monitoring and manipulating of verbal information in working memory, functional integration, organization and coordination, self-regulation, inhibition, planning, and using prior knowledge and experience to predict future events and actions in the service of speech and language processing as well as other processing domains.

One of the hallmarks of research on CIs is the enormous variability and individual differences in outcome and benefit. Given this problem, which is observed at all implant centers around the world, how can we begin to identify the underlying neurobiological and cognitive factors and explain the heterogeneity in speech and language outcomes? Are there a set of "core" attributes or common "defining features," or are there several different distinct subgroups of CI users? At this point, we cannot provide a definite answer to this question, but understanding the sources of variability in outcome has both clinical and theoretical significance, and additional research using new methods and experimental techniques will provide answers to these questions.

Some of the best CI users overlap on specific behavioral measures with hearing children on the low end of a distribution of scores. In contrast, other children with CIs do more poorly and get little benefit from their CIs. At present, it is unclear whether these individual differences lie on a continuum or whether there are specific subtypes of poor users. We also do not know what neurocognitive processes and underlying neural circuits are responsible for these differences. Are the low performers simply poor on all outcome measures, or is their performance restricted more selectively to only certain subtests and specific domains? These are important problems to explore in the future, because basic knowledge and understanding of the sources of variability in outcome will have several direct implications for diagnosis, treatment, and assessment.

Theoretical and Clinical Issues

One of the major problems of past research efforts on CIs, especially research on variability and individual differences in outcome, is that the field of CIs has been and continues to be intellectually isolated from the mainstream of research in cognition and neural sciences and is narrowly focused on clinical issues surrounding efficacy and outcomes. Cochlear implant researchers and clinicians have adopted an approach to hearing loss that ignores the role of functional connectivity and global systems-level integrative processes in speech and language (Luria, 1973).

A growing consensus among speech scientists and psycholinguists believes that speech perception and spoken language processing do not take place in isolation. Rather, these processes are heavily dependent on the contribution of multiple brain systems. All behavioral responses in any psychological task are a function of long sequences of processing operations. No part of the brain, even for sensory systems like vision and hearing, ever functions in isolation without multiple connections and linkages to other parts of the brain and nervous system. As Nauta (1964) pointed out many years ago, "It seems that if we try to discover the ways in which any part of the brain functions, it is only logical to try to find out in what way it acts within the brain as a whole . . . no part of the brain functions on its own, but only through the other parts of the brain with which it is connected" (p. 125). These observations apply equally well today in terms of research on CIs. We cannot continue to view profound deafness as merely a sensory loss that is disconnected from the rest of mind and brain.

Automatized and Controlled Processing

Our recent findings involving deaf children with CIs suggest that, in addition to the traditional demographic, medical, and educational variables that have been found to predict some proportion of the variance in traditional audiological measures of outcome and benefit, several additional sources of variance reflect the contribution of basic information processing skills commonly used in a wide range of language processing tasks, specifically, those which rely on rapid phonological encoding of speech and verbal rehearsal strategies in working memory and executive function. Thus, some proportion of the variability and individual differences in outcome following cochlear implantation is related to central auditory, neurocognitive, and linguistic factors that reflect how the initial sensory information transmitted by the CI is subsequently encoded and processed and how it is used by the listener in specific behavioral tasks that are routinely used to measure speech and language outcomes and assess benefit.

Can we identify a common factor that links these diverse sets of findings together? A coherent picture is beginning to emerge from all of these results. At least two factors contribute to success with a CI. One factor is the development and efficient use of "automatized" phonological processing skills (see Marschark & Wauters, this volume), typically carried out rapidly without conscious awareness or processing efforts. A second factor is the development of "controlled" processing, operations that require active attention, processing resources and mental effort, working memory, cognitive control, and executive function (similar findings are discussed by Hauser and Lukomski, this volume). Some children can adapt and overcome the first problem, which is related to encoding and registration of early sensory information, by using "controlled" conscious processes, but other children may have more difficulty overcoming basic sensory limitations. Deaf children who have delays or disturbances in both processing domains may be at much greater risk for doing poorly with their CIs.

The use of automatized phonological processing skills is a significant contributor above and beyond the traditional demographic, medical, and educational variables that have been found to be associated with outcome and benefit following cochlear implantation. Phonological analysis involves the rapid encoding and decomposition of speech signals into sequences of discrete, meaningless phonetic segments and the assignment of structural descriptions to these sound patterns that reflect the linguistically significant sound contrasts of words in the target language.

For many years, both clinicians and researchers have considered open-set tests of spoken word recognition performance to be the "gold standard" of outcome and benefit in both children and adults who have received CIs. The reason open-set tests are viewed in this way is because they require the use and coordination of several component processes including speech perception, verbal rehearsal, retrieval of phonological representations from short-term memory, and phonetic implementation strategies required for speech production, motor control, and response output. All of these subprocesses rely on rapid, highly automatized phonological processing skills for analysis and decomposition of the input signal in perceptual analysis and the reassembly and synthesis of these units into action sequences as motor commands and articulatory gestures for output and speech production. All of these open-set tests also load heavily on cognitive control processes and executive function. They require organization, integration, coordination, planning, inhibition, attention, monitoring, and manipulation of symbolic phonological representations in working memory, and they make extensive use of past experiences and immediate context to predict, modulate, and control future behavior.

When prelingually deaf children receive a CI as a treatment for their profound hearing loss, they do not simply have their hearing restored at the auditory periphery. After implantation, they receive novel stimulation to those specialized cortical areas of their brain that are critical for the development of spoken language and, specifically, for the development of automatized phonological processing skills that are used to rapidly encode, process, and reproduce speech signals linking up sensory and motor systems in new ways. Moreover, many different neural circuits in other areas of the brain also begin to receive inputs from the auditory cortex and brainstem, and these contribute to the global connectivity and integrative functions linking multiple brain regions in regulating speech and language processes in a highly coordinated manner.

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

Controlled Processing and Executive Dysfunction

A second factor uncovered in our research reflects differences in behavioral regulation, cognitive control, and executive function, domain-general metacognitive processes that are slow, effortful, and typically thought to be under conscious control of the individual. One of the reasons we have focused our recent research efforts on executive function in deaf children with CIs is that executive functions are domain-general processes that are involved in regulating, guiding, directing, and managing cognition, emotion and behavioral response, and actions across diverse environments, especially novel contexts in which active problem solving and adaptive skills are typically required. Our recent findings suggest that the sequela of deafness and delay in language are not domain-specific and restricted to only hearing and auditory processing. Other neurocognitive systems display disturbances, and these differences appear to reflect the operation of domain-general processes of cognitive control, self-regulation, and organization.

Another reason for our interest in cognitive control processes in spoken language processing is that executive function develops in parallel with other aspects of neural development, especially in the development of neural circuits in the frontal lobe, which are densely interconnected with other brain regions. The development of bidirectional connections among multiple brain regions suggests that the development of speech and spoken language processing may be more productively viewed within the broad context of development as an integrated functional system rather than a narrow focus on the development of hearing and the peripheral auditory system.

Moreover, large individual differences have been observed in the development of executive function within and across cognitive, emotional, and behavioral domains. Thus, variability in outcome and benefit following implantation may not only reflect contributions from basic domain-specific sensory, cognitive, and linguistic processes related directly to the development of hearing, speech, and language function but may also reflect domain-general control processes that are characteristic of global cognitive control, emotional regulation, and behavioral response and action.

Focusing new research efforts on executive function and frontal lobe disturbances in deaf children with CIs also provides a neurally grounded conceptual framework for understanding and explaining a diverse set of behavioral findings on attention and inhibition, memory and learning, visual–spatial processing, and sensory–motor function, traditional neurocognitive domains that have been studied extensively in other clinical populations that have acquired or developmental syndromes that reflect brain-behavior dysfunctions in these processing systems. Speech and language processing operations make extensive use of these neurocognitive domains, and it seems entirely appropriate to include these in any future investigations seeking to understand and explain the basis of variability and individual differences in speech and language outcome following cochlear implantation.

Recent theoretical developments in cognitive neuroscience have established the utility of viewing the development and use of speech and language as embodied processes linking brain, body, and world together as an integrated system (Clark, 1997). There is every reason to believe that these new theoretical views will provide fundamental new insights into the enormous variability and individual differences in outcome and benefit following cochlear implantation in profoundly deaf children and adults. Without knowing what specific biological and cognitive factors are responsible for the enormous individual differences in CI outcomes or understanding the underlying neurocognitive basis for variation and individual differences in performance, it is difficult to motivate and select a specific approach to habilitation and therapy after a child receives a CI. Deaf children who are performing poorly with their CIs are not a homogeneous group and may differ in numerous ways from each other, reflecting the dysfunction of multiple brain systems associated with congenital deafness and profound hearing loss. Moreover, it seems very unlikely that an individual child will be able to achieve optimal benefits from her CI without researchers and clinicians knowing why a specific child is having problems and what particular neurocognitive domains and information processing subsystems underlie these problems.

Acknowledgments

The research described in this chapter was supported by NIH-NIDCD Training Grant T32DC00012 and NIH-NIDCD Research Grants R01DC00111 and NIH-NIDCD R01DC00064 to Indiana University. We thank Luis Hernandez and Darla Sallee for their help and assistance on various phases of this work over the years.

References

Ackerman, P. L., Kyllonen, P. C., & Roberts, R. D. (1999). *Learning and individual differences.* Washington, DC: American Psychological Association.
Archibald, L.M.D. & Gathercole, S. E. (2007). The complexities of complex memory span: Storage and processing deficits in specific language impairment. *Journal of Memory and Language, 57,* 177–194.

Bachara, G. & Phelan, W. (1980). Visual perception and language levels of deaf children. *Perceptual and Motor Skills, 51,* 272.
Baddeley, A., Gathercole, S., & Papagno, C. (1998). The phonological loop as a language learning device, *Psychological Review, 105,* 158–173.
Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior, 14,* 575–589.
Beery, K. (1989). *The VMI developmental test of visual motor integration* (3rd revision). Cleveland: Modern Curriculum Press.
Bench, J., Kowal, A., & Bamford, J. (1979). The BKB (Bamford-Kowal-Bench) sentence lists for partially-hearing children. *British Journal of Audiology, 13,* 108–112.
Bergeson, T. & Pisoni, D. B. (2004). Audiovisual speech perception in deaf adults and children following cochlear implantation. In G. Calvert, C. Spence, & B. E. Stein (Eds.), *Handbook of Multisensory Integration.* Cambridge: MIT Press.
Burkholder, R. A. & Pisoni, D. B. (2003). Speech timing and working memory in profoundly deaf children after cochlear implantation. *Journal of Experimental Child Psychology, 85,* 63–88.
Burkholder, R. A. & Pisoni, D. B. (2006). Working memory capacity, verbal rehearsal speed, and scanning in deaf children with cochlear implants. In P. E. Spencer & M. Marschark (Eds.), *Advances in the spoken language development of deaf and hard-of-hearing children,* (pp. 328–357). New York: Oxford University Press.
Carpenter, P. A., Miyake, A., & Just, M. A. (1994). Working memory constraints in comprehension. In M. A. Gernsbacher (Ed.), *Handbook of psycholinguistics,* (pp. 1075–1122). San Diego: Academic Press.
Clark, A. (1997). *Being there: Putting brain, body, and world together again.* Cambridge, MA: MIT Press.
Cleary, M. & Pisoni, D. B. (2001). *Sequence learning as a function of presentation modality in children with cochlear implants.* Poster presented at CID New Frontiers Conference, St. Louis, MO.
Cleary, M., Pisoni, D. B., & Geers, A. E. (2001). Some measures of verbal and spatial working memory in eight- and nine-year-old hearing-impaired children with cochlear implants. *Ear, and Hearing, 22,* 395–411.
Cleary, M., Pisoni, D. B., & Kirk, K. I. (2002). Working memory spans as predictors of spoken word recognition and receptive vocabulary in children with cochlear implants. *The Volta Review, 102,* 259–280.
Conway, C. M., Karpicke, J., & Pisoni, D. B. (2007). Contribution of implicit sequence learning to spoken language processing: Some preliminary findings with hearing adults. *Journal of Deaf Studies and Deaf Education, 12,* 317–334.
Conway, C. M., Pisoni, D. B., Anaya, M., Karpicke, J., & Henning, S. (2008). *The role of implicit learning in spoken language development: Data from typically-developing children and deaf children with cochlear implants.* Manuscript in preparation.
Conway, C. M., Pisoni, D. B., Geers, A., Kronenberger, W. G., & Anaya, E. M. (2007). *Effects of cochlear implantation on executive function: Some preliminary findings.* Abstract submitted to the 10th International Conference

on Cochlear Implants and other Implantable Auditory Technologies. San Diego, CA, April, 2008.

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

Cowan, N. (2005). *Working memory capacity.* New York: Psychology Press.

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

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

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

Dillon, C. (2005). Phonological processing skills and the development of reading in deaf children who use cochlear implants. *Research on Spoken Language Processing, Technical Report No. 14:* Indiana University, Bloomington, IN.

Dunn, L. & Dunn, L. (1997). *Peabody picture vocabulary test* (3rd ed.). Circle Pines, MN: American Guidance Service.

Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence and functions of the prefrontal cortex. In A. Miyake & P. Shah. (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control.* London: Cambridge Press.

Erden, Z., Otman, S., & Tunay, V. (2004). Is visual perception of hearing-impaired children different from healthy children? *International Journal of Pediatric Otorhinolaryngology, 68,* 281–285.

Fagan, M. K., Pisoni, D. B., Horn, D. L., & Dillon, C.M. (2007). Neuropsychological correlates of vocabulary, reading, and working memory in deaf children with cochlear implants. *Journal of Deaf Studies and Deaf Education, 12*, 461–471.

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

Garner, W. R. (1974). *The processing of information and structure.* Potomac, MD: Lawrence Erlbaum.

Gaskell, M. G. (2007). *The Oxford handbook of psycholinguistics.* New York: Oxford University Press.

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

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

Geers, A., Brenner, C., & Davidson, L. (2003). Factors associated with development of speech perception skills in children implanted by age five. *Ear and Hearing, 24,* 24S–35S.

Geers, A., Nicholas, J., & Sedey, A. (2003). Language skills of children with early cochlear implantation. *Ear and Hearing, 24,* 46S97–58S.
Gioia, G. A., Isquith, P. K., Guy, S. C., & Kenworthy, L. (2000). *BRIEF™: Behavior Rating Inventory of Executive Function.* Psychological Assessment Resources, Inc.
Gioia, G. A., Isquith, P. K., Kenworthy, L., & Barton, R. M. (2002). Profiles of everyday executive function in acquired and developmental disorders. *Child Neuropsychology, 8,* 121–137.
Goldman-Rakic, P. S. (1988). Topography of cognition: Parallel distributed networks in primate association cortex. *Annual Reviews of Neuroscience, 11,* 137–156.
Gupta, P. & MacWhinney, B. (1997). Vocabulary acquisition and verbal short-term memory: Computational and neural bases. *Brain and Language, 59,* 267–333.
Harnsberger, J. D., Svirsky, M. A., Kaiser, A. R., Pisoni, D. B., Wright, R., & Meyer, T. A. (2001). Perceptual "vowel spaces" of cochlear implant users: Implications for the study of auditory adaptation to spectral shift. *Journal of the Acoustical Society of America, 109,* 2135–2145.
Hebb, D. O. (1961). Distinctive features of learning in the high animal. In J. F. Delafresnaye (Ed.), *Brain mechanisms and learning* (pp. 37–51). London and New York: Oxford University Press.
Horn, D., Davis, R. A. O., Pisoni, D. B., & Miyamoto, R. T. (2004). Visuomotor integration ability of pre-lingually deaf children predicts audiological outcome with a cochlear implant: A first report. *International Congress Series, 1273,* 356–359.
Horn, D., Davis, R., Pisoni, D., & Miyamoto, R. (2005a). Behavioral inhibition and clinical outcomes in children with cochlear implants. *Laryngoscope, 115,* 595–600.
Horn, D., Davis, R., Pisoni, D., & Miyamoto, R. (2005b). Development of visual attention skills in prelingually deaf children who use cochlear implants. *Ear and Hearing, 26,* 389–408.
Horn, D., Pisoni, D., Sanders, M., & Miyamoto, R. (2005). Behavioral assessment of pre-lingually deaf children prior to cochlear implantation. *Laryngoscope, 115,* 1603–1611.
Horn, D. L., Fagan, M. K., Dillon, C. M., Pisoni, D. B., & Miyamoto, R. T. (2007, in press). Visual-motor integration skills of prelingually deaf children: Implications for pediatric cochlear implantation. *Laryngoscope, 117*.
Horn, D. L., Pisoni, D. B., & Miyamoto, R. T. (2006). Divergence of fine and gross motor skills in prelingually deaf children: Implications for cochlear implantation. *Laryngoscope, 116,* 1500–1506.
Iverson, J. M. & Fagan, M. K. (2004). Infant vocal-motor coordination: Precursor to the gesture-speech system? *Child Development, 75,* 1053–1066.
Kaas, J. H., Merzenich, M. M., & Killackey, H. P. (1983). The reorganization of somatosensory cortex following peripheral nerve damage in adult and developing mammals. *Annual Review of Neuroscience,* 6, 325–356.
Karpicke, J. D. & Pisoni, D. B. (2004). Using immediate memory span to measure implicit learning. *Memory, and Cognition, 32,* 956–964.
Kirk, K. I., Pisoni, D. B., & Miyamoto, R. T. (2000). Lexical discrimination by children with cochlear implants: Effects of age at implantation and

communication mode. In S. B. Waltzman & N. L. Cohen (Eds.), *Cochlear implants* (pp. 252–254). New York: Thieme.

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

Korkman, M., Kirk, U., & Kemp, S. (1998). *NEPSY: A developmental neuropsychological assessment.* China: PsychCorp.

Kronenberger, W. G. (2006). *Learning Executive Attention Functioning (LEAF).* Department of Psychiatry, Indiana School of Medicine, Indianapolis, IN.

Kronenberger, W. G., Dunn, D. W., & Giauque, A. L. (1998). *Conduct-Hyperactive-Attention Problem-Oppositional Scale (CHAOS).* Department of Psychiatry, Indiana School of Medicine, Indianapolis, IN.

Lee, D., Lee, J., Oh, S. H., Kim, H., et al. (2001). Cross-modal plasticity and cochlear implants. *Nature, 409,* 149–150.

Lee, H., et al. (2005). Preoperative differences of cerebral metabolism relate to the outcome of cochlear implants in congenitally deaf children. *Hearing Research, 203,* 2–9.

Lenneberg, E. (1967). *Biological foundations of language.* New York: Wiley.

Locke, J., Bekken, K., McMinn-Larson, L., & Wein, D. (1995). Emergent control of manual and vocal-motor activity in relation to the development of speech. *Brain and Language, 51,* 498–508.

Luria, A. R. (1973). *The working brain: An introduction to neuropsychology.* New York: Basic Books.

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

Melton, A. W. (1963). Implications of short-term memory for a general theory of memory. *Journal of Verbal Learning and Verbal Behavior, 2,* 1–21.

Miller, E. K. & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Reviews in Neuroscience, 24,* 167–202.

Myklebust, H. R. & Brutten, M. (1953). A study of the visual perception of deaf children. *Acta Oto-laryngol, Suppl. 105. p. 126.*

Nauta, W. J. H. (1964). Discussion of 'Retardation and facilitation in learning by stimulation of frontal cortex in monkeys.' In J. M. Warren & K. Akert (Eds.), *The Frontal Granular Cortex and Behavior* (p. 125). New York: McGraw-Hill.

NIH. (1988). *Cochlear implants*. NIH Consensus Statement, May 4, Vol. 7.

NIH. (1993). *Early identification of hearing impairment in infants and young children*. NIH Consensus Statement, March 1–3, Vol. 11.

NIH. (1995). *Cochlear implants in adults and children*. NIH Consensus Statement 1995 May 15–17; 13, 1–30.

Osberger, M., Robbins, A., Todd, S., & Riley, A. (1994). Speech intelligibility of children with cochlear implants. *Volta Review, 96,* 169–80.

Penny, C. G. (1989). Modality effects and the structure of short-term verbal memory. *Memory, and Cognition, 17,* 398–422.

Pisoni, D. B. (1997). Some thoughts on "normalization" in speech perception. In K. Johnson, and J. W. Mullennix (Eds.), *Talker variability in speech processing* (pp. 9–32). San Diego: Academic Press.

Pisoni, D. B. (2000). Cognitive factors and cochlear implants: Some thoughts on perception, learning, and memory in speech perception. *Ear and Hearing, 21,* 70–78.

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

Pisoni, D. B. & Cleary, M. (2004). Learning, memory, and cognitive processes in deaf children following cochlear implantation. In F. G. Zeng, A. N. Popper, & R. R. Fay (Eds.), *Springer handbook of auditory research: Auditory prosthesis,* SHAR Volume X, 377–426. New York: Springer.

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

Pisoni, D. B. & Davis, R.A.O. (2003). Sequence learning as a predictor of outcomes in deaf children with cochlear implants. In *Research on spoken language processing progress report no. 26* (pp. 319–330). Bloomington, IN: Speech Research Laboratory, Indiana University.

Pisoni, D. B. & Geers, A. (2001). Working memory in deaf children with cochlear implants: Correlations between digit span and measures of spoken language processing. *Annals of Otology, Rhinology, and Laryngology, 109,* 92–93.

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

Quittner, A., Smith, L., Osberger, M., Mitchell, T., & Katz, D. (1994). The impact of audition on the development of visual attention. *Psychological Science, 5,* 347–53.

Riesen, A. H. (1975). *The developmental neuropsychology of sensory deprivation.* New York: Academic Press.

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

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

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

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

Savelsbergh, G., Netelenbos, J., & Whiting, H. (1991). Auditory perception and the control of spatially coordinated action of deaf and hearing children. *Journal of Child Psychology and Psychiatry, 32,* 489–500.

Schorr, E. A. (2005). *Social and emotional functioning of children with cochlear implants.* Unpublished Master's Thesis, University of Maryland, College Park, MD.

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

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

Siegel L., Saigal, S., Rosenbaum, P., Morton, R. A., Young, A., Berenbaum, S., & Stoskopf, B. (1982). Predictors of development in preterm and full-term infants: A model for detecting the at risk child. *Journal of Pediatric Psychology, 7,* 135–148.

Smith, L., Quittner, A., Osberger, M., & Miyamoto, R. (1998). Audition and visual attention: The developmental trajectory in deaf and hearing populations. *Developmental Psychology, 34,* 840–850.

Sparrow, S., Balla, D., & Cicchetti, D. (1984). *Vineland Adaptive Behavioral Scales.* Circle Pines, MN: American Guidance Service.

Spencer, P. & Delk, L. (1985). Hearing-impaired students' performance on tests of visual processing: Relationships with reading performance. *American Annals of the Deaf, 134,* 333–337.

Staller, S. J., Pelter, A. L., Brimacombe, J. A., Mecklenberg, D., & Arndt, P. (1991). Pediatric performance with the Nucleus 22-Channel Cochlear Implant System. *American Journal of Otology, 12,* 126–136.

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

Tait, M., Lutman, M. E., & Robinson, K. (2000). Preimplant measures of preverbal communicative behavior as predictors of cochlear implant outcomes in children. *Ear, and Hearing, 21,* 18–24.

Taylor, K. (1999). Relationship between visual motor integration skill and academic performance in kindergarten through third grade. *Optometry and Vision Science 76,* 69–73.

Teoh, S. W., Pisoni, D. B., & Miyamoto, R. T. (2004a). Cochlear implantation in adults with prelingual deafness: I. Clinical results. *Laryngoscope, 114,* 1536–1540.

Teoh, S. W., Pisoni, D. B., & Miyamoto, R. T. (2004b). Cochlear implantation in adults with prelingual deafness: II. Underlying constraints that affect audiological outcomes. *Laryngoscope, 114,* 1714–1719.

Teuber, H. L. (1964). The riddle of frontal lobe function in man. In J. M. Warren & K. Akert (Eds.), *The frontal granular cortex and behavior* (pp. 410–444). New York: McGraw-Hill.

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

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

Watkins, M. J., Watkins, O. C., & Crowder, R. G. (1974). The modality effect in free and serial recall as a function of phonological similarity. *Journal of Verbal Learning and Verbal Behavior, 13,* 430–447.

Waltzman, S. B., Cohen, N. L., Gomolin, R. H., Green, J. E., Shapiro, W. H., Hoffman, R. A., & Roland, J. T., Jr. (1997). Open-set speech perception in congenitally deaf children using cochlear implants. *American Journal of Otology, 18,* 342–349.

Waltzman, S. B., Cohen, N. L., Gomolin, R. H., Shapiro, W. H., Ozdamar, S. R., & Hoffman, R. A. (1994). Long-term results of early cochlear implantation in congenitally and prelingually deafened children. *American Journal of Otology, 15,* 9–13.

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

Wiegersma, P. & Van der Velde, A. (1983). Motor development of deaf children. *Journal of Child Psychology and Psychiatry 24,* 103–111.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin and Review, 9,* 625–636.