CHAPTER

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Executive Function, Cognitive Control, and Sequence Learning in Deaf Children with Cochlear Implants

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Abstract

Clinical research on deaf children with cochlear implants has been intellectually isolated from the mainstream of current research and theory in neuroscience, cognitive psychology, and developmental neuropsychology. As a consequence, the major clinical research problems have been narrowly focused on studies of speech and language outcomes and the efficacy of cochlear implantation as a medical treatment for profound hearing loss. As noted in both of the National Institutes of Health (NIH) consensus statements on cochlear implants in 1988 and 1995 (NIDCD, 1988, 1995), little, if any, research has investigated the underlying psychological and neurocognitive factors that are responsible for the enormous individual differences and variability in the effectiveness of cochlear implants. In this chapter, we report some new research findings on executive function, sequence memory, and cognitive control in prelingually deaf children who have received cochlear implants. Our results demonstrate that several domain-general neurocognitive processes related to executive function and cognitive control processes, such as working memory capacity, fluency-speed, inhibition, and organization-integration sequencing skills, are strongly associated with traditional clinical speech and language outcome measures. These specific neurocognitive processes reflect the global coordination, integration, and functional connectivity of multiple underlying brain systems used in speech perception, production, and spoken language processing. We argue that these executive function and organization-integration processes contribute an additional unique source of variance to speech and language outcomes above and beyond the conventional demographic, medical, and educational factors. Understanding the neurocognitive processes responsible for variability in spoken language processing will help both clinicians and researchers explain and predict individual differences in speech and language outcomes following cochlear implantation. Moreover, our results also have direct application to improving the diagnosis, treatment, and early identification of young deaf children who may be at high risk for poor outcomes following cochlear implantation.

Keywords: cochlear implant, executive function, deaf, children, memory, speech perception, language

Our long-term goal is to understand and predict the enormous variability in speech and language outcomes in deaf children who have received cochlear implants as a treatment for profound deafness. As noted in both of the National Institute on Deafness and Other Communication Disorders (NIDCD) consensus statements on cochlear implants in 1988 and 1995, individual differences and variability in speech and language outcomes are significant clinical problems that have not been addressed adequately in the past. Little, if any, progress has been made in understanding the neurobiological mechanisms and neurocognitive processes that are responsible for the variability observed in speech and language outcomes following cochlear implantation.

Most of the past work on cochlear implants has been concerned primarily with documenting the "efficacy" of cochlear implantation as a medical treatment for profound deafness, focusing research efforts on demographic, medical, and educational variables as predictors of outcome and benefit. With the average age of implantation steadily decreasing because of the widespread use of universal newborn hearing screening, the ability to reliably predict the "effectiveness" of cochlear implants from behavioral measures obtained from infants and young children prior to implantation becomes critical to providing appropriate habilitation following implantation. Understanding sources of variability in speech and language outcomes after cochlear implantation is a complex and challenging problem requiring multidisciplinary research efforts from scientists with backgrounds in neuroscience, cognitive psychology, and developmental neuropsychology.

A Neurocognitive Approach to Individual Differences in Outcomes

To understand, explain, and predict variability in outcome and benefit, it is necessary to situate the problem of individual differences in a much broader theoretical framework that extends well beyond the narrow clinical fields of audiology and speech pathology and fully acknowledges variability in brain–behavior relations as a natural consequence of biological development of all living systems (Sporns, 1998). Development involves interactions over time between the biological state of the individual (genetics, biological structures, and characteristics) and specific environmental experiences (sensory input, external events that influence development such as toxic exposures). There is an increasing recognition that outcomes are not exclusively genetically or environmentally predetermined. Environmental experience allows complex biological systems to self-organize during the process of development (Thelen & Smith, 1994). Alteration in early auditory experience by electrical stimulation through a cochlear implant supports a process of neurobiological reorganization that draws on and influences multiple interacting neurocognitive processes and domains and is not isolated to only speech-language functioning.

The enormous variability observed in a wide range of speech and language outcome measures following cochlear implantation may not be unique to this particular clinical population at all but may reflect instead more general underlying sources of variability observed in speech and language in healthy typically developing normal-hearing children as well as adults (Cicchetti & Curtis, 2006). Moreover, because of the important contributions of learning and memory to the development of spoken language processing, it is very likely that the sources of the individual differences observed in speech and language outcomes in deaf children with cochlear implants also reflect variation in the development of domain-general neurocognitive processes, processes that are involved in linking and coordinating multiple brain systems together to form a functionally integrated information processing system (Ullman & Pierpont, 2005).

To investigate the sources of variability in performance and understand the neural and cognitive processes that underlie variation in outcome and benefits following implantation, it is necessary to substantially broaden the battery of outcome measures to assess a wider range of behaviors and information processing skills beyond simply the traditional clinical audiological speech and language assessment measures that have been routinely used in the past by researchers working on cochlear implants. Furthermore, it is also important to recognize that a child's failure to obtain optimal benefits and achieve age-appropriate speech and language milestones from his or her cochlear implant may not be due directly to the functioning of the cochlear implant itself but may reflect complex interactions among a number of contributing factors (Geers, Brenner, & Davidson, 2003).

In our research program, we adopt the general working assumption that many profoundly deaf children who receive cochlear implants, especially children who are performing poorly, may have other contributing neural, cognitive, and affective sequelae resulting from a period of deafness and auditory deprivation combined with a language delay before implantation. The enormous variability observed in speech and language outcomes may not be due to hearing per se or to processes involved in the early sensory encoding of speech at the auditory periphery (Hawker, Ramirez-Inscoe, Bishop, Twomey, O'Donoghue, & Moore, 2008). Evidence is now rapidly accumulating to suggest that other central cortical and subcortical neurobiological and neurocognitive processes contribute additional unique sources of variability to outcome and benefit that are not assessed by the traditional battery of speech and language measures.

Brain–Behavior Relations

Our approach to the problems of variability in outcome and benefit following cochlear implantation is motivated by several recent findings and new theoretical developments that suggest that deafness and hearing impairment in children cannot be viewed in isolation as a simple sensory impairment (see also Conrad, 1979; Luria, 1973; Myklebust, 1954, 1964; Myklebust & Brutten, 1953). The enormous variability in outcome and benefit reflects numerous complex neural and cognitive processes that depend heavily on functional connectivity of multiple brain areas working together as a complex integrated system (Luria, 1973). As Nauta (1964) pointed out more than 40 years ago, "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). As described in subsequent sections, we believe this is a promising new direction to pursue in clinical research on individual differences in profoundly deaf children who use cochlear implants.

Domain-general Cognitive Factors

Our recent work with preimplant visual–motor integration (VMI) tests that use only visual patterns and require reproduction and construction processes has found significant correlations with a range of conventional clinical speech and language outcome measures obtained from deaf children following implantation. Similarly, our recent findings on nonword repetition, talker discrimination, and implicit learning of probabilistic sequential patterns presented in the sections to follow suggest that an important additional source of variance in speech and language outcomes in deaf children with cochlear implants is associated with domain-general nonlinguistic executive-organizational-integrative (EOI) processes that involve executive function (EF), cognitive control (CC), and self-regulation (Blair & Razza-Peters, 2007; Figueras, Edwards, & Langdon, 2008; Hauser, Lukomski, & Hillman, 2008).

There is now good agreement among cognitive scientists that these so-called "control processes" rely critically on global systemwide executive attention processes that reflect organization-integration, coordination, functional connectivity, and close interactions of multiple neural circuits and subsystems that are widely distributed across many areas of the brain (Sporns, 2003). Although these EOI processes overlap partially with elements of the traditional construct of global intelligence, these two broad domains of cognitive functioning can be distinguished in several ways.

First, global intelligence includes functions and abilities, such as crystallized knowledge, reasoning, long-term memory, and concept formation, that are not generally thought to be a part of EOI processes (Kaufman & Lichtenberger, 2006; Lezak, Howieson, Loring, & Hannay, 2004). Second, EOI processes are minimally dependent on the specific content of the information being processed; that is, they can be applied to almost any kind of neural or cognitive representation such as verbal, nonverbal, visual–spatial, sensory–motor (Hughes & Graham, 2002; Van der Sluis, deJong, & van derLeij, 2007). Global intelligence includes a component of content in the form of explicit declarative knowledge, accumulated experience, and acquired algorithms for problem solving. Third, recent neuroimaging studies have found differences in EOI processing ability and its relationship to brain function, even in groups of subjects that are matched on measures of global intellectual ability (e.g., Mathews, Kronenberger, Wang, Lurito, Lowe, & Dunn, 2005).

Executive-Organizational-Integrative Abilities in Cochlear Implant Outcomes

We hypothesize that EOI abilities are particularly important for speech-language development following cochlear implant because of strong reciprocal relations between the development of spoken language processing skills and the development of EOI abilities (Deary, Strand, Smith, & Fernandes, 2007; Hohm, Jennen-Steinmetz, Schmidt, & Laucht, 2007). Spoken language and verbal mediation processes provide the schemas and knowledge structures for symbolic representations that can be used for comprehension-integration (e.g., mental representation using language) and cognitive control, both of which are important EOI abilities (Bodrova & Leong, 2007; Diamond, Barnett, Thomas, & Munro, 2007; Lamm, Zelazo, & Lewis, 2006).

Additionally, early auditory experience promotes the ability to integrate temporal sequences into wholes (e.g., chunking auditory patterns into meaningful sounds and linguistic units) and to engage in fluent processing of temporal patterns. Executive-organizational-integrative processing also allows for the active control of selective attention, use of working memory, fluent speeded processing, and integration of multiple sources of information during spoken language processing. More efficient EOI processing therefore promotes better spoken language skills, whereas better language provides the key building blocks for the development of EOI abilities through verbal mediation and feedback processes (Bodrova & Leong, 2007). Because hearing loss, even mild hearing loss, interferes with critical early spoken-language experiences, we suggest that development of key EOI skills may be at risk in deaf children. A cochlear implant restores some of the components of auditory experience to a "fragile" EOI system, which in turn, becomes a fundamental influence on the ability to use spoken language to build speech and language processing skills that are key outcomes following cochlear implant.

Preliminary findings from our research, taken together with the theoretical approach articulated earlier, suggest that four key EOI areas may be involved in speech-language outcome following cochlear implant: working memory, fluency-efficiency-speed, concentration-vigilance-inhibition, and organization-integration. These abilities allow spoken language to be processed rapidly (fluency-efficiency-speed) into meaningful symbolic units (organization-integration), stored (working memory), and actively assigned meaning (organization-integration) while the individual maintains a focus on the relevant stimulus information (concentration-vigilance) and resists distracting impulses (inhibition). The need to process enormous amounts of novel auditory sensory input in the development of speech-language skills following cochlear implant therefore draws heavily on these domain-general EOI areas. A child's ability to effectively integrate, coordinate, and utilize these EOI abilities will impact on speech-language outcomes.

The hypothesis motivating our research program is that many deaf children who use cochlear implants may display delays or dysfunctions in several neurocognitive information processing domains in addition to their primary hearing loss and language delay. Some deaf children with cochlear implants may not show "age-appropriate" scores on a variety of conventional neuropsychological tests that, on the surface, appear to have little, if anything, directly to do with domain-specific sensory aspects of hearing or speech perception and spoken language processing, but reflect instead domain-general processes. Variability in these basic elementary information processing skills may ultimately be responsible for some of the individual differences observed in audiological, speech, and language outcome measures.

Nonword Repetition and Phonological Decomposition

To obtain additional knowledge about the underlying cognitive and linguistic processes that are responsible for the variation in speech and language outcomes following implantation and to broaden the information processing domains used in assessment, we carried out an unconventional nonword repetition study with a large group of deaf children to examine how they use sublexical phonological knowledge (Cleary, Dillon, & Pisoni, 2002; Dillon, Burkholder, Cleary, & Pisoni, 2004). When we first proposed using this novel experimental procedure, the cochlear implant clinicians in our center argued that deaf children would not be able to do a task like this, because they did not know any of the nonwords and they could only do immediate repetition and reproduction tasks with words that they were familiar with and had in their mental lexicons. We explained that nonword repetition has been shown in numerous studies to be a valuable experimental methodology and research tool that could provide new fundamentally different information that was not available from any of the other standard clinical assessment instruments currently in use. Moreover, several studies have reported that nonword repetition scores were strongly correlated with vocabulary development and other language learning milestones in hearing children and other clinical populations (Gathercole & Baddeley, 1990; Gathercole, Hitch, Service, & Martin, 1997).

In our first nonword repetition study (Cleary, Dillon, & Pisoni, 2002), 88 pediatric cochlear implant users were asked to listen to recorded nonsense words that conformed to English phonology and phonotactics (e.g., "altupatory") and immediately repeat back what they heard over a loudspeaker to the examiner. Several measures of their performance on this task were obtained and then correlated with open-set word recognition scores from the Lexical Neighborhood Test (LNT), Forward Digit Span, Speech Intelligibility, Speaking Rate, Word Attack, and Rhyme Errors. The Word Attack and Rhyme Errors were obtained from an isolated single-word reading task that was collected as part of a larger research project carried out by Ann Geers and her colleagues (see Geers & Brenner, 2003).

As shown in Table 29.1, the transcription scores for both consonants and vowels, as well as the perceptual ratings of the nonwords obtained from a group of normal-hearing adults were all strongly correlated with the traditional clinical outcome measures we examined, suggesting that a common set of phonological representations and processing skills are used across a wide range of different language processing tasks, even single-word reading tasks.

Although nonword repetition appears at first glance to be a simple information processing task, it is actually a complex psycholinguistic process that requires the child to perform well on each of the individual component processes involving speech perception, phonological encoding and decomposition, verbal rehearsal and maintenance in working memory, retrieval and phonological reassembly,

Table 29.1 Nonword repetition scores

	Consonants ($N = 76$)	Vowels ($N = 76$)	Accuracy Ratings ($N = 76$)
LNT easy words	+.83***	+.78***	+.76***
LNT hard words	+.85***	+.71***	+.70***
MLNT	+.77***	+.74***	+.77***
Forward Digit Span	+.60**	+.62**	+.76***
Speech Intelligibility	+.91***	+.88***	+.87***
Speaking Rate	–.84***	–.81***	–.85***
Word Attack (Reading)	+.75***	+.72***	+.78***
Rhyme Errors (Reading)	–.63**	–.68**	–.54*

*$p<.05$, **$p<.01$, ***$p<.001$
Partial correlations between nonword repetition scores and several speech and language outcome measures (controlling for performance IQ, age at onset of deafness and communication mode) based on Cleary, Dillon, and Pisoni (2002); Carter, Dillon, and Pisoni (2002); Dillon, Cleary, Pisoni, and Carter (2004); and Dillon, Burkholder, Cleary, and Pisoni (2004).

phonetic implementation, and speech production. Moreover, the nonword repetition task, like other imitation or reproduction tests, requires additional organizational-integrative processes that link these individual component processes together to produce a unitary coordinated verbal response as output.

What unique and special properties does the nonword repetition task have that other conventional clinical speech and language tests lack? First, the stimuli used in nonword repetition tasks are novel sound patterns that children have not heard before. Thus, children must make use of robust adaptive behaviors and language processing strategies that draw on past linguistic experience in novel ways. Second, the nonword repetition task requires the child to consciously control and focus his or her attentional resources exclusively on the phonological sound properties of the stimulus patterns rather than the symbolic/linguistic attributes of the meanings of the words because there is no lexical entry in the mental lexicon for these particular stimulus patterns. Finally, the nonword repetition task, like other open-set spoken word recognition tests and reproduction tasks requires the subject to rapidly carry out phonological decomposition, reassembly of the structural description of the sound pattern, and verbal rehearsal of a novel and unfamiliar phonological representation in working memory, as well as implementation and reconstruction of a vocal articulatory–motor response linking perception and action. Given these specific processing activities and the heavy demands on cognitive control and executive attention, it is not at all surprising that nonword repetition has proven to be very good at diagnosing a wide range of language disorders and delays that involve disturbances in rapid phonological processing of spoken language (Gathercole & Baddeley, 1990; Gathercole, Hitch, Service, & Martin, 1997).

Executive Function and Organizational-Integration Processes

Inhibition Processes in Speech Perception

Our interest in executive function and cognitive control processes began almost by accident with a small-scale pilot study carried out by Miranda Cleary that was originally designed to assess the talker recognition skills of deaf children with cochlear implants (Cleary & Pisoni, 2002). Using a same–different discrimination task, children heard two short meaningful English sentences in a row, one after the other, and were asked to determine if the sentences were produced by the same talker or different talkers. Half of the sentences in each set were produced by the same talker and half were produced by different talkers. Within each set, half of the sentences were linguistically identical and half were different. The results of this study are shown in Figure 29.1 for two groups of children, 8- and 9-year-old deaf children with cochlear implants, and a younger group of 3- to 5-year-old normal-hearing, typically developing children who served as a comparison group.

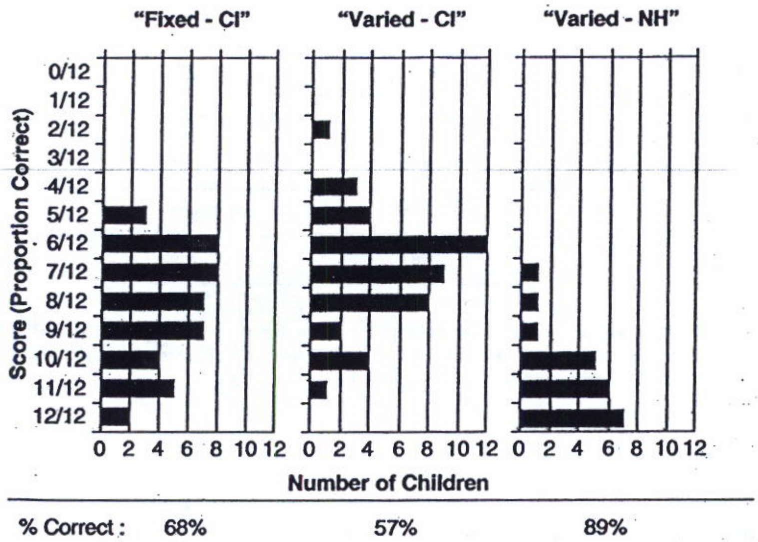

Fig. 29.1 Distribution of "same–different" sentence discrimination scores for cochlear implant users and normal-hearing controls in fixed- and varied-sentence conditions based on data reported by Cleary and Pisoni (2002).

Although the hearing 3- to 5-year-olds had little difficulty identifying whether two sentences were produced by different talkers in the varied-sentence condition as shown in the right-hand panel of Figure 29.1, the deaf children with cochlear implant had considerably more difficulty in carrying out this task. If the linguistic content of the two utterances was the same (left panel), children with cochlear implants performed the talker-discrimination task better than chance (67% correct). However, when the linguistic content of the two sentences differed in the varied sentence condition (middle panel), the performance of deaf children with cochlear implants did not differ from chance (58% correct) and was significantly worse than the group of younger normal-hearing children (89% correct).

The talker discrimination findings obtained by Cleary and Pisoni (2002) are theoretically significant because they suggest that pediatric cochlear implant users have considerable difficulty inhibiting irrelevant linguistic information in this sentence processing task. When both sentences are linguistically the same in the fixed-sentence conditions, the child can simply judge whether the voice is the same in both conditions because there is no competing semantic information to affect their discrimination response. In the varied-sentence condition, however, the child must be able to consciously control his or her attention and actively ignore and inhibit the differences in sentence meaning, the more dominant response mode, in order to selectively focus attention on the sound structure to make a decision about the speaker's voice.

An examination of the errors produced in the varied-sentence condition showed that the cochlear implant users displayed a significant response bias to incorrectly respond "different" more often than "same" for these pairs of sentences. In contrast, the normal-hearing children showed no evidence of any response bias in this condition. The differences observed in talker discrimination performance across these two sentence conditions suggest that basic sensory-auditory discriminative capacities are not the primary factor that controls performance in the same-different sentence discrimination task. Rather, discrimination performance is influenced by differences between the two groups in their ability to actively use cognitive control strategies to encode, maintain, monitor and manipulate representations of the talker's voice in working memory and selectively attend to a specific component perceptual dimension of the speech signal. These findings were even more remarkable because the control group of normal-hearing children was 3 years younger than the group of deaf children with cochlear implants. This initial study was followed up with a more extensive investigation of talker discrimination skills of deaf children with cochlear implants, which revealed strong correlations between talker discrimination and a wide range of speech and language outcome measures (see Cleary, Pisoni, & Kirk, 2005).

Neurocognitive Measures

To broaden the measures of outcome and benefit following implantation beyond the traditional endpoints speech and language assessments, we recently completed a new study that was designed to obtain additional neuropsychological measures of EF, CC, and EOI processes from a group of 5- to 10-year-old deaf children with cochlear implants. All but one of these children received their cochlear implants before 3 years of age. A group of chronologically age-matched typically developing, normal-hearing children was also recruited to serve as controls. Both groups received a battery of neuropsychological tests designed to assess selected aspects of EF and CC including verbal and spatial working memory capacity, inhibition, and processing speed, as well as fine motor control.

In addition to conventional performance measures of EF and CC obtained in the laboratory, we also obtained several additional measures using three parental report behavioral rating scales to assess EF and behavioral regulation, learning and executive attention, and attentional control and self-regulation in everyday real-world settings. More details of this study are reported by Conway et al. (in press-a). For now, however, we summarize a subset of the findings here for three of the neurocognitive performance tests, Fingertip Tapping (FTT), Design Copying (DC), and Stroop Color-word Naming (Stroop) that revealed differences in EOI functioning between the two groups of children (see also Figueras et al., 2008; Hauser et al., 2008, Pisoni et al., 2008). In the next section, we report the results of the three behavior rating scales.

NEPSY Fingertip Tapping (FTT) and Design Copying (DC)

Two of the performance measures from the NEPSY neuropsychological battery, the FTT and DC tests, revealed differences in performance between the cochlear implant and normal-hearing groups. The FTT subtest is part of the NEPSY sensory functions core domain and is designed to assess finger dexterity and motor speed. In the Repetitive Finger Tapping condition, the child is asked to make a circle with his or her thumb and index finger opening and closing it as fast as he or she can. In the Sequential Fingertip Tapping condition, the child taps the tips of his or her thumb to the index, middle, ring, and pinky making a circle with each finger. Both tests are carried out with the preferred and nonpreferred hands. The DC subtest of the NEPSY is part of the visuospatial processing domain that is used to assess a child's nonverbal visuospatial skills such as body movement and hand–eye coordination. DC measures the child's ability to reproduce and construct visual patterns. The children were given 18 geometric designs and were asked to copy each design using paper and pencil. The DC is similar to the VMI that we used with younger children in our previous work, which was successful in uncovering preimplant behavioral predictors of outcome (Horn, Fagan, Dillon, Pisoni, & Miyamoto, 2007). The results for both the FTT and DC tests indicated that deaf children with cochlear implants performed more poorly than age-matched normal-hearing control children. Moreover, the mean scores for the cochlear implant group on the FTT were not only significantly lower than the normal-hearing children's scores, but they were also atypical relative to the published normative data. These results revealed weaknesses and delays in sensory-motor and visual-spatial domains that are consistent with our hypothesis that domain-general organizational-integrative processes are at risk in deaf children with cochlear implants.

Stroop Color Word Naming

Both groups of children were also administered the Stroop Color Word Test (SCWT), which consists of three subtests: a word reading subtest that requires reading a series of 100 alternating words (either red, green, or blue) aloud as quickly as possible, a color naming subtest that requires naming a series of 100 alternating colors (indicated by X's in the colors of red, green, or blue), and a color-word subtest that requires naming the color of ink used to print each of the words (red, green, or blue, when the word name and ink color are different). Because it is much easier to read words than name colors, the color-word subtest of the SCWT is considered to be an excellent measure of the ability to inhibit a more automatic dominant response (word reading) in favor of a more effortful color naming response. Automatic word reading interferes with color naming on the color-word subtest because the printed word and the color of the ink are different and compete with each other for attention and processing resources. Word reading causes interference with the more difficult controlled-processing task of color naming. However, this interference effect occurs only to the extent that word reading is more fluent and automatic than color naming.

Individuals with less fluent reading skills or delayed phonological processing skills often perform better on the color-word subtest because they experience less interference from the (normally automatic) word reading component of that subtest (Golden, Freshwater, & Golden, 2003). Increases in reading proficiency cause greater interference and, in turn, greater relative impairment in color-word subtest scores.

Results of the SCWT revealed similar performance speed on the color-word subtest for the two groups, although the cochlear implant group performed significantly more slowly on the word reading subtest. However, the two groups did not differ on the color naming subtest. The pattern of differences in word and color naming scores is consistent with less proficient phonological processing in the cochlear implant group and indicates that the word reading task was less automatized for the deaf children with cochlear implants. The cochlear implant group showed less interference from the word reading component of the color-word task and would have been expected to do better on the color-word task compared to the normal-hearing group, a pattern that is consistent with findings that less proficient readers do better than more proficient readers on the color-word task (assuming that other cognitive abilities are matched between the groups). The failure to find differences between groups on the color-word subtest may also reflect greater resistance to interference in the normal-hearing group than in the cochlear implant group. The pattern of Stroop word reading subtest results observed with the cochlear implant group further suggests less robust automatized lexical representations of color words in memory, as well as possible delays in verbal fluency and atypical attentional switching skills in reading isolated color words aloud.

BRIEF, LEAF, and CHAOS Rating Scales of Executive Function

To obtain measures of executive function as they are realized in everyday real-world environments like home, school, or preschool settings, outside the highly controlled conditions of the audiology clinic or research laboratory, we used a neuropsychological instrument called the Behavior Rating Inventory of Executive Function (BRIEF). Three different forms of the BRIEF are available commercially from PAR, with appropriate norms (Psychological Assessment Resources [PAR], Inc., 1996). One form was developed for preschool children (BRIEF-P: 2.0–5.11 years); another for school-aged children (BRIEF: 5–18 years), and finally one was also developed for adults (BRIEF-A: 18–90 years). The BRIEF family of products was designed to assess executive functioning in everyday environments (see Gioia, Isquith, Guy, & Kenworthy, 2000).

The BRIEF consists of a rating-scale behavior inventory that is filled out by parents, teachers, and/or daycare providers to assess a child's executive functions and self-regulation skills. It contains eight clinical scales that measure specific aspects of executive function related to inhibition, shifting of attention, emotional control, working memory, planning, and organization, among others. Scores from these subscales are then combined to construct two aggregate scales for the Behavioral Regulation Index (BRI) and the Metacognitive Index (MI). Each rating inventory also provides an overall Global Executive Composite (GEC) 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 with deaf children who use cochlear implants. From our preliminary work so far, we believe that this instrument may provide new additional converging 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. Others are obtained after implantation and have turned out to have excellent clinical utility in the management and counseling of children with cochlear implants, especially poorer-performing children.

The BRIEF parent report rating inventory combined with clinical observations, parent interviews, and speech perception, and language and speech production assessments, has added an important new clinical component to our research and has generated numerous discussions with our colleagues in pediatric neuropsychology. Some parents of younger children often inquire whether their child's behaviors are similar to other children of the same age. Parents of older children have reported that their child is having more difficulty socially or academically, and can list concrete changes in behavior at home and performance in school. In both cases, parents are looking for normative benchmarks and specific suggestions because they either don't know if their child's behavior is typical for their age, or they want to know how to address manifested problems.

The information on executive function and cognitive control provided by the BRIEF clinical scales provides a quantifiable platform for broadening our discussions with parents to include possible underlying causes of particular behaviors and the effects of those behaviors on everyday real-world activities, as well as test performance. These discussions often lead to suggestions for intervention and aural rehabilitation. Discussions have included book recommendations, the role of parent training in effective behavior management, and referrals to child behavior specialists in our autism and attention-deficit hyperactivity disorder (ADHD) clinic. The BRIEF has also been used in our center to track changes in executive function and cognitive control over time and document improvements from one assessment interval to the next.

Our initial analysis of scores obtained on the BRIEF from 30 normal-hearing 5- to 8-year-old children and 19 hearing-impaired 5- to 10-year-old children with cochlear implants revealed elevated scores on several subscales. Figure 29.2a shows a summary of the BRIEF T-Scores for the GEC composite scale and the two aggregate scales, the MI and the BRI. The GEC, MI, and BRI scores were all significantly elevated for deaf children with cochlear implants than for normal-hearing children, although none of the means for the cochlear implant group fell within the clinically significant range.

Panels b and c in Figure 29.2 show the T-scores for the individual clinical scales of the BRIEF. Examination of the eight individual clinical subscales showed statistically significant differences in five of the BRIEF scales: initiation (INT), working memory (WM), planning and organization (PO), shifting (SH), and emotional control (EC). No differences were observed in organization of materials (OM), monitoring (MNTR), or inhibition (INH). The BRIEF scores provide additional converging evidence from measures of everyday real-world behaviors that multiple processing systems are linked together in development and that disturbances resulting from deafness and language delay are not domain-specific and only narrowly restricted to hearing, audition, and the processing auditory signals. The effects of deafness and language delay appear to be more widely distributed among many different neural systems and neurocognitive domains.

Two other parent- and teacher-report checklists have been developed at our ADHD clinic to evaluate executive functioning related to learning (Learning Executive and Attention Functioning scale [LEAF]) and behavior problems (Conduct-Hyperactive-Attention Problem-Oppositional Scale [CHAOS]) (Kronenberger & Dunn, 2008). Comparison of the CHAOS and LEAF scores between the cochlear implant and normal-hearing groups revealed elevated scores on most of the clinical subscales for the children with cochlear implants. In particular, as shown in Figure 29.3a and b, statistically significant differences were observed on the learning, memory, attention, speed of processing, sequential processing, complex information processing, and novel problem-solving subscales on the LEAF, and on the attention problems and hyperactivity scales on the CHAOS shown in Figure 29.3c. No differences were observed for organization and reading on the LEAF or for the oppositional problems and conduct disorder subscales on the CHAOS.

These new findings 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, processes not typically considered to be comorbid with deafness and sensory deprivation. The scores on the BRIEF, LEAF, and CHAOS rating scales provide additional converging evidence and support for the general hypothesis that multiple processing systems are linked together in development, and that disturbances resulting from deafness and language delays are not domain-specific and restricted only to hearing, speech perception, and processing spoken language. The disturbances appear to be more broadly distributed among many different brain systems that are used in language processing, including other domains such as problem solving, writing, and numerical cognition, as well as emotional control, self-regulation, and control of action in novel situations requiring adaptive behaviors.

Implicit Learning of Sequential Patterns

Very little is currently known about how learning of complex sequential patterns contributes to language outcomes following cochlear implantation. At a fundamental level of analysis, all spoken language consists of sequences of linguistic units (phonemes, syllables, and words) built from a small inventory of elementary speech sounds organized in a linearly ordered temporal sequence (Lashley, 1951). These units of spoken language do not occur randomly, but are highly regular and tightly structured according to complex probabilistic relations that make human language predictable and learnable (Miller & Selfridge, 1950; Rubenstein, 1973). After acquiring knowledge about the probabilistic relations governing word order, an individual's knowledge of these sequential probabilities in language can enable a listener to reliably identify and predict the next word that will be spoken in a sentence (Elman, 1990; Kalikow, Stevens, & Elliott, 1977; Miller & Selfridge, 1950).

Several researchers have argued recently that language development reflects the operation of

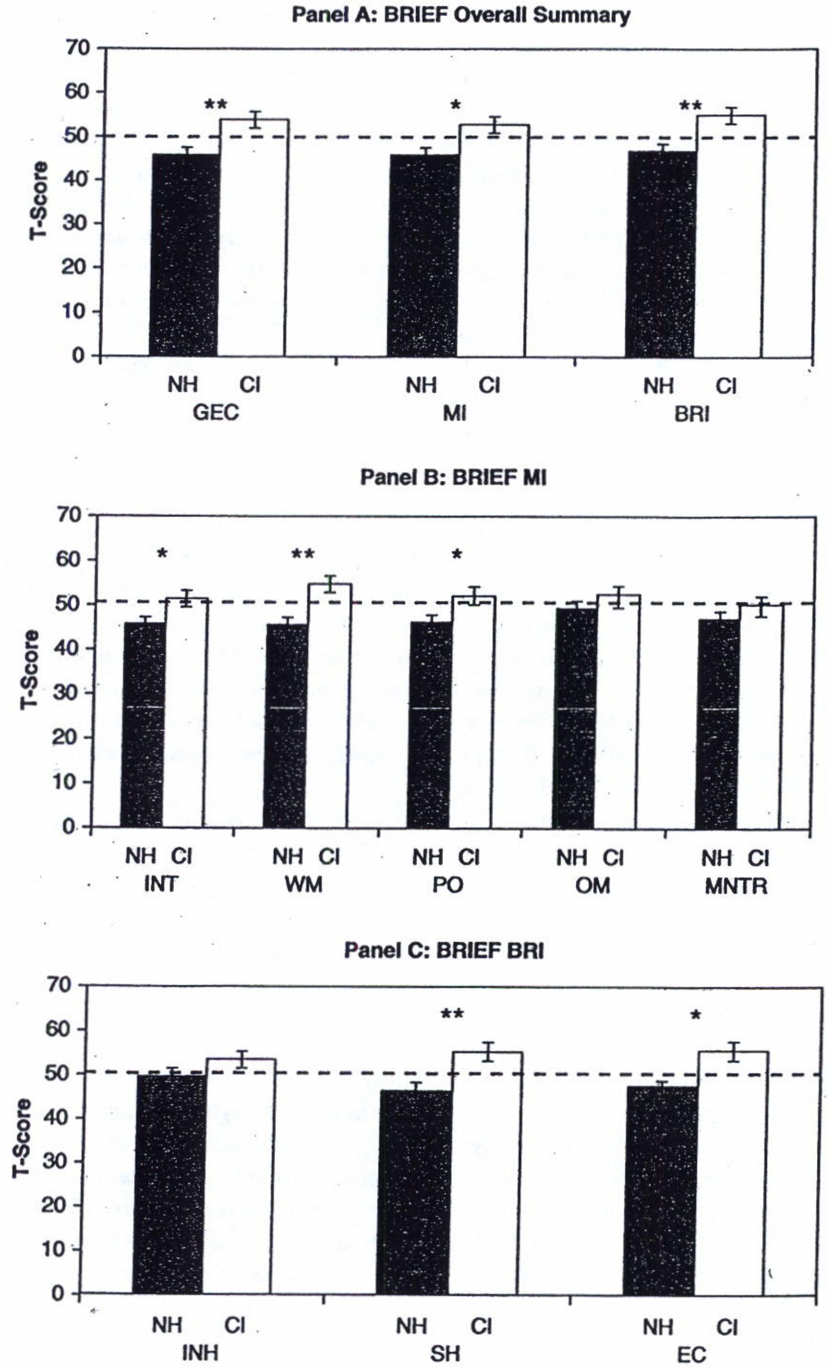

Fig. 29.2 Mean T-Scores for normal-hearing children and deaf children with cochlear implants obtained from the BRIEF parent-report behavioral rating inventory. Panel A shows the T-Scores for the Global Executive Composite (GEC), Meta Cognitive Index (MI) and the Behavior Regulation Index (BRI). Panel B shows the five individual MI clinical scales: Initiation (INT), Working Memory (WM), Planning and Organization (PO), Organization of Materials (OM) and Monitoring (MNTR). Panel C shows the three individual BRI clinical scales: Inhibition (INH), Shifting (SH) and Emotional Control (EC).

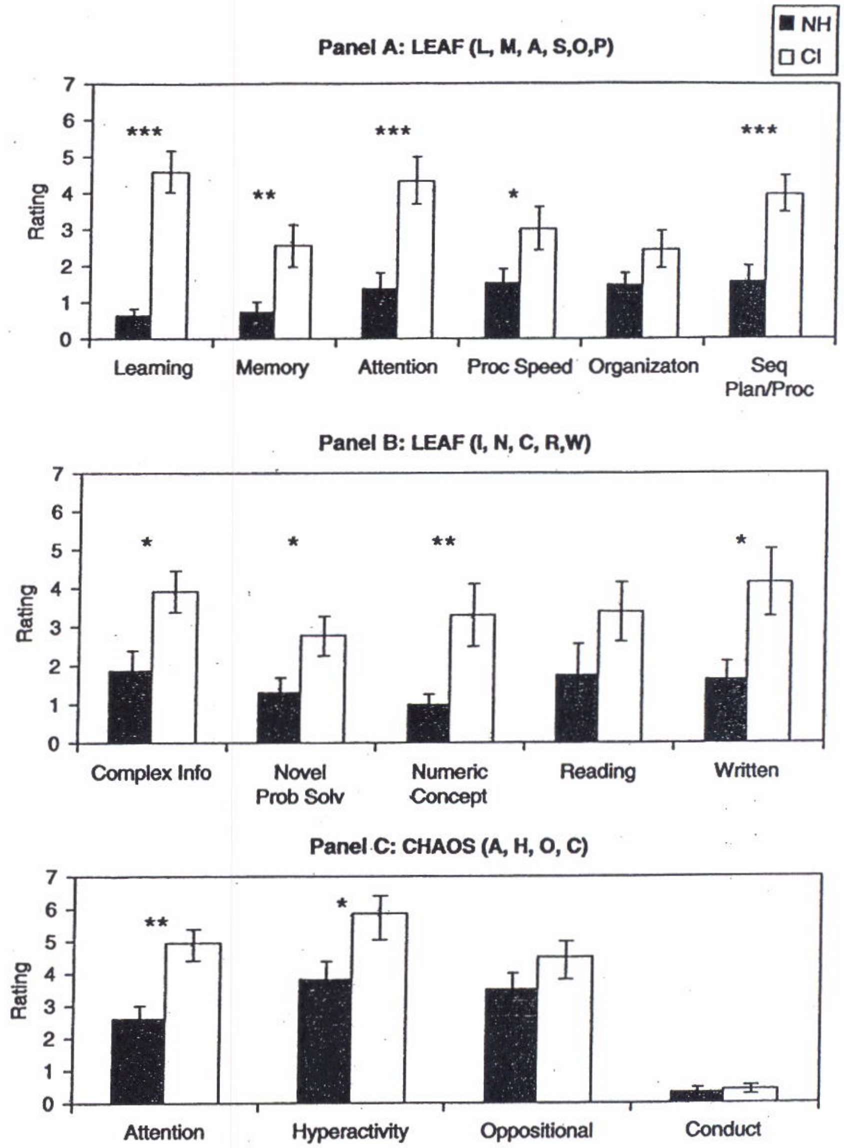

Fig. 29.3 Mean ratings for the normal-hearing children and deaf children with cochlear implants obtained from the LEAF parent-report behavioral rating inventory. Panel A shows the mean scores for: Learning, Memory, Attention, Processing Speed, Organization and Sequential Planning and Processing. Panel B shows the mean scores for: Complex Information Processing, Novel Problem Solving, Numerical Concepts, Reading and Writing. Panel C shows the mean ratings for the normal-hearing children and deaf children with cochlear implants obtained from the CHAOS parent-report behavioral rating inventory for: Attention, Hyperactivity, Oppositional and Conduct Disorders.

fundamental learning processes related to acquiring knowledge of complex probabilistic patterns. Implicit or "statistical learning" is currently thought to be one of the basic learning mechanisms used in language acquisition (Altmann, 2002; Cleeremans, Destrebecqz, & Boyer, 1998; Saffran, Senghas, & Trueswell, 2001; Ullman, 2004). There are many published examples of infants (Saffran, Aslin, & Newport, 1996), children (Meulemans & Van der Linden, 1998), adults (Conway & Christiansen, 2005), neural networks (Elman, 1990), and even nonhumans (Hauser, Newport, & Aslin, 2000) demonstrating implicit learning capabilities.

These studies have demonstrated that humans, at least under typical (i.e., "normal") conditions of development, are equipped with the necessary raw learning capabilities to acquire the complex probabilistic structure found in language. Furthermore, recent findings from our research group have revealed a close empirical link between individual differences in implicit sequence learning and spoken language processing abilities (Conway, Baurenschmidt, Huang, & Pisoni, 2010; Conway, Karpicke, & Pisoni, 2007).

In our initial studies, young healthy adults carried out a visual implicit sequence learning task and a sentence perception task that required listeners to recognize words under degraded listening conditions. The test sentences were taken from the Speech Perception in Noise Test (SPIN) and varied on the predictability of the final word (Kalikow et al., 1977). Performance on the implicit sequence learning task was found to be significantly correlated with performance on the speech perception task—specifically, for the high predictability SPIN sentences that had a highly predictable final word. This result was observed even after controlling for common sources of variance associated with nonverbal intelligence, short-term memory, working memory, and attention inhibition (see Conway et al., 2010).

The findings obtained with adults suggest that general abilities related to implicit learning of sequential patterns are closely coupled with the ability to acquire and use information about the predictability of words occurring in the speech stream, knowledge that is critical for the successful acquisition of linguistic competence. The more knowledge that an individual acquires about the underlying sequential patterns of spoken language, the better one is able to use one's long-term knowledge of those patterns to perceive and understand novel spoken utterances, especially under highly degraded or challenging listening conditions. Although these initial studies provided evidence for an important empirical link between implicit learning and language processing in normal-hearing adults, in order to better understand the development of implicit learning it is necessary to investigate implicit sequence learning processes in both typically developing and atypically developing populations, specifically, profoundly deaf children who have been deprived of sound and the normal environmental conditions of development conducive to and appropriate for language learning.

In a recent study, we measured implicit sequence learning in a group of deaf children with cochlear implants and a chronologically age-matched control group of normal-hearing typically developing children to assess the effects that a period of auditory deprivation and delay in language may have on learning of complex visual sequential patterns (Conway et al., in press-b). Some evidence already exists that a period of auditory deprivation occurring early in development may have secondary cognitive and neural sequelae in addition to the obvious first-order hearing-related sensory effects (see Conrad, 1979; Luria, 1973; Myklebust & Brutten, 1953). Specifically, because sound is a physical signal distributed in time, lack of experience with sound may affect how well a child is able to encode, process, and learn sequential patterns and encode and store temporal information in memory (Fuster, 1995, 1997, 2001; Marschark, 2006; Rileigh & Odom, 1972; Todman & Seedhouse, 1994). Exposure to sound may also provide a kind of "auditory scaffolding" in which a child gains specific experiences and practice with learning and manipulating sequential patterns in the environment.

Based on our recent implicit visual sequence learning research with adults, we predicted that deaf children with cochlear implants would show disturbances in visual implicit sequence learning because of their lack of experience with auditory temporal patterns early on in development. We also predicted that sequence learning abilities would be associated with several different measures of language development in both groups of children.

Two groups of 5- to 10-year-old children participated in this study. One group consisted of 25 deaf children with cochlear implants; the second group consisted of 27 age-matched typically developing, normal-hearing children. All children carried out two behavioral tasks: an implicit visual sequence learning task and a sentence perception task. Several clinical measures of language outcome were available for the cochlear implant children from our larger longitudinal study. Scores on these tests were also obtained for the normal-hearing children. Our hypothesis was that if some aspects of language development draw on general learning abilities, then we should observe correlations between performance on the implicit visual sequence learning task and several different measures of spoken language processing. Measures of vocabulary knowledge and immediate memory span were also collected from all participants in this study, to rule out obvious mediating variables that might be responsible for any observed correlations. The presence of correlations between the two tasks even after partialing out the common sources of variance associated with these other measures would provide support for the hypothesis that implicit learning is *directly* associated with spoken language development, rather than being mediated by a third contributing factor.

Visual Implicit Sequence Learning Task

Two artificial grammars (Grammars A and B) were used to generate the colored sequences used in the implicit learning task. These grammars specified the probability of a particular color occurring given the preceding color in sequence. Sequence presentation consisted of colored squares appearing one at a time, in one of four possible positions in a 2 × 2 matrix on a computer touchscreen. The four elements (1–4) of each grammar were randomly mapped onto each of the four screen locations as well as four possible colors (red, blue, yellow, and green). The assignment of stimulus element to position/color was randomly determined for each subject; however, for each subject, the mapping remained consistent across all trials. Grammar A was used to generate 16 unique sequences for the learning phase and 12 sequences for the test phase. Grammar B was used to generate 12 novel sequences for the test phase.

For the implicit learning task, the children were told that they would see sequences of four colored squares displayed on the touch screen. The squares would flash on the screen in a pattern, and their job was to remember the pattern of colors on the screen and reproduce each pattern at the end of each trial. The procedures for both the learning and test phases were identical and, from the perspective of the subject, there was no indication of separate phases at all. The only difference between the two phases was which sequences were used. In the Learning Phase, the 16 learning sequences from Grammar A were presented first. After completing the reproduction task for all of the learning sequences, the experiment seamlessly transitioned to the Test Phase, which used the 12 novel sequences from Grammar A and 12 novel Grammar B test sequences.

The colored squares appeared one at a time, in one of four possible positions on the touchscreen. The four colors (red, blue, yellow, and green) of each grammar were randomly mapped onto each of the four screen location. The assignment of stimulus element to position/color was randomly determined for each subject; however, for each subject, the mapping remained consistent across all trials. The children were not told that there was an underlying grammar for any of the learning or test sequences or that there were two types of sequences in the Test Phase. The child simply observed the patterns and then reproduced the visual sequences.

Eisenberg Sentence Perception Task

For this task, we used a set of English lexically controlled sentences developed by Eisenberg, Martinez, Holowecky, and Pogorelsky (2002). The stimuli consisted of 20 lexically easy (i.e., high word frequency, low neighborhood density) and 20 lexically hard (i.e., low word frequency, high neighborhood density) meaningful English sentences. The sentences were presented through a loudspeaker at 65 dB SPL. The children were instructed to listen closely to each sentence and then repeat back what they heard to the examiner, even if they were only able to perceive one word of the sentence. All of the test sentences were presented in random order to each child. Responses were recorded onto digital audio tape and were later scored off-line based on number of keywords correctly repeated for each sentence. The sentences were played in the quiet, without any degradation to the deaf children with cochlear implants. For the normal-hearing children, the original sentences were spectrally degraded to simulate a cochlear implant with a four-channel sine-wave vocoder (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995; www.TigerSpeech.Com) to reduce their performance from ceiling levels.

In the implicit learning task, a sequence was scored correct if the participant reproduced each test sequence correctly in its entirety. Sequence span scores were then calculated using a weighted method in which the total number of correct test sequences at a given length was multiplied by the length, and then scores for all lengths were added together (see Cleary, Pisoni, & Geers, 2001). We calculated separate sequence span scores for Grammar A and Grammar B test sequences for each subject.

For each subject, we also calculated an implicit learning score (LRN), which was the difference in span scores between the learned grammar (Grammar A) and the novel grammar (Grammar B). The LRN score measures generalization indicating the extent that sequence memory spans improved for sequences that had been previously experienced during the initial Learning Phase. This score reflects how well memory spans improve for *novel* sequences that were constructed by the same grammar that subjects had previously experienced in the Learning Phase, relative to span scores for novel sequences created by the new grammar.

For the Eisenberg sentence perception task, percent keyword correct scores were calculated separately for easy and hard sentences. Each child received a forward and backward digit span score, reflecting the number of digit lists correctly repeated. Each child also received a standardized Peabody Picture Vocabulary Test (PPVT) score based on how many pictures were correctly identified and their chronological age.

Group Differences in Implicit Learning

Figure 29.4a shows the average implicit learning (LRN) scores for both groups of children. For the

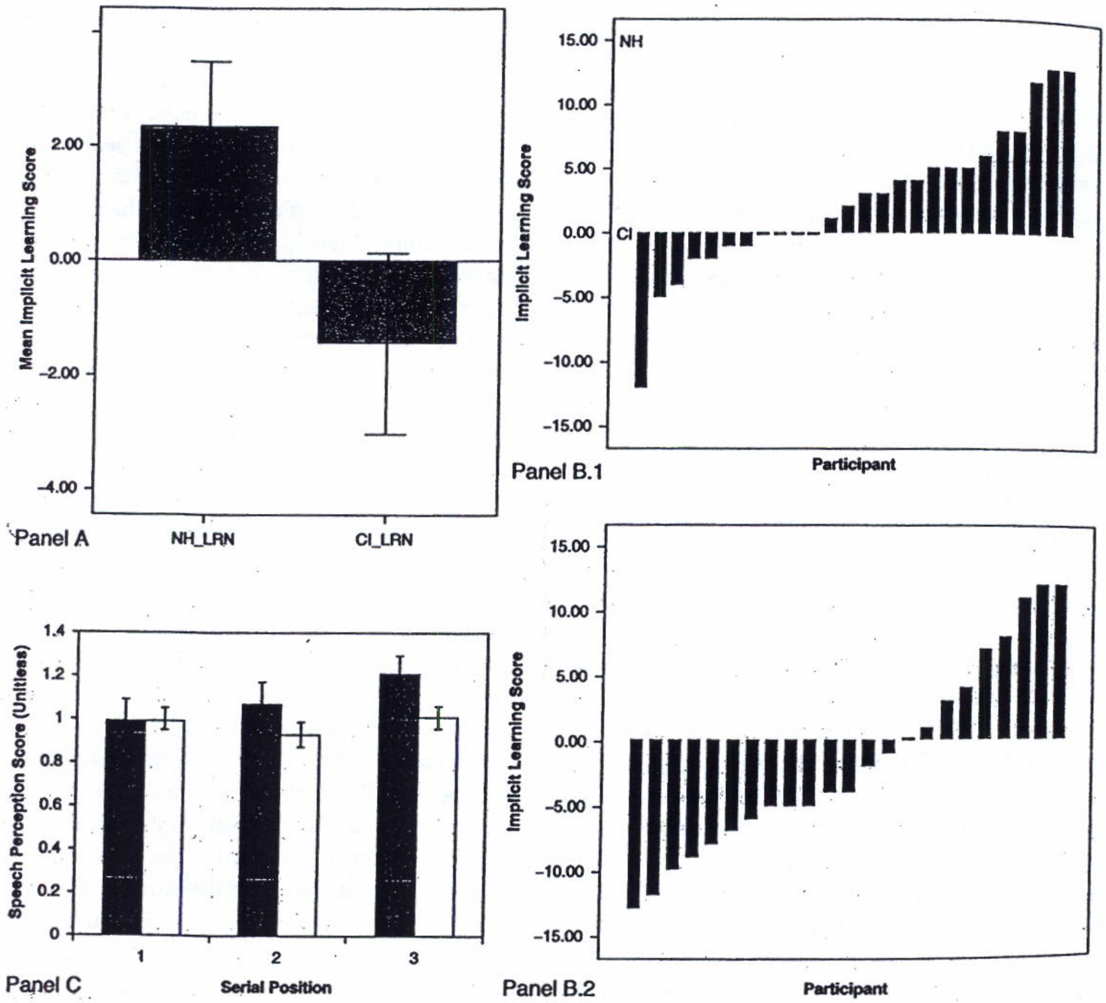

Fig. 29.4 Panel A shows the average visual implicit learning scores for normal-hearing children (*left*) and deaf children with cochlear implants (*right*). Panel B shows the implicit learning scores for individual children in the normal-hearing group (*Panel B.1*) and cochlear implant group (*Panel B.2*), ranked ordered from lowest to highest. Panel C shows the word recognition scores for normal-hearing (*gray*) and cochlear implant children (*white*) as a function of serial position within sentences for Word 1, Word 2, and Word 3. The ordinate shows a difference score that is computed by dividing the score at each word position by the score at Word 1, for the normal-hearing and cochlear implant groups separately.

normal-hearing children, the average implicit learning score (2.5) was significantly greater than 0, $t(25) = 2.24$, $p < .05$, demonstrating that, as a group, the normal-hearing children showed better learning of test sequences with the same statistical structure as the sequences from the Learning Phase. On the other hand, the average implicit learning score for the cochlear implant children was –1.43, a value that was not statistically different from 0, $t(22) = -.91$, $p = .372$. We also conducted a univariate ANOVA with the factor of group (normal-hearing, cochlear implant), which revealed a statistically significant effect of group on the implicit learning scores, $F(1, 47) = 4.3$, $p < .05$. On average, the normal-hearing group showed greater implicit learning than the cochlear implant group, who in turn essentially showed no implicit learning on this task.

In addition to comparing group means, we also examined the distribution of individual scores for each of the two groups of children on the implicit learning task. Figure 29.4b shows the implicit learning scores for each individual participant in the normal-hearing group (top) and the cochlear implant group (bottom). Whereas 19 of 26 (73%) of the normal-hearing children showed an implicit learning score of 0 or higher, only 9 of 23 (39%) of the cochlear implant children showed a score above 0. Chi-square tests revealed that the proportion of learners to non-learners was significantly different for the normal-hearing children, $\chi^2(1) = 5.54$, $p < .05$, but not for the cochlear implant children, $\chi^2(1) = 1.08$, $p = 0.297$. That is, more than half of the normal-hearing children showed an implicit learning effect, whereas this was not the case with the cochlear implant children.

The present results demonstrate that deaf children with cochlear implants show atypical visual implicit sequence learning compared to age-matched normal-hearing children. This result is consistent with the hypothesis that a period of deafness and language delay may cause secondary disturbances and/or delays in the development of visual sequencing skills. In addition, for the cochlear implant children, we computed a partial correlation between their implicit learning score and age at implantation, with chronological age partialed out. Implicit learning was negatively correlated with the age at which the child received his or her implant and positively correlated with the duration of implant use. That is, the longer the child was deprived of auditory stimulation, the lower the visual implicit learning scores; correspondingly, the longer the child had experience with sound via his or her implant, the higher the implicit learning scores. These correlations suggest that exposure to sound (via a cochlear implant or otherwise) has secondary indirect effects on basic learning processes that are not directly associated with hearing, speech perception or language development per se; longer implant use appears to be associated with better ability to implicitly learn complex visual sequential patterns and acquire knowledge about the underlying abstract grammar that generated the patterns.

Implicit Learning and Sentence Perception

The observed individual differences in implicit learning were also correlated with performance on the Eisenberg sentence perception task, which measured how well a child can perceive words in meaningful sentences, a language processing task that involves the use of both bottom-up sensory perceptual processes as well as top-down conceptual knowledge of language. Based on our earlier work with adults, we hypothesized that implicit sequence learning would be directly related to the use of top-down knowledge in speech perception and, therefore, we predicted a significant association between these two tasks. To assess this prediction, we calculated partial correlations between the implicit learning score and the two sentence perception scores (lexically easy sentences and lexically hard sentences), while controlling for the common variance associated with chronological age, forward digit span, backward digit span, and PPVT, and, for the cochlear implant children, age at implantation and articulation abilities as measured by scores obtained from the Goldman-Fristoe Test of Articulation (GFTA).

We found that implicit learning scores for deaf children with cochlear implants were associated with their ability to effectively use sentence context to guide speech perception, as reflected by the sentence perception difference score for combined lexically easy and hard sentences. Implicit learning was significantly correlated with the sentence perception difference scores, specifically, for the lexically hard sentences. These results suggest that better implicit learning abilities result in more robust knowledge of the sequential predictability of words in sentences, which leads in turn to better use of sentence context to aid speech perception, as reflected in the sentence perception difference score.

These results suggest that for the cochlear implant children, implicit learning is used to acquire information about word predictability in language, knowledge that can be brought to bear under conditions in which sentence context can be used to help perceive the next word in an utterance. If this is the case, then we would expect that the cochlear implant children, who scored worse as a group overall on implicit learning, will also be impaired on their ability to make use of the preceding context of a sentence to help them perceive the next word.

Figure 29.4c shows the performance of correctly identifying the three target words in the sentence perception task, as a function of the position in the sentence (first, second, or third), for the normal-hearing and cochlear implant children. Sentence context can do very little to aid perception of the first target word in the sentence; however, context is useful to help perceive the second and third target words, but only if the child has sufficient top-down knowledge of word order regularities. Indeed, the normal-hearing children showed an improvement in speech perception for the second and third target words. Their performance on the last word was statistically greater than performance on the first word, $t(25) = 4.2$, $p < .001$. In contrast, the cochlear implant children failed to show the same contextual facilitation. Their performance on the third word was no different than their performance on the first word in each sentence, $t(22) = .106$, $p = .92$. Unlike the normal-hearing children, the deaf children with cochlear implants do not appear to be using sentence context predictably to help them perceive the final word in the sentence. Thus, one way in which weak implicit learning abilities may reveal themselves are in situations in which word predictability and sentence context can be used together as a processing heuristic to guide spoken language perception.

Implicit Learning and Language Outcomes in Deaf Children with Cochlear Implants

We also found that implicit learning was positively and significantly correlated with three subtests of the Clinical Evaluation of Language Function-4 (CELF-4): Concepts and Following Directions, Formulated Sentences, and Recalling Sentences (Semel, Wiig, & Secord, 2003). These subtests involve understanding and/or producing sentences of varying complexity, tasks in which knowledge of word order predictability—that is, statistics of sequential probabilities in language—can be brought to bear to improve performance. Implicit learning was also positively and significantly correlated with receptive language on the Vineland Adaptive Behavior Scales (Sparrow, Balla, & Cicchetti, 1984).

The pattern of correlations obtained in our recent study suggests that implicit learning may be most strongly related to the ability to use knowledge of the sequential structure of language to better process, understand, and produce meaningful sentences, especially when sentence context can be brought to bear to aid processing. Importantly, this association does not appear to be mediated by chronological age, age of implantation, short-term or working memory, vocabulary knowledge, or the child's ability to produce speech. Moreover, these findings were modality-independent. The implicit sequence learning task used only visual patterns, whereas the sentence perception task relied on an auditory-only presentation of spoken sentences.

It is possible that experience with sound and auditory patterns via a cochlear implant, which generate complex, serially arrayed signals, provides a deaf child with critical experiences in perceiving and learning sequential patterns and establishing strong links between speech perception and production. A period of deafness early in development deprives a child of experience in dealing with complex sequential auditory input, which affects his ability to encode and process sequential patterns in other sense modalities as well (Myklebust & Brutten, 1953). Once electrical hearing is introduced via a cochlear implant, a profoundly deaf child begins for the first time to gain experience with auditory sequential input. The positive correlation between length of cochlear implant use and implicit learning scores obtained even when chronological age was partialed out suggests that early experience and interactions with sound via a cochlear implant improves a deaf child's ability to learn complex nonauditory visual sequential patterns. Thus, it is possible that, given enough exposure and experiences with sound via a cochlear implant, a deaf child's implicit learning abilities will eventually improve to age-appropriate levels.

To explain these findings, we suggest that sound affects cognitive and linguistic development by providing a perceptual and cognitive "scaffolding" of time and serial order, upon which temporal sequencing functions are based (Conway, Pisoni, & Kronenberger, 2009). From a neurobiological standpoint, it is known that lack of auditory stimulation early in development results in a decrease of myelination and fewer projections out of auditory cortex (Emmorey, Allen, Bruss, Schenker, & Damasio, 2003)—which may also include connectivity to the frontal lobe. Neural circuits in the frontal lobe, specifically the prefrontal cortex, are believed to play a critical role in learning, planning, and executing sequences of thoughts and actions (Fuster, 1995, 1997, 2001; Goldman-Rakic, 1988; Miller & Cohen, 2001). It is therefore possible that the lack of auditory input and exposure to sound sequences early on in development, and the corresponding reduction of auditory-frontal connectivity, fundamentally alters the neural organization of the frontal lobe and the extensive connections it has with other brain circuits (Wolff & Thatcher, 1990), thus impacting the development of sequencing functions regardless of input modality (Miller & Cohen, 2001).

Theoretical and Clinical Implications

Many of the deaf children with cochlear implants tested in our studies also have comorbid disturbances and/or delays in several basic underlying neurocognitive processes that subserve information processing systems used in spoken language processing, and these disturbances appear to be, at least in part, secondary to their profound hearing loss and delay in language development (Conrad, 1979; Rourke, 1989, 1995). A period of profound deafness and auditory deprivation during critical developmental periods before implantation affects neurocognitive development in a variety of ways. Differences resulting from both deafness and subsequent neural reorganization and plasticity of multiple brain systems may be responsible for the enormous variability observed in speech and language outcome measures following implantation. Without knowing what specific underlying neurobiological and neurocognitive factors are responsible for the individual differences in speech and language outcomes, it is difficult to recommend and select an appropriate and efficacious approach to habilitation and speech-language therapy after a child receives a cochlear implant. More importantly, the deaf children who are performing poorly with their cochlear implants are not a homogeneous group, and may differ in numerous ways from one another, reflecting dysfunction of multiple brain systems associated with congenital deafness and profound hearing loss. From a clinical perspective, it seems very unlikely that an individual child will be able to achieve optimal speech and language benefits from his or her cochlear implant without knowing why the child is having speech and language problems and which particular neurocognitive domains underlie these problems.

Some profoundly deaf children with cochlear implants do extremely well on traditional audiological speech and language outcome measures, whereas other children have much more difficulty. The enormous variability in outcome and benefit following cochlear implantation is a significant clinical problem in the field, and it has not received adequate attention by research scientists in the past. Obtaining a better understanding of the neurocognitive basis of individual differences in outcomes will have direct implications for diagnosis, treatment, and early identification of deaf children who may be at high risk for poor outcomes after implantation. New knowledge about the sources of variability in speech and language outcomes will also play an important role in intervention following implantation in terms of selecting specific methods for habilitation and treatment that are appropriate for an individual child. We have now identified two potential areas of neurocognitive functioning that may underlie variability in speech and language outcomes: EOI processes and implicit sequence learning abilities.

The bulk of clinical research on cochlear implants has been intellectually isolated from the mainstream of current research and theory in neuroscience, cognitive psychology, and developmental neuropsychology. As a consequence, the major clinical research issues have been narrowly focused on speech and language outcomes and efficacy of cochlear implantation as a medical treatment for profound hearing loss. Little basic or clinical research in the past has investigated the underlying neurobiological and neurocognitive bases of the individual differences and variability in the effectiveness of cochlear implants. Moreover, few studies have attempted to identify reliable early neurocognitive predictors of outcome and benefit or systematically assessed the effectiveness of specific intervention and habilitation strategies after implantation. We believe these are important new areas of clinical research on cochlear implants that draw heavily on basic research and theory representing the intersection of several closely related disciplines that deal with the relations between brain, behavior and development, memory and learning, attention, executive function, and cognitive control.

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