Developmental Science

Developmental Science 14:1 (2011), pp 69–82 DOI: 10.1111/j.1467-7687.2010.00960.x

PAPER

Implicit sequence learning in deaf children with cochlear implants

Christopher M. Conway,[1] David B. Pisoni,[2,3] Esperanza M. Anaya,[2] Jennifer Karpicke[4] and Shirley C. Henning[3]

1. *Department of Psychology, Saint Louis University, USA*
2. *Department of Psychological and Brain Sciences, Indiana University, USA*
3. *Department of Otolaryngology-Head and Neck Surgery, Indiana University School of Medicine, USA*
4. *Department of Speech, Language, and Hearing Sciences, Purdue University, USA*

Abstract

Deaf children with cochlear implants (CIs) represent an intriguing opportunity to study neurocognitive plasticity and reorganization when sound is introduced following a period of auditory deprivation early in development. Although it is common to consider deafness as affecting hearing alone, it may be the case that auditory deprivation leads to more global changes in neurocognitive function. In this paper, we investigate implicit sequence learning abilities in deaf children with CIs using a novel task that measured learning through improvement to immediate serial recall for statistically consistent visual sequences. The results demonstrated two key findings. First, the deaf children with CIs showed disturbances in their visual sequence learning abilities relative to the typically developing normal-hearing children. Second, sequence learning was significantly correlated with a standardized measure of language outcome in the CI children. These findings suggest that a period of auditory deprivation has secondary effects related to general sequencing deficits, and that disturbances in sequence learning may at least partially explain why some deaf children still struggle with language following cochlear implantation.

Introduction

Deaf children with cochlear implants (CIs) provide a unique opportunity to study brain plasticity and neural reorganization. In some sense, this research effort can be thought of as the modern equivalent of the so-called 'forbidden experiment' in the field of language development: it provides an ethical research opportunity to study the effects of the introduction of sound and spoken language on cognitive and linguistic development after a period of auditory deprivation. Whereas most previous work with this population has investigated the development of auditory perception, speech perception, and spoken language development, relatively few studies have examined more global learning and cognitive capabilities.

There is in fact some indication that a period of auditory deprivation occurring early in development may have secondary cognitive and neural ramifications in addition to the obvious hearing-related effects. Specifically, because sound by its very nature is a temporally arrayed signal, a lack of experience with sound may affect how well one is able to encode, process, and learn serial patterns in any modality (Marschark, 2006; Rileigh & Odom, 1972; Todman & Seedhouse, 1994). Exposure to sound may provide a kind of 'auditory scaffolding' in which a child gains vital experience and practice with learning and representing sequential patterns in the environment (Conway, Pisoni & Kronenberger, 2009). If true, then a lack of experience with sound may delay the development of domain-general processing skills that rely on the encoding and learning of temporal or sequential patterns, even for non-auditory input. In fact, previous findings do suggest that profound deafness may result in disturbances to non-auditory abilities related to processing temporal or serial order information (e.g. Horn, Davis, Pisoni & Miyamoto, 2005; Knutson, Hinrichs, Tyler, Gantz, Schartz & Woodworth, 1991; Pisoni & Cleary, 2004; Rileigh & Odom, 1972). Even so, the ability to *learn* complex, non-auditory sequential patterns has not been explored in children who are profoundly deaf.

Fundamental learning abilities related to acquiring complex probabilistic patterns – i.e. implicit, statistical, or sequential learning – have been argued to be

Address for correspondence: Christopher M. Conway, Department of Psychology, 222 Shannon Hall, Saint Louis University, 3511 Laclede Avenue, St Louis, MO 63103, USA; e-mail: cconway6@slu.edu

important for cognitive development, especially in regard to successful language acquisition and processing (Altmann, 2002; Cleeremans, Destrebecqz & Boyer, 1998; Conway, Bauernschmidt, Huang & Pisoni, 2010; Conway & Pisoni, 2008; Saffran, Senghas & Trueswell, 2001; Ullman, 2004). At its most fundamental level, spoken language consists of a series of sounds (phonemes, syllables, words) occurring sequentially (Lashley, 1951). Language acquisition in part likely involves general learning mechanisms that are used to extract and process regularities in any complex sequential domain, be it linguistic or not. 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 robust implicit sequence learning capabilities. These 'existence proofs' have proven beyond a doubt that the human (and possibly nonhuman) organism, at least under typical developmental conditions, is equipped with relatively powerful, raw learning capabilities for acquiring complex, probabilistic sequential patterns.

In the case of profound deafness, although a CI provides the means to successfully develop age-appropriate speech and language abilities, it is well known that some children obtain little language benefit other than the awareness of sound from their implant (American Speech-Language-Hearing Association, 2004). Some of this variation in outcome has been shown to be due to certain demographic factors, such as age at implantation and length of deafness (Kirk, Miyamoto, Lento, Ying, O'Neil & Fears, 2002; Tomblin, Barker & Hubbs, 2007). However, these demographic variables leave a large amount of variance unexplained. It is likely that intrinsic cognitive factors, especially fundamental learning and memory abilities, contribute to language outcomes following implantation (Pisoni, 2000). Disturbances in implicit sequence learning specifically may hold the key to understanding the enormous range of variation in language development in this population (Pisoni, Conway, Kronenberger, Horn, Karpicke & Henning, 2008).

In this paper, we explore these issues by examining implicit sequence learning in deaf children with CIs compared to an age-matched group of normal-hearing children. The aims are twofold: to assess the effects that a period of auditory deprivation and language delay may have on domain-general sequence learning skills; to investigate the possible role that sequence learning plays in language outcomes following cochlear implantation. Our hypothesis is that deaf children with CIs may show disturbances in visual implicit sequence learning as a result of their relative lack of experience with sequential (auditory) patterns early on in development. Furthermore, if implicit sequence learning is important for successful language acquisition, then we would expect that sequence learning performance will be associated with measures of language development, with better sequence learners showing the best language outcomes post-implantation.

Experiment

Two groups of children participated, deaf children with CIs, and an age-matched group of typically developing, normal-hearing (NH) children. All children were tested on an implicit sequence learning task. We also collected a clinical measure of language outcome for the CI children. We reasoned that if language development is based in part on general, fundamental learning abilities, then it ought to be possible to observe empirical associations between performance on the implicit sequence learning task and a measure of language development. Several additional measures of memory and language were also collected from all participants in order to rule out alternative mediating variables – such as vocabulary knowledge or immediate memory span – responsible for any observed correlations. Observing a correlation between the two tasks even after partialing out the common sources of variance associated with these other measures would provide converging support for the conclusion that implicit learning is *directly* associated with spoken language development, rather than being mediated by a third underlying factor.

The sequence learning task used here is based on the Milton Bradley game 'Simon' and was developed to be used specifically with hearing-impaired children (see Cleary, Pisoni & Geers, 2001; Pisoni & Cleary, 2004). In this task, visual color sequences are presented. After each sequence presentation, the child is asked to reproduce it by pressing the panels of a touch-sensitive screen. Unbeknownst to the participants, in the initial phase, all sequences are generated from an underlying artificial grammar that dictates the order in which particular colors can occur in the sequence (Karpicke & Pisoni, 2004). Learning is assessed by the extent to which immediate serial recall improves for novel sequences having the same underlying structure (i.e. conforming to the artificial grammar) compared to novel sequences that are not consistent with the grammar. Several recent studies (Botvinick, 2005; Conway, Karpicke & Pisoni, 2007; Jamieson & Mewhort, 2005; Karpicke & Pisoni, 2004) as well as a number of older, classic studies (Miller, 1958; Reber, 1967) have looked at improvements to immediate serial recall as a measure of implicit learning. As argued by Redington and Chater (2002), this indirect method for measuring sequence learning is arguably superior to that typically used in most artificial grammar learning studies, explicit grammaticality judgments, which likely depend on metacognitive awareness. Especially considering the age of the participants, using an indirect measure of learning that does not depend on explicit or consciously controlled strategies seems ideal.

Method

Participants

Deaf children with CIs

Twenty-five prelingually, profoundly deaf children were recruited through the DeVault Otologic Research Laboratory at the Indiana University School of Medicine, Indianapolis. Inclusion criteria included chronological age 5–10 years, onset of profound bilateral hearing loss (90 dB or greater) by age 2, had received a cochlear implant by age 4, had used their implant for a minimum of 3 years, and were native speakers of English. Except for two children with bilateral implants and one child who had a hearing aid in the non-implanted ear, all children had a single implant. For the three children with bilateral hearing, testing was conducted with only one CI activated (the original implant). Although several of the children had been exposed to Signed Exact English, none of the children relied exclusively on sign or gesture, and all children were tested using oral-only procedures. Aside from hearing loss, there were no other known cognitive, motor, or sensory impairments. For their time and effort, the children's parents/caregivers received monetary compensation.

Normal-hearing children

Twenty-seven typically developing, NH children were recruited through Indiana University's 'Kid Information Database' and through the Life Education and Resource Home Schooling Network of Bloomington, IN. Inclusion criteria included chronological age 5–10 years and native speakers of English. Parental reports indicated no history of a hearing loss, speech impairment, or cognitive or motor disorder. For their participation, children received a small toy and their parents received monetary compensation.

Exclusion criteria

For both groups of participants, children's data were excluded based on the following criteria. First, if any child refused to participate in portions of the tasks and/or displayed inattention or lack of motivation, their data were excluded. This criterion resulted in two of the CI children being excluded from subsequent analyses. Second, if any child's performance on the primary experimental measure, the Simon learning game (described below), was more than 2 standard deviations from the group mean, their data were excluded. This criterion resulted in one of the NH children being excluded. In total, two CI children and one NH child were excluded, resulting in a total of 23 CI children and 26 NH children included in all analyses subsequently reported.

Participant characteristics

Table 1 summarizes the demographic characteristics of the 23 CI children and 26 NH children included in all analyses. In addition to chronological age and two measures specific to the CI group (age at implantation and duration of CI use), five additional measures were collected in order to provide a comparison between the groups on both verbal and nonverbal abilities. These are described next.

Verbal ability was assessed through the forward and backward digit span tasks of the WISC-III intelligence scale (Wechsler, 1991) as well as the Peabody Picture Vocabulary Test (PPVT) (3rd edn.). In the digit span tasks, digits were played through loudspeakers and the child's task was to repeat the digits back in correct order. Subjects received a point for each list that they correctly recalled in each digit span task. Generally, the forward digit span task is thought to reflect the involvement of processes that maintain and store verbal items in short-term memory for a brief period of time, whereas the backward digit span task reflects the operation of controlled attention and higher-level executive processes that manipulate and process the verbal items held in immediate memory (Rosen & Engle, 1997). The PPVT is a standard measure of vocabulary development (Dunn & Dunn, 1997). In this task, participants are shown four pictures on a single trial. They are prompted with a particular English word and then asked to pick the picture that most accurately depicts the word. For each

Table 1 *Participant characteristics*

	CI children[a]			NH children[b]				
Measure	*M*	*SD*	Range	*M*	*SD*	Range	*t*(47)	*p*
Age	90.1	19.9	61–118	87.8	11.8	65–104	0.5	0.60
Age Implant	21.2	8.3	10–39	–	–	–	–	–
CI Duration	68.9	19.4	36–98	–	–	–	–	–
FD	4.9	1.6	2–8	7.0	1.9	5–12	−4.3	0.0001
BD	2.5	1.5	0–5	3.7	1.0	2–6	−3.5	0.001
PPVT	85.9	12.2	59–107	114.3	12.7	90–139	−7.9	0.0001
CMS-T	11.4	3.2	6–16	11.5	3.0	5–15	−0.1	0.90
CMS-D	10.7	2.9	5–15	11.6	2.0	5–14	−1.2	0.22

Note: Age is given in months; Age Implant, age at cochlear implantation (in months); CI Duration, duration of cochlear implant use (in months); FD, forward digit span score; BD, backward digit span score; PPVT, Peabody Picture Vocabulary Test scaled score; CMS-T, Children's Memory Scale (Total) scaled score; CMS-D, Children's Memory Scale (Delayed test) scaled score.
[a] $n = 23$; [b] $n = 26$.

child, a scaled score is derived based on comparison with a large normative sample.

Nonverbal ability was assessed through the 'dot locations' subtest of the Children's Memory Scale (CMS; Cohen, 1997). In this test of nonverbal visual-spatial learning and memory, the children were shown a picture of six blue dots on a large white background. The dot pattern was presented to the child for 5 seconds before being taken out of sight. The child was then asked to reproduce the dot pattern from memory by placing six blue chips onto a 3×4 grid. This occurred a total of three times using the same dot pattern on each trial. Next, a trial of red dots was presented and the child was asked to reproduce it. The red dot trial was not scored, but rather served as a distracter. The child was then asked to recall from memory the initial blue dot pattern that had been presented three times ('short delay' trial). At the conclusion of the experiment (after a delay of approximately 30 minutes), the child was asked once more to reproduce the blue dot pattern from memory ('long delay' trial). The child's pattern reproductions were scored based on total number of chips placed correctly on the grid. As per standard procedure, the raw scores were converted into scaled scores, taking into account the age of the child, resulting in two scaled scores: visual-spatial learning 'total' score (sum of scores on trials 1–3 plus the short delay trial); and visual-spatial 'long delay' score (score on the long delay trial).

As Table 1 shows, the children were well matched in regard to both chronological age and visual (nonverbal) memory abilities as assessed by the dot pattern subtest of the CMS. However, the NH children exceeded the CI children on their forward and backward digit spans and receptive vocabulary scores, a finding that is consistent with previous research using this population (Cleary *et al.*, 2001; Pisoni & Cleary, 2004).

Apparatus

A Magic Touch® touch-sensitive monitor displayed the visual stimuli and recorded participant responses for the sequence learning task.

Stimulus materials

For the sequence learning task, we used two artificial grammars to generate the stimuli (cf. Jamieson & Mewhort, 2005). These grammars, depicted in Table 2, specify the probability of a particular element (color) occurring given the preceding element. For each stimulus sequence, the starting element (1–4) was randomly determined and then the listed probabilities were used to determine each subsequent element, until the desired length was reached. Grammar A was used to generate 16 unique sequences for the learning phase (six of length 2 and five each of lengths 3 and 4) and 12 sequences for the test phase (four each of lengths 3–5), hereafter referred to as the 'grammatical test sequences'. Grammar B was used to generate

Table 2 *Grammars A and B used in the implicit learning task*

Colors/ locations (n)	Grammar A (n + 1)				Grammar B (n + 1)			
	1	2	3	4	1	2	3	4
1	0.0	0.5	0.5	0.0	0.0	0.0	0.0	1.0
2	0.0	0.0	1.0	0.0	0.5	0.0	0.0	0.5
3	0.5	0.0	0.0	0.5	0.0	1.0	0.0	0.0
4	1.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0

Note: Grammars show transition probabilities from position n of a sequence to position n + 1 of a sequence for four colors labeled 1–4.

12 sequences for the test phase as well (four each of lengths 3–5), hereafter referred to as the 'ungrammatical test sequences'. All learning and test phase sequences are listed in the Appendix.

Procedure

The deaf children with CIs were tested by a trained Speech Language Pathologist at the Devault Otologic Research Laboratory, Department of Otolaryngology, Indiana University School of Medicine, Indianapolis. The NH children were tested in a sound-attenuated booth in the Speech Research Laboratory at Indiana University, Bloomington. All testing procedures were identical for both groups of children. This was accomplished by creating a written protocol manual specifying the procedures and language used for the experiments with both groups of children. Both experimenters followed this manual precisely. In addition, the two experimenters met regularly with the first author to discuss matters related to procedure as well as occasionally observing one another's test sessions in order to keep testing procedures as close as possible for all children. For both groups of children, the study consisted of 10 tasks in a session lasting 60–90 minutes, with breaks provided as needed. However, data from only four of the tasks are reported here (sequence learning, digit spans, PPVT, and CMS).

Before beginning the experiment, all NH children received and passed a brief pure-tone audiometric screening assessment in both ears. Both groups of children were also given a brief color screening, which consisted of presenting four blocks to the children, each of a different color (blue, green, red, yellow), and asking them to point to each and name the color. This was done to ensure that the children could perceive and name each of the four colors used in the implicit learning task. All children passed this screening. Following the screening, all children were given the sequence learning task, followed by the digit span tasks and the vocabulary test.

In addition, for the deaf children with CIs, we included a standardized clinical measure of language outcome. As part of the children's regular visits to the Department of Otolaryngology, 17 of the 23 children were assessed on three core subtests of the Clinical Evaluation of Language Fundamentals, 4th edn. (CELF-4), an assessment tool for diagnosing language disorders in children (Semel, Wiig & Secord, 2003). These three subtests measure aspects of general language ability: Concepts and Following Directions (C&FD), Formulated Sentences (FS), and Recalling Sentences (RS). A brief description of these three subtests is provided in Table 3 (see Paslawski, 2005, for a review and description of all subtests).

Sequence learning task

For the visual sequence learning task, participants were given the following instructions:

> You are going to see some squares of different colors on this computer screen. The squares will flash on the screen in a pattern. Your job is to try to remember the pattern of colors that you see on the screen. After each pattern, you will see all four colors on the screen. You need to touch the colors in the same pattern that you just saw. For example, if you saw the pattern red-green-blue, you would touch the red square, then the green square, and then the blue square. Touch where it says 'continue' on the bottom of the screen when you're finished. Always use your (preferred) hand to touch the screen and rest your arm on this gel pad.

After explaining the instructions to each child, the experimenter gave each child two practice trials to assess whether they understood the instructions. Only after successful demonstration that they understood the instructions did the experiment continue.

Unbeknownst to participants, the task actually consisted of two parts, a Learning Phase and a Test Phase. The procedures for both phases were identical and in fact, 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 were presented in three blocks: the six length-2 sequences first, then the five length-3 sequences, and finally the five length-4 sequences; within each block, sequences were presented in random order. After completing the sequence reproduction task for all of the learning sequences, the experiment seamlessly transitioned to the Test Phase, which used the 12 novel grammatical and 12 novel ungrammatical test sequences. Test sequences were presented in three blocks: the eight length-3 sequences first, the eight length-4 sequences next, and finally the eight length-5 sequences; within each block, sequences were presented in random order.

Sequence presentation consisted of colored squares appearing one at a time, in one of four possible positions on the touchscreen (upper left, upper right, lower left, lower right). 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, green). The assignment of stimulus element to position/color was randomly determined for each subject; however, for each subject, the mapping always remained consistent across all trials.

After a colored square appeared for 700 msec, the screen was blank for 500 msec, and then the next color of the sequence appeared. After the entire sequence had been presented, there was a 500-msec delay and then the four panels appeared on the touch screen that were the same size and same color as the four locations that were used to display each sequence. The subject's task was to watch a sequence presentation and then to reproduce the sequence they saw by pressing the appropriate buttons in the correct order as dictated by the sequence. When they entered their response, they were instructed to press a 'Continue' button at the bottom of the screen, and then the next sequence was presented after a 3-sec delay. A schematic of the sequence learning task is shown in Figure 1.

Participants were not told that there was an underlying grammar for any of the learning or test sequences, nor that there were two types of sequence in the Test Phase. From the standpoint of the participant, the sequence task was solely one of observing and then reproducing a series of visual sequences.

Table 3 *CELF-4 subtest description*

Subtest	Description
C&FD	Measures auditory comprehension and recall of utterances of increasing length and complexity
FS	The child is given a word or words and must generate spoken sentences in reference to a picture cue
RS	A sentence imitation task

Note: C&FD, Concepts and Following Directions; FS, Formulated Sentences; RS, Recalling Sentences.

Results

In the sequence learning task, a sequence was scored correct if the participant reproduced each test sequence correctly in its entirety. For each group, separate accuracy (% correct) scores were computed for the Learning and Test phases. Because of the relatively short duration of the Learning Phase, accuracy scores for this phase are not expected to reflect grammar learning *per se*; rather, performance in this phase presumably reflects children's ability to accurately reproduce visual sequences from immediate memory. On the other hand, as is typical in artificial grammar learning studies, the Test Phase has been constructed such that it will indeed provide a way to measure the children's sequence learning abilities for the artificial grammar. This is achieved by comparing recall performance for novel grammatical test sequences relative to ungrammatical test sequences. To the extent that sequence learning has occurred, one would expect recall for the grammatical patterns to exceed those for the ungrammatical ones (see Jamieson & Mewhort, 2005; Karpicke & Pisoni, 2004; Miller, 1958).

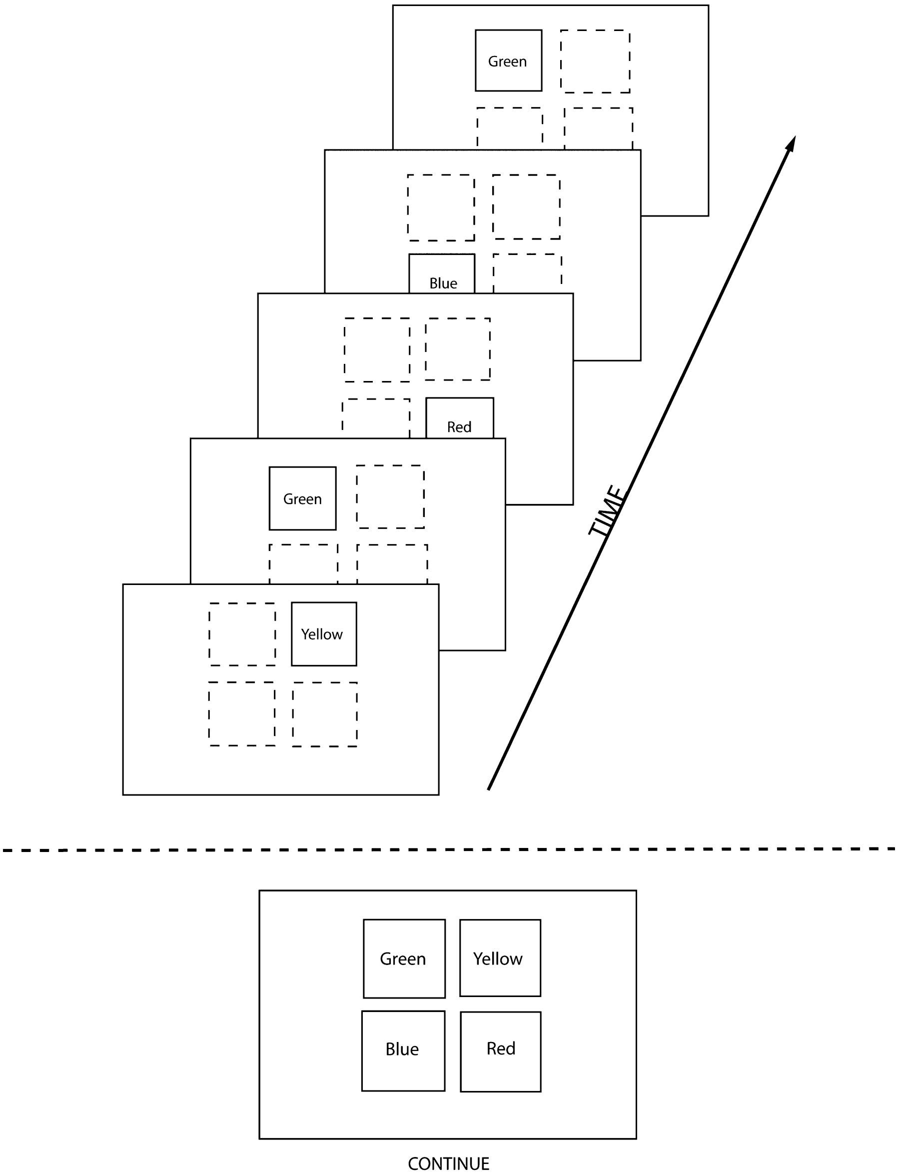

Figure 1 *Depiction of the visual implicit learning task used in the experiment, similar to that used in previous work (Conway* et al.*, 2007; Karpicke & Pisoni, 2004). Participants view a sequence of colored squares (700-msec duration, 500-msec ISI) appearing on the computer screen (top) and then, 500 msec after sequence presentation, they must attempt to reproduce the sequence by pressing the touch-panels in correct order (bottom). The next sequence occurs 3000 msec following their response.*

The Learning Phase results revealed no differences between the two groups in the number of sequences correctly reproduced: 76.19% vs. 72.56% for the NH and CI groups, respectively ($t(47) = .61$, $p = .55$). This suggests that the CI children can accurately reproduce visual sequences from immediate memory just as well as the NH children. Importantly, it also provides a very nice control, because the equivalent Learning Phase performances for the two groups suggest that both groups of children understood the task instructions equally well, ruling out the possibility that any differences occurring in the Test Phase results are due to such confounds.

While the Learning Phase results indicate no overall difference in the ability to immediately recall and reproduce visual sequences, the Test Phase results on the other hand did reveal group differences. As shown in Figure 2, the NH group correctly reproduced a significantly greater number of grammatical compared to ungrammatical test sequences (59.0% vs. 53.2%; $t(25) = 2.25$, $p < .05$). This finding demonstrates that as a group the NH children showed better immediate serial recall for novel test sequences having the same statistical/sequential structure as the ones from the Learning Phase. On the other hand, the CI group did not show a difference in performance for the grammatical compared to ungrammatical test sequences (50.0% vs. 52.5%; $t(22) = -.77$, $p = .50$). Thus, on average, the NH group showed evidence of implicit sequence learning on this task, whereas the CI children essentially showed no learning.

For each subject we also calculated a learning score (LRN), the difference in accuracy between the gram-

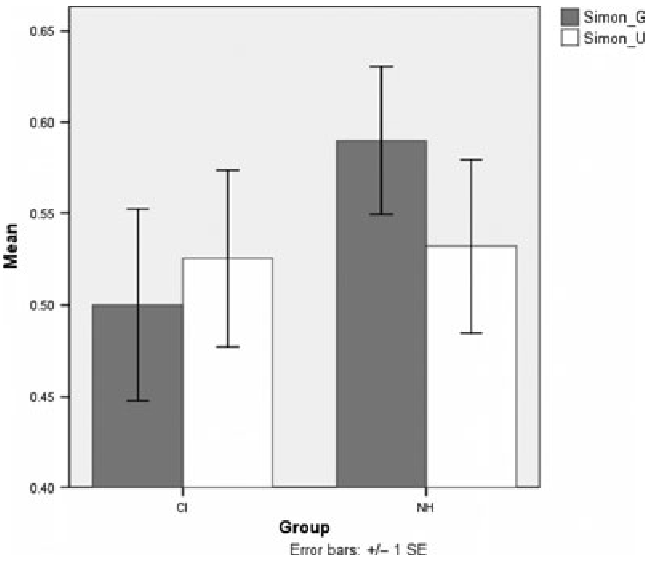

Figure 2 *Average grammatical sequence (black) and ungrammatical sequence (white) % correct scores for CI children (left) and NH children (right). Error bars represent ± 1 standard error.*

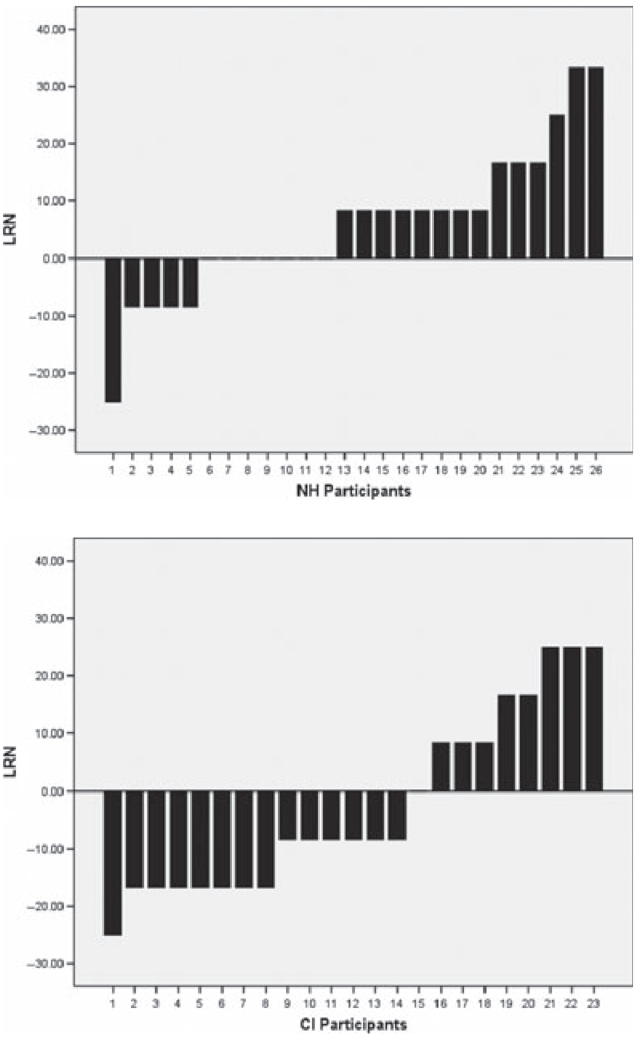

Figure 3 *Implicit learning scores for each individual participant in the NH (top) and CI groups (bottom), ranked order from lowest to highest.*

matical and ungrammatical test sequences. The LRN score reflects the extent to which sequence memory spans improved for sequences derived from the same grammar as in the Learning Phase and therefore is a quantifiable measure of implicit sequence learning. Consistent with the above analyses, the NH group's learning score (5.8%[1]) was significantly greater than the CI group's score (−2.5%; $t(47) = -2.01$, $p < .05$).

In addition, Figure 3 shows a comparison of the distribution of individual LRN scores for each of the two groups of children (NH group on the top and CI group on the lower panel). Whereas about half (53.8%; 14/26) of the NH children showed a sequence learning score greater than 0, only about one-third (34.7%; 8/23) of the CI children did.

Finally, we computed partial correlations between sequence learning and age at implantation and duration of implant use, while controlling for chronological age. Sequence learning was negatively correlated with the age at which the child received their implant ($r = -.410$, $p = .058$, two-tailed) and positively correlated with the duration of implant use ($r = .410$, $p = .058$, two-tailed).[2] That is, the longer the child was deprived of auditory stimulation early in development, the lower their visual sequence learning scores (see Figure 4); correspondingly, the longer the child had experience with sound via the implant, the higher their sequence learning scores.

Consistent with the hypothesis that a period of deafness (and/or language delay) may cause secondary difficulties with domain-general sequencing skills, the present results reveal that deaf children with CIs display atypical visual implicit sequence learning abilities. Moreover, the partial correlations suggest that both the length of auditory deprivation and the amount of exposure to sound via a cochlear implant has secondary consequences not directly associated with hearing or language development *per se*. The amount of experience with sound, or lack thereof, appears to affect the ability to implicitly learn complex visual sequential patterns.

Implicit learning and language outcomes in deaf children with CIs

The question we next turn to is whether individual differences in sequence learning are associated with

[1] It could be objected that an increase of 5.8% for grammatical vs. ungrammatical sequences is a trivial gain. However, the magnitude of learning in much of the artificial grammar learning literature is often within the 5–10% range. Especially considering the age range of the participants and the extremely short period of exposure to the grammatical patterns, a 5.8% learning gain score is not insubstantial.

[2] As pointed out by an anonymous reviewer, because each child's chronological age is the sum of age at implantation and duration of implant use, these two variables are complementary and not free to vary. Thus, it is not surprising that the partial correlations of sequence learning with these two variables are identical (though opposite in sign).

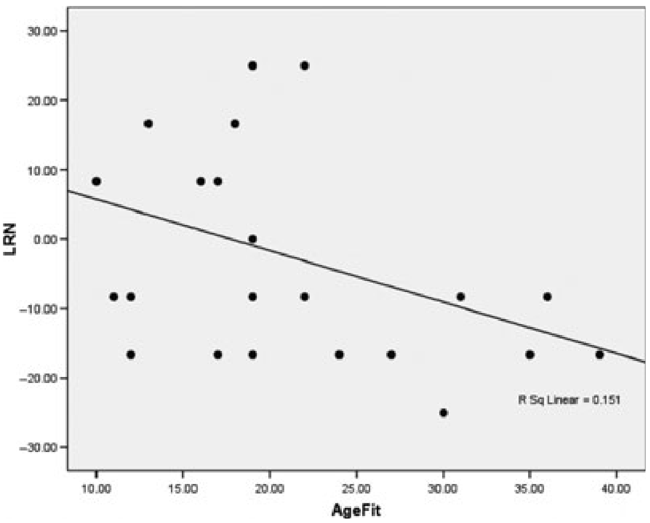

Figure 4 *Scatter plot showing the association between implicit learning and the age at which each child received their implant.*

language outcomes in the CI group. We conducted bivariate correlations between the LRN score and the three subtest scaled scores of the CELF-4. Sequence learning was positively and significantly correlated with two of the subtests of the CELF-4: Formulated Sentences (r = .571, p < .05, two-tailed; see Figure 5), and Recalling Sentences (r = .540, p < .05, two-tailed). Although not significant, the correlation with the third subtest, Concepts and Following Directions, was also positive (r = .469, p = .058, two-tailed). For the most part, these correlations remained significant even after controlling for the common variance associated with duration of CI use, forward digit span, backward digit span, and vocabulary scores (PPVT) (see Table 4). Especially

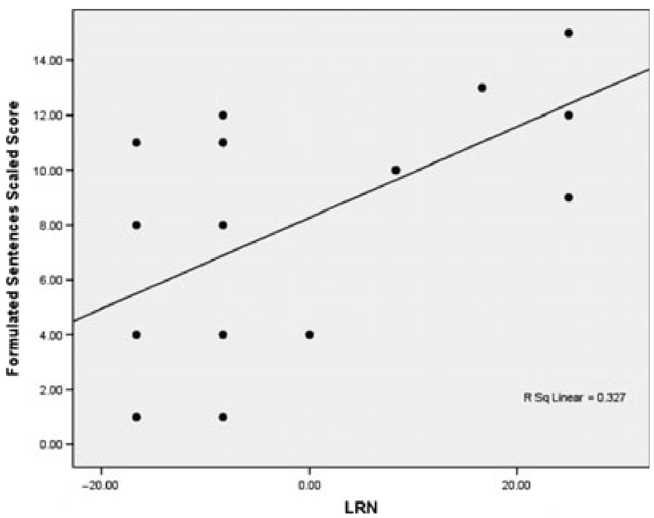

Figure 5 *Scatter plot showing the association between a standardized measure of language outcome (Formulated Sentences from the CELF-4) and implicit learning for the deaf children with CIs.*

robust was the correlation between sequence learning and the Formulated Sentences subtest.

In contrast, immediate serial recall of the sequential patterns, as measured by accuracy for the sequences from the Learning Phase, was not correlated with language outcomes. None of the correlations between Learning Phase performance and the three standardized language outcome scores was significant: Concepts and Following Directions (r = −.163, p = .531), Formulated Sentences (r = −.223, p = .391), and Recalling Sentences (r = −.227, p = .38). In fact, not only were the correlations non-significant, but they were in the opposite direction from what one would expect to see if immediate serial recall were contributing to language outcomes. These findings are consistent with the idea that *sequence learning* specifically, separate from mere serial recall, is a critical factor contributing to language outcome in this population. This point is discussed in full in the General Discussion section.

In summary, visual sequence learning abilities were found to be associated with a standardized measure of language outcome in deaf children who have received a cochlear implant. Because the CELF-4 consists of a standardized score that takes into account the age of each child, the observed correlations are not merely due to chronological age. More importantly, the observed correlations between sequence learning and language outcomes also do not appear to be mediated by short-term/working memory or vocabulary knowledge. The present results demonstrate that children who show the best performance on the sequence learning task also are the ones displaying the best language outcomes. Taken together with the findings that the CI group showed impaired sequence learning, these findings raise the intriguing possibility that individual differences in domain-general sequence learning are partially responsible for the large range of variation in language outcomes following implantation.

General discussion

The goals of this study were to assess (1) the visual sequence learning abilities in deaf children with CIs and

Table 4 *Partial correlations between implicit learning and language outcome measures in deaf children with CIs*

Controlling	C/FD	FS	RS
AgeImp	.434	.484	.464
UseLength	.531*	.613*	.553*
FWdigit	.407	.498*	.461
BWdigit	.428	.550*	.518*
PPVT	.480	.729**	.646**

Note: * p < .05; ** p < .01, two-tailed. AgeImp, age at implantation; UseLength, length of CI use; C/FD, Concepts and Following Directions scaled score on the CELF-4; FS, Formulated Sentences scaled score on the CELF-4; RS, Recalling Sentences scaled score on the CELF-4; FWdigit, forward digit span; BWdigit, backward digit span; PPVT, Peabody Picture Vocabulary Test (scaled score).

(2) whether individual differences in sequence learning can account for some of the enormous range of variability in language outcomes following cochlear implantation. The results showed that, as a group, the CI children performed significantly worse on the visual sequence learning task compared to the age-matched group of NH children. Furthermore, implicit sequence learning was found to be significantly correlated with a standardized measure of language development. We discuss both of these findings in turn.

Effects of auditory deprivation on sequence learning

The artificial grammars used here were created such that it is possible to isolate exactly what is learned (not a trivial endeavor when using more 'traditional' finite-state grammars). The two grammars are completely orthogonal to one another based on pair-wise transitions. For instance, in Grammar A, the '1' can only be followed by a '2' or '3', whereas in Grammar B, the '1' can only be followed by the '4'. This is true of every pair-wise transition. Therefore, presumably to learn the 'grammar' requires learning these pair-wise transitions. The fact that the CI children as a group essentially show no learning is quite striking, given that learning pair-wise transitions would appear to be a relatively fundamental form of sequence learning (see also Pisoni & Cleary, 2004).

The group differences in visual sequence learning are consistent with the hypothesis that a period of auditory deprivation may have major secondary effects on brain and cognition that are not specific to hearing or the processing of sound by the auditory modality. There is existing evidence that auditory learning and plasticity is reduced, even after cochlear implantation, due to a reorganization of auditory cortex following a period of auditory deprivation (Kral & Eggermont, 2007). However, the present set of findings suggests that non-auditory implicit sequence learning may also be impaired.

Sound is unique among sensory input in several important ways. Compared to vision and touch, sound appears to be more attention-demanding (Posner, Nissen & Klein, 1976), especially early in development (Robinson & Sloutsky, 2004). Sound is also intrinsically a temporal and sequential signal, one in which time and serial order are of primary importance (Hirsh, 1967). Indeed, previous work in healthy typical-developing adults suggests that auditory processing of time and serial order is superior to the other senses. Auditory advantages have been found in tasks involving temporal processing (Sherrick & Cholewiak, 1986), rhythm perception (Kolers & Brewster, 1985; Repp & Penel, 2002), immediate serial recall (Glenberg & Swanson, 1986; Penney, 1989), sequential pattern perception (Handel & Buffardi, 1969), and implicit sequence learning (Conway & Christiansen, 2005, 2009). These findings suggest an intimate link between auditory cognition and the processing of temporal and sequential relations in the environment. In addition, some previous work has suggested that the profoundly deaf (including those with and without CIs) show disturbances in (non-auditory) functions related to time and serial order, including: rhythm perception (Rileigh & Odom, 1972); attention to serially presented stimuli (Horn *et al.*, 2005; Knutson *et al.*, 1991; Quittner, Smith, Osberger, Mitchell & Katz, 1994); immediate serial recall (Marschark, 2006; Pisoni & Cleary, 2004; Todman & Seedhouse, 1994); motor sequencing (Horn, Pisoni & Miyamoto, 2006); and aspects of executive function and cognitive control (Hauser, Lukomski & Hillman, 2008; Pisoni *et al.*, 2008). Furthermore, the introduction of sound via a cochlear implant appears to progressively improve certain sequencing abilities over time (Horn *et al.*, 2005).

It is possible that experience with sound and auditory patterns, which are complex, serially arrayed signals, provides a child vital experience with perceiving and learning sequential patterns. Under this view, a period of deafness early in development deprives a child of the essential experience of dealing with complex sequential auditory input, which, it would appear, affects their ability to deal with sequential patterns in other sense modalities as well. Once hearing is introduced via the CI, a child begins for the first time to gain experience with auditory sequential input. The positive correlation between length of CI use and sequence learning scores which we found – obtained even when chronological age was partialed out – suggests that experience with sound via a CI improves one's ability to learn complex non-auditory sequential patterns. Thus, it is possible that given enough exposure to sound via a CI, a deaf child's sequence learning abilities will eventually improve to age-appropriate levels. Alternatively, it may be that there is a sensitive period that significantly limits the time period in which auditory input can provide a scaffolding for sequence learning skill; in such a case, cochlear implantation in older children would do little to improve sequence learning.

An examination of the three CI children who had bilateral hearing (although they were tested with only one implant activated) shows an additional intriguing finding: these children were among the best performers of the group on the sequence learning task. Whereas the average sequence learning score for the CI group was negative (−2.5%), all three of these children had positive learning scores (8.3%, 16.7%, 25%), performing very similarly to the best NH children. Thus, a greater experience with sound (via bilateral hearing) may have an even more beneficial effect on the development of sequence learning skills.

An important and intriguing population to explore in the future are profoundly deaf children without cochlear implants who are users of a gestural language such as American Sign Language (ASL). Arguably, ASL also contains a rich source of temporal and sequential information and therefore its use may alleviate some of the sequence learning disturbances seen in the present sample of children. On the other hand, signed languages, compared to spoken languages, have relatively limited sequential contrasts and instead rely heavily on nonlinear and simultaneous spatial expressions to convey information (Wilson & Emmorey, 1997). As such, it could be expected that deaf users of sign language would also show difficulties with sequential processing. In the case of immediate serial recall, this does appear to be the case (Boutla, Supalla, Newport & Bavelier, 2004).

From a neurobiological standpoint, it is known that lack of auditory stimulation results in a decrease of myelination and fewer projections out of auditory cortex (Emmorey, Allen, Bruss, Schenker & Damasio, 2003) – which presumably includes connectivity to the frontal lobe. The frontal lobe, and specifically the prefrontal cortex as well as Broca's area, are believed to play an essential role in learning, planning, and executing sequences of thoughts and actions (Fuster, 1995, 2001). It is therefore possible that the lack of auditory input early on in development, and corresponding reduction of auditory-frontal activity, fundamentally alters the neural organization of the frontal lobe and connections to other brain circuits (Wolff & Thatcher, 1990), impacting the development of sequencing functions regardless of input modality. An alternative possibility (though not necessarily mutually exclusive) is that language experience, rather than sound *per se*, may affect sequence learning skills, a possibility raised in the next section.

Sequence learning and language development

The second primary finding of this study was that sequence learning performance was significantly correlated with language outcomes in the CI group. Based on previous work with healthy adults (Conway *et al.*, 2010; Conway *et al.*, 2007), we hypothesized that visual sequence learning abilities would be associated with language outcomes in deaf children with CIs. In support of this hypothesis, we found that the CI children's sequence learning scores were positively and significantly correlated with a standardized clinical measure of language outcome. These correlations remained significant even after partialing out the effects of auditory digit spans and general vocabulary knowledge. The present findings suggest a close coupling between the development of general (non-auditory) sequence learning skills and spoken language.

Importantly, whereas sequence learning performance was correlated with language outcomes, performance during the Learning Phase of the task was not correlated with the language outcome measures (ps > .38). This has an important implication regarding the role of verbal mediation on this task. It could be argued that because the Simon learning game presumably involves verbal rehearsal, the reason for the observed correlations between sequence learning and language is merely that both are indices of verbal abilities. It is certainly plausible that when a participant sees a color pattern, they may be covertly rehearsing the color names in order to help them reproduce the sequence (e.g. 'blue – red – yellow – blue'). Adult participants do appear to covertly verbalize the color patterns, which means this task could be fruitfully considered a visual/verbal learning task (see Conway *et al.*, 2007). On the other hand, there is evidence that children within the age ranges of our participants do not spontaneously engage in verbal rehearsal strategies (Ornstein, Naus & Liberty, 1975; Naus, Ornstein & Aivano, 1977). Even if some children were engaging in verbal rehearsal strategies, the fact that Learning Phase performance was not correlated with language outcomes indicates that only (verbal) sequence learning is associated with language development, not (verbal) immediate serial recall. Thus, these findings are still a novel contribution because they show that sequence *learning*, above and beyond sequence *memory*, is coupled with aspects of language development. Furthermore, verbal sequence learning may be neurocognitively distinct from (nonverbal) visuospatial sequence learning (Conway & Pisoni, 2008; Goschke, Friederici, Kotz & van Kampen, 2001), with only the former being related to language acquisition.

There are at least three explanations for the observed correlations between sequence learning and language outcomes: (1) sequence learning abilities may causally contribute to language development; (2) sequence learning and language processing may develop on a similar timescale but are independent of one another; or (3) differences in language skill may affect sequence learning abilities, rather than the other way around. Possibility number 2 is unlikely to be correct, based on other studies that have also found a link between sequential learning and language. For instance, several studies have found that domain-general implicit learning abilities may be disturbed in children and adults with specific language impairment (Evans, Saffran & Robe-Torres, 2009; Plante, Gomez & Gerken, 2002; Tomblin, Mainela-Arnold & Zhang, 2007) and dyslexia (Howard, Howard, Japikse & Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini & Vicari, 2006; Vicari, Marotta, Menghini, Molinari & Petrosini, 2003). Thus there appears to be a close coupling between language competence and domain-general sequence learning abilities; when one of these two abilities is disturbed, the other appears to be as well. Therefore, sequence learning and language do not appear to develop independently of each other.

Alternatives number 1 and number 3 both appear viable, based on our data and on previous findings and theory. It has been argued previously that language learning and processing depend in part on domain-general sequence learning mechanisms (Cleeremans *et al.*, 1998; Conway & Pisoni, 2008; Saffran *et al.*, 2001; Ullman, 2004). For instance, the neurocognitive mechanisms underlying the processing of both language and music appear to be somewhat co-extensive (e.g. Patel, 2003), with Broca's area possibly being a 'supramodal' sequence processor, especially for complex hierarchical sequences (Forkstam, Hagoort, Fernandez, Ingvar & Petersson, 2006; Greenfield, 1991). Therefore, sequential processing mechanisms may be recruited for language acquisition. However, it may also be possible that experience with the complexities of language, especially grammatical relations, promotes better learning of complex patterns more generally, be they linguistic or not. This, to our knowledge, is an unexplored yet intriguing possibility. Interestingly, the processing of grammatical relations in language appears to be heavily influenced by language experience, whereas the learning of lexical/semantic categories is much less so (Neville, Mills & Lawson, 1992). Therefore, if grammatical processing is heavily experience-dependent, and if grammar learning is at least partially based on general sequential processing mechanisms, then one's experience with language (specifically grammar) could possibly affect domain-general sequence learning.

To help tease apart the direction of causality between implicit sequence learning and language development, a longitudinal design would be useful. Such a design could help determine if implicit learning abilities predict subsequent language abilities assessed several years later, or vice versa. For instance, this approach has been used to show that particular perceptual and cognitive abilities measured early in infancy or childhood, such as speech perception or working memory, have a measurable effect on subsequent language processing abilities assessed later (Baddeley, Gathercole & Papagno, 1998; Bernhardt, Kemp & Werker, 2007; Gathercole & Baddeley, 1989; Newman, Bernstein Ratner, Jusczyk, Jusczyk & Dow, 2006; Tsao, Liu & Kuhl, 2004).

One additional interesting implication of the current findings is that sequence learning as measured here does not appear to be completely specific to the sensory modality of the input. If it were, then hearing status ought not to impact visual sequence learning, nor would there be a correlation between visual sequence learning and spoken (auditory) language comprehension. Previous work has suggested a modality-specific locus to aspects of implicit sequence learning (e.g. Conway & Christiansen, 2006; Keele, Ivry, Mayr, Hazeltine & Heuer, 2003). For example, most neuroimaging studies of implicit learning have revealed modality-specific brain regions directly related to the learning process itself (e.g. Lieberman, Chang, Chiao, Bookheimer & Knowlton, 2004; Skosnik, Mirza, Gitelman, Parrish, Mesulam & Reber, 2002).

On the other hand, it has been argued that implicit learning results in knowledge that is abstract or amodal in nature, independent of the physical qualities of the stimulus (Altmann, Dienes & Goode, 1995; Reber, 1993). Although these findings appear at odds with one another, it may be the case that implicit learning involves both stimulus-specific and domain-general processes (Conway & Pisoni, 2008). Under this view, implicit sequence learning likely involves multiple levels of learning including learning simple stimulus–response associations or modality-specific patterns (that recruit unimodal brain regions) as well as higher-order forms of learning that could be considered more abstract or domain-general (that recruit the prefrontal cortex, Broca's area, or striatum). The manner in which both modality-specific and domain-general implicit learning processes interact has yet to be fully specified. One interesting avenue for future research would be to examine both visual and auditory sequence learning in hearing-impaired populations, with the expectation that while both types of learning may be disturbed (due to domain-general effects of auditory deprivation on sequencing skills), auditory learning would be worst (due to modality-specific effects).

Aside from their theoretical importance, from a clinical standpoint, the current findings with CI children are important because they suggest that individual differences in basic sequence learning abilities may provide a principled explanation for why some deaf children with CIs achieve near-typical levels of speech and language outcomes whereas other children do not. Several recent studies have been devoted to understanding the nature of the enormous variation in language outcome in deaf children who receive a CI (e.g. Dawson, Busby, McKay & Clark, 2002; Horn *et al*., 2005; Horn *et al*., 2006; Knutson, 2006; Pisoni & Cleary, 2004). The current results are clinically important because they may provide both the prediction of audiological benefit from a CI and the formulation of new intervention programs that specifically target the development of implicit sequence learning skills in deaf children who are doing poorly with their CIs. In particular, interventions focused on the training of cognitive sequencing skills and executive functions (e.g. Jaeggi, Buschkuehl, Jonides & Perrig, 2008; Klingberg, Fernell, Olesen, Johnson, Gustafsson, Dahlstrom, Gillberg, Forssberg & Westerberg, 2005) may provide benefits above and beyond the standard audiological-based treatment strategies.

Conclusion

In sum, the present findings suggest that a period of auditory deprivation early in development may negatively impact implicit sequence learning abilities, which has profound implications for understanding variation in neurocognitive development and plasticity in both normal-hearing and deaf populations. In addition, these results revealed a direct empirical link between visual implicit sequence learning and language outcome, suggesting that basic cognitive learning abilities related to encoding sequential structure – independent of immediate serial recall abilities – may be an important foundational aspect of language development. In line with other recent findings (e.g. Evans *et al*., 2009; Plante *et al*., 2002; Tomblin, Mainela-Arnold & Zhang, 2007), we suggest that it would be fruitful to investigate implicit sequence learning in other populations with language delays or cognitive disorders, such as children with specific language impairment or autism.

Acknowledgements

This project was supported by the following grants from the National Institute on Deafness and Other Communication Disorders: R03DC009485, T32DC00012, and R01DC00111. We wish to thank Linda Smith and Char Wozniak for their help with accessing the Kid Information Database. We also wish to thank Luis Hernandez for invaluable technical assistance, and Lauren Grove for her help in manuscript preparation. Finally, we are especially indebted to all of the children and parents who took part in this study.

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Received: 5 June 2008
Accepted: 2 December 2009

Appendix

Learning and test sequences used in the implicit learning task

Sequence length	Learning sequence	Test sequence (A)	Test sequence (B)
2	4-1		
2	3-1		
2	1-3		
2	2-3		
2	1-2		
2	3-4		
3	4-1-3	2-3-4	3-2-1
3	2-3-1	1-3-1	2-4-2
3	1-2-3	4-1-2	4-2-4
3	1-3-4	3-1-3	2-4-3
3	3-4-1		
4	1-2-3-4	1-3-1-3	3-2-4-2
4	3-1-2-3	3-4-1-2	1-4-2-4
4	1-2-3-1	4-1-2-3	4-2-1-4
4	4-1-3-1	3-1-3-4	2-1-4-3
4	2-3-1-3		
5		1-2-3-1-2	4-3-2-1-4
5		4-1-3-4-1	1-4-3-2-4
5		3-1-2-3-1	3-2-1-4-2
5		1-2-3-4-1	4-2-4-2-4