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Development of Visual Attention Skills in Prelingually Deaf Children Who Use Cochlear Implants[1]

David L. Horn,[2] Rebecca A.O. Davis[2] and David B. Pisoni

Speech Research Laboratory
Department of Psychology
Indiana University
Bloomington, Indiana 47405

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[2] Devault Otologic Research Laboratory, Department of Otolaryngology-Head & Neck Surgery, Indiana University School of Medicine, Indianapolis, Indiana 46220

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Abstract. The goal of this paper is to determine the effect of length of cochlear implant (CI) use and other factors on the development of sustained visual attention in prelingually deaf children, and to investigate the relations between sustained visual attention and audiological outcomes with an implant. It includes retrospective analysis of data collected before cochlear implantation and over several years after implantation. Two groups of prelingually deaf children, one >6 years old (n=41) and one <6 years old (n=47) at testing, were given an age-appropriate Continuous Performance Task (CPT). In both groups, children monitored visually-presented numbers for several minutes and responded whenever a target number appeared. Hit rate, false alarm rate, and signal detection parameters were dependent measures of sustained visual attention. A number of independent variables were tested for effects on CPT performance. Several audiological outcome measures were found to be correlated with CPT scores. Mean CPT performance was low compared to published norms for normal-hearing children. CPT scores improved as a function of length of CI use over at least two years of use. In the younger group, a higher number of active electrodes predicted better CPT performance. In the older group, CPT performance after two years of CI use was correlated with vocabulary knowledge. These findings suggest that cochlear implantation in prelingually deaf children leads to improved sustained visual processing of numbers over two or more years of CI use.

Introduction

Prelingually deaf children with cochlear implants (CIs) are a unique clinical population to study because they have experienced a period of auditory deprivation prior to the development of significant speech and language skills. The success of many deaf children in acquiring oral language skills from the electrical stimulation provided by a CI is impressive. Although clinical outcomes have been found to be quite variable in this population (Blamey, Sarant, Paatsch, Barry, Bow, Wales, Wright, Psarros, Rattigan, & Tooher, 2001; Pisoni, Cleary, Geers, & Tobey, 2000; Sarant, Blamey, Dowell, Clark, & Gibson, 2001), most children's scores on a range of speech perception, language, and speech intelligibility tests improve with CI use (Miyamoto, Svirsky, Kirk, Robbins, Todd, & Riley, 1997; Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000; Tyler, Fryauf-Bertschy, Kelsay, Gantz, Woodworth, & Parkinson, 1997).

Physical device limits, such as reduced spectral resolution and compressed dynamic range, have been shown to play a role in limiting the speech perception abilities developed by prelingually deaf children who use CIs. Nevertheless, some children are able to use these degraded signals to develop age appropriate speech perception and language skills with a CI. In contrast, other children obtain only awareness of sound with a CI and their speech and language skills remain significantly delayed compared to their normal-hearing peers. The sources of this outcome variability have yet to be fully revealed. Studies that have looked into pre-implant predictors of CI performance have reported effects of early implantation, communication mode, device type, and dynamic range (Geers, Brenner, & Davidson, 2003; Geers, Nicholas, & Sedey, 2003; Kirk, 2000; Tobey, Geers, Brenner, Altuna, & Gabbert, 2003). However, a large portion of outcome variance remains unexplained by these demographic and medical factors (Pisoni et al., 2000; Sarant et al., 2001).

A major paradigm shift in the study of pediatric CI outcomes has been emerging from recent investigations of the neurocognitive abilities of prelingually deaf children (Pisoni et al., 2000). The premise of this approach is that individual differences in speech and language outcomes in prelingually deaf children may reflect underlying differences in central auditory processing and related neurocognitive functions such as working memory, attention, and executive functions. These central processes are not specific to audition or language, yet they may play important roles in perceiving speech, acquiring language, and developing the sensory-motor abilities crucial to producing highly intelligible speech.

Two major research objectives can be identified in the study of neurocognitive processes of prelingually deaf children with CIs. The first is to describe how individual cognitive processes may be altered in children who have experienced a period of auditory deprivation. The second is to assess relationships between individual cognitive functions and speech/language outcomes. Both objectives may reveal important predictors of benefit and new insights into sources of individual differences in clinical outcomes with a CI. Furthermore, research on central auditory and cognitive factors may provide the theoretical basis for therapeutic cognitive and behavioral interventions for deaf children who are struggling with their implants.

Sustained visual attention is one cognitive process that has been studied in prelingually deaf children with CIs. Sustained attention is a form of attention that is responsible for the “continuous allocation of processing resources for the detection of rare events,” (Parasuraman, 1998). This ability is crucial for the efficient exploration of the environment and the support of other perceptual and cognitive processes. Experimentally, sustained visual attention capacity can be measured reliably by continuous performance tasks (CPTs) in which subjects are asked to respond to low frequency target stimuli. Experimental manipulations of these tasks in normal hearing subjects have demonstrated the fragile nature of sustained visual attention. Performance has been shown to decline with increased task length, lower signal salience, faster stimulus rate, and higher memory load (Parasuraman, 1998).

The most widely used task for measuring sustained visual attention is the CPT. Originally developed by Rosvold, Mirskey, Sarason, Bransome, and Beck (1956), several newer CPTs have since been designed and normed for clinical use (Conners, 2000; Gordon, McClure, & Aylward, 1996; Greenberg, 1991). These CPTs possess moderate clinical validity for detecting attentional disorders such as ADHD in children at risk for these conditions (Barkley, 1991; Forbes, 1998). In a CPT, children are asked to monitor a stream of visually presented stimuli and respond by pressing a key each time they detect a target stimulus. Detection rate depends on two independent factors: perceptual sensitivity (ability to distinguish targets from non-targets), and expectations of target frequency (Parasuraman, 1998). Because CPTs are visual information processing tasks that have no auditory demands, they have been used to assess the visual attention skills of both deaf children and adults.

In the first study of sustained visual attention skills of prelingually deaf children with CIs, Quittner, Smith, Osberger, Mitchell, and Katz (1994) administered a CPT to three groups of children: prelingually deaf children with CIs, prelingually deaf children who used hearing aids, and normal-hearing children. Children were assigned to one of two age groups: younger (6- to 8-year olds) and older (9- to 13-year olds). Overall, Quittner et al. found that children in the older group performed better than children in the younger group demonstrating an effect of chronological age on sustained visual attention. In addition, Quittner et al. reported a main effect of hearing. Across age groups, normal-hearing children performed better than both children with CIs and children with hearing aids (HAs). However, the authors also found an interaction between age and group. In the early age range, both groups of prelingually deaf children had lower mean CPT scores than the normal-hearing children. In the older age range, however, the children with CIs performed as well as normal-hearing children while the mean performance of children with HAs was below that of both the children with CIs and normal-hearing children.

In a second experiment, Quittner et al. reported findings from a longitudinal study of CPT performance in prelingually deaf children with CIs and a group of deaf children who used HAs. Each child was tested twice, about eight months apart. The children with CIs were tested only after implantation (about 10 and 18 months post-implantation). The results from this experiment were consistent with the results of the first experiment: children with CIs showed more improvement in mean CPT performance than children with HAs over the 8 month interval. From the results of these two experiments, Quittner et al. concluded that children who experienced a period of profound prelingual deafness prior to cochlear implantation are delayed in their development of visual attention skills. Moreover, they interpreted the findings from their two experiments as evidence that access to sound with a CI produced more typical development of visual attention skills than a HA in prelingually deaf children.

Although no attempt was made to control for length of CI use, Quittner et al. suggested that the effects of a CI on visual attention were relatively rapid as indicated by their findings in Experiment 2. They also suggested that visual attention skills were unlikely to be related to speech and language outcomes in the children with CIs' because gains in these skills typically emerge more slowly, after several years of CI use (Fryauf-Bertschy, Tyler, Kelsay, & Gantz, 1992; Miyamoto, Osberger, Robbins, Myres, & Kessler, 1993). However, Quittner et al. did not report any speech and language outcome data, nor did they assess the relations between CPT performance and speech/language outcomes in either of their two experiments.

In a follow-up study with a larger sample of children, Smith, Quittner, Osberger, and Miyamoto (1998) attempted to replicate the earlier findings reported by Quittner et al. Once again, CPT scores were obtained from prelingually deaf children with CIs, prelingually deaf children with HAs, and normal-hearing children. Each of these groups were subdivided into 6 age groups: 6-, 7-, 8-, 9-, 11-, and 13-years-old. Like Quittner et al., Smith et al. found an interaction between chronological age and group. At 6, 7, and 8 years of age, both groups of deaf children had lower mean CPT scores than normal-hearing children. In contrast, at 9, 11, and 13 years of age, deaf children with CIs performed equally to normal-hearing children on the CPT. Both of these groups had higher mean CPT performance than the children who used HAs.

To explain the interaction between cochlear implantation and chronological age, Smith et al. hypothesized that access to sound (either with a normal cochlea or a CI) before or during a critical developmental period was important for children to acquire typical sustained visual attention skills. The implantation of deaf children with a CI before or during the critical period lead to faster maturation of their visual attention skills, compared to children with HAs, until they reached age appropriate levels compared to children with normal hearing. The authors reasoned that, prior to the onset of the critical period for visual attention development, deaf children with CIs would show no developmental advantage over deaf children with HAs in acquiring these skills. Smith et al. attributed the lack of an effect of a CI in the 6-8 year old children as evidence that this critical period began at around age 7-8 years old.

However, in a second experiment, Smith et al. tested a younger group of prelingually deaf children (4-7 years old) who used either CIs or HAs on an easier version of the CPT. In the original CPT, children were asked to detect a two-number sequence. In the easier CPT, children were only asked to detect single target stimuli. This new version had a lower working memory load than the original CPT, and is recommended and normed for children aged 3-5 years (Gordon et al., 1996). Children with CIs displayed higher mean CPT scores than children with HAs, indicating that CI use affected the development of sustained visual attention even in younger children than those who were tested previously. Therefore, the lack of an observed effect of a CI in 6-8 year-old children on the original CPT may have been due to the difficulty of the task as Smith et al.'s second experiment demonstrated that auditory experience had an effect on visual attention at even younger ages than previously tested. Although a critical period might exist for the development of the visual attention, the age of onset remained undefined by the results reported by Smith et al.

Any interpretation of the interaction between chronological age and cochlear implantation reported by Quittner et al. and Smith et al. is limited by the fact that neither study controlled for length of CI use, which varied between 6 months and 6 years. This confounding variable may have been responsible for the observed interaction because children in the younger CI group may have had fewer years of experience with their CIs than children in the older group. Although Smith et al. reported that length of CI use and CPT performance were not correlated in their study, these results do not rule out an effect of length of CI use over the first few years of CI use. Indeed, Quittner et al. had concluded that the effect of a CI on visual attention skills was relatively rapid. However, because chronological age and length of CI use were not controlled, the source of the interaction between chronological age and cochlear implantation cannot be determined from either Quittner et al.'s or Smith et al.'s data.

Although Smith et al. and Quittner et al. attributed the CI effect to deaf children having access to sound, they also did not systematically examine the role of demographic, medical, or audiological factors on CPT performance. They did assess the effect of mode of communication training and found no differences in CPT performance between children in oral communication (OC) programs (deaf children who learn to communicate primarily through listening, lip-reading, and oral skills) and total communication (TC) programs (deaf children who incorporate a manual correlate of their spoken language along with oral skills). However, they did not assess other variables such as IQ, etiology of deafness, CI type, gender, or other factors which may have been at least partially responsible for the reported CI effect.

Why should access to sound provided by a CI, and not a HA, provide benefits for visual attention development? The aided auditory thresholds of the two groups of deaf children in Quittner et al. were quite similar, indicating that both devices were equal in terms of their effect on sound detection. Perhaps, something about the nature of the auditory information provided by a CI lead to the improved sustained visual attention skills in this population. HAs function by amplifying ambient noise to stimulate the functional hair cells remaining in a cochlea damaged by sensori-neuronal hearing loss (SNHL). Processing of this amplified signal by the profoundly deaf cochlea leads to a significant amount of spectral distortion, limiting the effectiveness of HAs for improving speech perception (Niparko, Kirk, Mellon, McConkey-Robbins, Tucci, & Wilson, 2000). In contrast, CIs extract specific speech cues encoded in the time-varying spectrum of speech and use this information to directly stimulate the auditory nerve (Niparko et al., 2000). Despite carrying impoverished acoustic-phonetic information about speech, a CI may be better suited than an HA for speech perception in profoundly deaf individuals who have great difficulty understanding speech (Niparko et al., 2000).

Possibly, the benefits of a CI for speech and language development in profoundly deaf individuals are related to the neural mechanisms responsible for the improvements in sustained visual attention skills with a CI. For instance, improved auditory perceptual acuity, rather than simple access to sound, might lead to improvements in sustained visual attention skills. Perhaps gains in language skills and other related cognitive processes enable deaf children to perform better on the CPT. One way to begin to answer these hypotheses would be to calculate correlations between speech and language test scores and CPT scores. These relations were not examined by either Quittner et al. or Smith et al. or by any other study of sustained visual attention in deaf children.

In a recent report, Tharpe, Ashmead, and Rothpletz (2002) have raised several criticisms about the conclusions of Quittner et al. and Smith et al. and suggested that their results may have reflected differences in IQ between the test populations. To deal with this concern, Tharpe et al. conducted a study of CPT performance in prelingually deaf children with CIs, prelingually deaf children with HAs, and normal-hearing children in which non-verbal IQ of each subject was measured and used as a covariate in all analyses. Tharpe et al. failed to find any differences in mean CPT performance between children with CIs and deaf controls. They were unable to replicate the earlier differences in CPT scores between normal-hearing children and either group of deaf children reported by Quittner et al. and Smith et al. Tharpe et al. interpreted these results as evidence that the benefit of a CI on sustained visual attention reported by Quittner et al. and Smith et al. was due to differences in IQ rather than differences in visual attention.

While Tharpe et al.'s conclusions might be correct, their findings must be interpreted cautiously for several reasons. First, the sample size used in their study was extremely small (only 8 subjects in each subject group) compared to the larger samples used by Quittner et al. and Smith et al. Second, the study design used by Tharpe et al. was fundamentally different from the designs used by Quittner et al. and Smith et al. in which chronological age was an independent variable. Although Tharpe et al. have raised several important issues and suggested further areas of research on visual attention, their study was not a comprehensive attempt to replicate either of the earlier studies.

Finally, the CPT scores reported by Tharpe et al. were close to ceiling performance. They used a different CPT than the one used by Quittner et al. and Smith et al., and the mean d's were 3.5 and above. d' is a parametric measure of perceptual sensitivity computed using the principles of signal detection theory and d's above 3 suggest ceiling performance. It is possible that Tharpe et al. failed to detect any differences in CPT performance between deaf children with CIs and deaf children with HAs because their CPT was simply too easy for these children. Indeed, Quittner et al. and Smith et al. reported a much wider range of means for d' in their studies (1.4 – 4.5 in Quittner et al.).

To summarize, three studies of sustained visual attention development in prelingually deaf children with CIs have been reported in the literature to date. In the recent study by Tharpe et al., no differences between deaf children with CIs, deaf children with HAs, or normal-hearing children were observed when non-verbal IQ was controlled. However, several methodological factors make Tharpe et al.'s results difficult to compare with the results from the previous studies by Quittner et al. and Smith et al. which both found a beneficial effect of a CI on the development of sustained visual attention in prelingually deaf children. More work is needed in order to understand the effect of length of CI use and chronological age as these variables were confounded in the previous studies. Furthermore, we do not know what other demographic or medical variables might influence sustained visual attention skills of deaf children. Finally, the relations between oral speech and language skills and sustained visual attention skills have not yet been systematically assessed. The present study was designed to explore these unanswered questions.

Our first aim was to investigate the effect of CI use on sustained visual attention skills using a design which controlled for the independent effects of length of CI use and chronological age. We hypothesized that visual attention skills would be affected by both length of CI use and chronological age. We were also interested in determining the time-course of the effects of CI use: Do visual attention skills increase rapidly during the first year of use as suggested by Quittner et al. and Smith et al., or do they change more gradually over time after implantation? Finally, we were interested in determining whether there was an interaction between length of CI use and chronological age as predicted by Smith et al.'s critical period hypothesis: the effect of a CI use would be seen in children during a critical age range, but not before or after this age range.

Our second aim of this study was to determine if several medical, audiological, or demographic characteristics of prelingually deaf children would affect the development of sustained visual attention skills after cochlear implantation. Although some of these factors are known to play a role in the development of auditory/oral speech and language skills with a CI, the effects of these variables on other cognitive skills in prelingually deaf children such as sustained visual attention are largely unknown.

Finally, our third aim was to assess the relations between sustained visual attention skills and several traditional audiological outcome measures of speech perception, language acquisition, and speech intelligibility. As mentioned previously, no attempt was made in any of the previous studies to examine the relations between sustained visual attention skills and clinical outcome measures of speech and language. If gains in sustained visual attention in deaf children are correlated with gains in speech and language skills, this would have important implications for predicting individual clinical outcomes with a CI, and for understanding the underlying cognitive mechanisms of audiological benefit with a CI.

We report two experiments with similar longitudinal designs, measures, and independent variables. The major difference between the two experiments was the ages of the children. The first experiment included children older than 6 years of age and the second experiment included a younger group of children. Two different age-appropriate CPTs were used to assess sustained visual attention skills in each group of children.

Experiment I

Method

Participants. We conducted a retrospective analysis of longitudinal clinical data gathered at the Indiana University School of Medicine Cochlear Implant Program. The subjects were part of a larger comprehensive, prospective clinical study of speech and language outcomes in deaf children with CIs. Table 1 provides a summary of the medical, audiological, and demographic characteristics of our sample. The group included 41 prelingually deaf children (profoundly deaf by 2.5 years old) who received CIs by 9 years of age. All children were implanted with Nucleus 22 devices. Mean age of implantation was 6.2 years old. Fifteen children used OC and 26 used TC at the time of testing. Over 68% had a congenital hearing loss and the most common acquired etiology was meningitis. A subset of children (n=19) had pre-implant non-verbal IQ scores (WISC or WIPSI) in their charts and the mean standardized score was 101.3.

Children were tested once every 6-12 months from before implantation to three years post-implantation. Interval data were collapsed into one of four intervals: pre-implant, one year post-implant, two years post-implant, and three years post-implant. Not all children were tested at each interval, as is common in clinical populations, creating missing data cells. Missing data occurred for several reasons. Some children moved away from the Indianapolis area after implantation and were unable to continue the study. Also, because our clinical participants are given a large number of tests during each visit, they are often too tired or not cooperative enough to complete all of the tests.

Medical	**Etiology**	**1 genetic, 1 CMV, 11 meningitis, 28 unknown**
	Ear of Implantation (n=37)	**17 right, 20 left**
Audiological	**Mean Pure Tone Average (n=26) (dB HL)**	**111.8 (6.478)***
	Mean Number of active electrodes (n=34)	**20.1 (3.59)***
	Mean Age of implantation (yrs.)	**6.20 (1.60)***
Demographic	**Gender**	**19 female, 22 male**
	Communication mode	**15 OC, 26 TC**
	Mean non-verbal IQ (n=19)	**101.3 (16.53)***

Table 1. Medical, audiological, and demographic characteristics of participants in Experiment I (standard deviations in parentheses)

Procedures. The CPT used in the present study was the “School-age CPT” (Gordon et al., 1996), the same CPT used in the studies by Quittner et al. and Smith et al. This test format is recommended for use in normal-hearing children from 6-16 years old. The experimental apparatus consists of a free-standing button box with one blue key below an LCD display. While this apparatus is capable of running a number of different tests, the school-age CPT is a 9 minute CPT in which target and non-target numbers appear at random in the center of a viewing screen at 1 second intervals. Children were instructed to press a key every time a “9” appeared following a “1.” They were instructed to refrain from pressing the key when non target numbers appeared or when “9” appeared following any number other than “1.” No feedback was given during the task other than general encouragement. Instructions were given in the child’s preferred mode of communication. Children were tested with an experimenter, but not their caregiver, present in the room.

Each time a correct response (key press) was made when the target number appeared, the computer internally scored a “hit.” Each time a key press was made when a non-target number appeared, the computer internally scored a “false alarm.” The Gordon CPT apparatus automatically computes the total number of hits, misses, and false alarms from which the hit rates and false alarm rates were computed manually.

We used these raw scores to compute two additional measures based on methods used in signal detection theory (SDT; Green & Swets, 1966). Perceptual sensitivity, or d', was computed as the difference between the z scores for hit rate and false alarm rates. This measure is used to assess the subject’s ability to discriminate visual targets from non-targets. A second measure, β, was computed as the ordinate for hit rate divided by the ordinate for false alarm rate. β reflects the response bias of the subject. More conservative (i.e. less impulsive) responders will have higher β scores than less conservative, or more impulsive responders. Although there is some controversy over the use of parametric measures in cases where the assumptions of SDT are not necessarily true (Pastore, Crawley, Berens, & Skelly, 2003), we included these measures in our analyses along with hit rate and false alarm rate because earlier studies of CPT performance in deaf children and adults have used d' and β as measures of sustained visual attention. Thus, we report results in terms of d' and β for the sake of comparison to previous studies, however, we also report results in terms of hit rate and false alarm rate where appropriate.

Because we did not collect data from a control group of age-matched normal-hearing children, we used the published percentile norms as a benchmark for comparative purposes. The Gordon CPT manual publishes norms for children from 6-16 years old (Gordon et al., 1996). We did not perform any statistical analyses using these standardized data, and used them only for descriptive purposes.

At our center, a large battery of tests are used to assess oral speech and language skills of children with CIs. From this battery, we selected five tests as representative outcome scores for our sample of children. Open-set speech perception was measured using the Phonetically Balanced Kindergarten (PBK) test (Haskins, 1949). This test is administered using live voice presentation and is scored by word and phoneme. Children hear a spoken word and are asked to repeat the word aloud to the examiner. The words used in this test are phonetically balanced, English monosyllables.

Sentence comprehension was measured with the Common Phrases test (Osberger, Miyamoto, Zimmerman-Philips, Kemink, Stroer, Firszt, & Novak, 1991) in which percent correct scores reflect the child's ability to repeat a sentence or follow a command. This test is typically administered in auditory (CPA), visual (CPV), and auditory plus visual (CPAV) modalities. We used scores from all these presentation formats.

Vocabulary knowledge was assessed with the Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn, 1997). At our center, this test is administered in the child's preferred mode of communication. Each vocabulary item is presented either orally or manually. The child then chooses from four pictures, one of which correctly corresponds to the meaning of the word.

The Reynell Developmental Language Scales 3rd edition (RDLs; Reynell & Huntley, 1985) was administered to assess both receptive (RR) and expressive (RE) language skills. The receptive scales measure 10 different skills including word recognition, sentence comprehension, and verbal comprehension of ideational content. The expressive language scales assess skills such as spontaneous expression of speech and picture description. Like the PPVT, the RDL was administered in the child's preferred mode of communication.

Speech intelligibility was assessed using the Beginner's Intelligibility Test (Osberger, Robbins, Todd, & Riley, 1994). Audio recordings were made of children repeating a list of 10 sentences given to them by a clinician. These recordings were then presented to three naïve adult listeners who were asked to transcribe what they thought the children were saying. Intelligibility scores are based on the number of words correctly transcribed by the adult listeners. Each of these tests, including the CPT, was administered in an Otolaryngology clinical setting by licensed health professionals who had received special training in working with children with CIs.

Results

As noted earlier, because our participants were drawn from a larger clinical population enrolled in a long-term longitudinal study of CI outcomes, we could not always obtain CPT scores for each child at each test interval. A traditional repeated measures ANOVA would, therefore, eliminate data from any child who was not tested at each interval. However, such an analysis can often lead to skewed results as well as underestimates of variability (Schafer & Graham, 2002). We therefore employed several statistical techniques using the SAS Mixed Procedure (Wolfinger & Chang, 1995) to analyze our data. The SAS Mixed procedure utilizes a maximum-likelihood estimation method to create a model without eliminating any participants (Schafer & Graham, 2002). In this manner, systematic selection biases can be avoided by using data from all children, even those who were not tested at each interval, in the test design. Table 2 lists the number of participants who were tested on the CPT at each of the test intervals.

	Preimplant	Year 1	Year 2	Year 3
Experiment 1 (schoolage CPT)	6	17	30	15
Experiment 2 (preschool CPT)	19	30	23	4

Table 2. Number of participants tested on the CPT tasks at each testing interval

CPT performance of prelingually deaf children with CIs compared to normative sample. As described in the previous section, we calculated normative percentile scores from the CPT raw scores. Table 3 shows the percentile means for hit rates and false alarm rates at each interval along with the number of participants at each interval. Examination of these scores reveals that the prelingually deaf children performed poorly on the school-age CPT compared to the normative sample in term of both hits and false alarms. The highest mean normative scores were found in children who had used their implants for two years. However, these means were only at the 36th and 16th percentiles for hit rate and false alarm rate respectively.

Gordon Test	Test Interval	Percentile Mean (SD)
Hit Rate	0 (n=3)	23.0 (27.0)
	1 (n=16)	27.5 (34.8)
	2 (n=26)	36.6 (32.9)
	3 (n=15)	17.9 (25.8)
False Alarms	0 (n=2)	3.0 (0.0)
	1 (n=16)	12.5 (11.2)
	2 (n=25)	16.3 (18.9)
	3 (n=14)	14.9 (22.0)

Table 3. Percentile CPT Scores at each interval of testing from Experiment 1 (school-age CPT)

Effects of chronological age. The results obtained from the SAS mixed model revealed significant effects of chronological age on hit rate ($F(1, 34.7) = 15.93$, $p < 0.01$), and d' ($F(1, 39.5) = 13.15$, $p < 0.01$). No significant effects were found for β or false alarm rate. Thus, our sample of prelingually deaf children with CIs demonstrated an increase in hit rate and increase in perceptual sensitivity as a function of age. This effect is illustrated in Figures 1a and 1b as a function of chronological age. In all of our subsequent analyses with the mixed model, we controlled for the effect of chronological age.

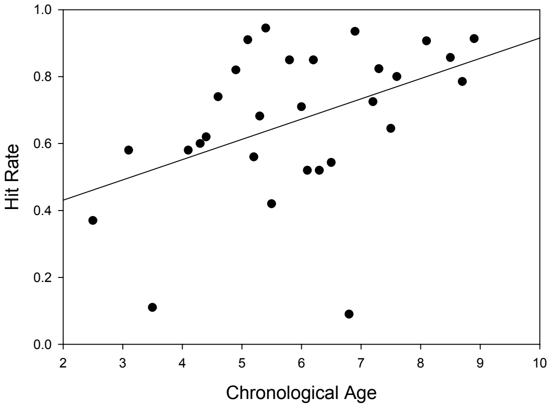

Figure 1a. Hit rate on the school-age CPT as a function of chronological age. Some data points overlap; all individual data points are plotted with a line of best

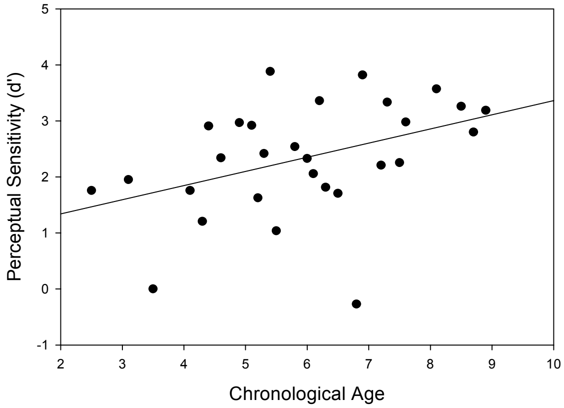

Figure 1b. Perceptual sensitivity (d') on the school-age CPT as a function of chronological age. Some data points overlap; all individual data points are plotted with a line of best fit.

Effects of length of CI use. The SAS mixed model produced estimated means for hit rate, false alarm rate, d' and β as a function of length of CI use. The estimated mean hit rate increased from 0.60 (*SE*=0.11) before cochlear implantation to 0.76 (*SE*=0.06) after three years of CI use, a significant effect ($F(3,27.9) = 3.08$, $p < 0.05$). The estimated mean for d' also increased with length of CI use from 2.08 (*SE*=0.57) to 2.86 (*SE*=0.25) pre implant and after 3 years of use respectively ($F(3,23.8) = 4.46$, $p < 0.05$). In contrast, length of CI use did not significantly affect β or false alarm rate. Figures 2a and 2b illustrate the significant effects of length of CI use.

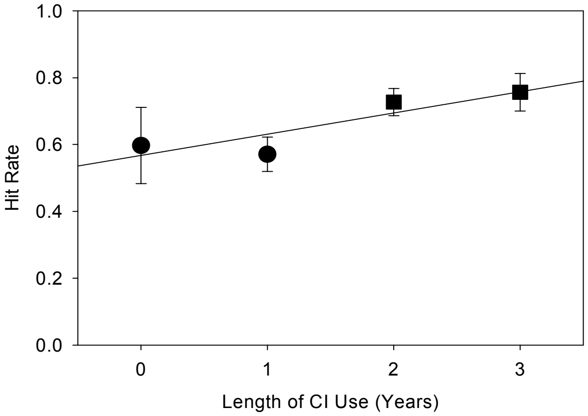

Figure 2a. Hit rate on the school-age CPT as a function of length of CI use in years. Different shaped data points are used to represent significantly different means at different lengths of CI use.

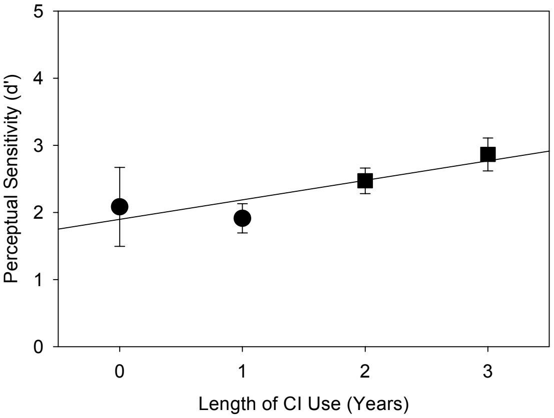

Figure 2b. Perceptual sensitivity (d') on the school-age CPT as a function of length of CI use. Different shaped data points are used to represent significantly different performance means at different lengths of CI use.

Tukey's post hoc comparisons were carried out to assess differences between each post-implant interval. In Figure 2a and 2b, means which differed significantly from each other are represented by data points of different shapes. Figure 2a shows that hit rate increased significantly, as a function of length of CI use, between post-implant years 1 and 2 (Tukey's $p < 0.05$), and years 1 and 3 (Tukey's $p < 0.05$), but no significant increase was found between years 2 and 3 (Tukey's $p = 0.97$). Figure 2b shows that perceptual sensitivity (d') followed a similar pattern, increasing between years 1 and 2 (Tukey's $p < 0.01$) and years 1 and 3 (Tukey's $p < 0.01$), but not between years 2 and 3 (Tukey's $p = 0.39$).

Effects of medical, audiological, and demographic variables. The effects of medical, audiological and demographic variables on CPT scores were examined in separate analyses using SAS mixed models which controlled for chronological age and length of CI use. We found no significant effects on school-age CPT scores for any of the variables described in Table 1.

Correlations between visual sustained attention and speech and language outcome measures. We computed simple bivariate correlations between the four CPT measures and each of the speech and language outcome measures using scores obtained at two years post-implantation. As shown in Table 4, significant correlations (p <0.05) were only found between vocabulary (PPVT) and both hits and false alarms on the CPT (*r*'s 0.45 and –0.47 respectively). No other significant correlations were observed between CPT scores and speech/language outcome measures. Because many of the speech and language outcome measures are often correlated with chronological age, we conducted univariate regression analyses with PPVT score as the dependent measure, hit rate or false alarm rate as the independent measures, and chronological age as a covariate. Using this model, the relations observed between false alarms and PPVT scores remained significant ($F(1,19)=6.1$, p <0.05). However, the relations between hits and PPVT scores were not significant when chronological age was controlled ($F(1,21)=2.277$, p >0.05). Thus, a lower rate of false alarms on the CPT was associated with greater vocabulary knowledge scores obtained after two years of implant use.

Outcome Measure	**Hit Rate**	**False Alarms**	**d'**	**Beta**
PBK	ns	ns	ns	ns
CP V	ns	ns	ns	ns
CP AV	ns	ns	ns	ns
PPVT	0. 45*	- 0.53*	ns	ns
RE	ns	ns	ns	ns
RR	ns	ns	ns	ns
BIT	ns	ns	ns	ns

Table 4. Bivariate correlations between school-age CPT scores and outcome measures
* p< 0.05 level (two tailed)

Discussion

The low mean percentile CPT scores demonstrated by the children in our study are consistent with the earlier findings reported by Quittner et al. and Smith et al. that, across ages, prelingually deaf children show atypical sustained visual attention skills compared to normal-hearing children. Depending on the length of CI use, approximately one-third to one-half of children fell into the "abnormal" clinical range as defined in the Gordon CPT manual (Gordon et al., 1996). However, similar proportions of children performed in the "normal" range suggesting that not all deaf children displayed atypical sustained visual attention skills. From the means of the percentile scores, it appeared that children showed more atypical performance for false alarms than for number of hits.

The SAS mixed model used here allowed us to measure the effects of chronological age and length of CI use separately as continuous independent variables. Similarly to Quittner et al. and Smith et al., we found a significant effect of chronological age on CPT performance. We also found that CPT performance increased with CI use. Over three years of CI use, prelingually deaf children showed an increase in hit rate and perceptual sensitivity when the effect of chronological age was partialled out.

These findings suggest that sustained visual attention abilities of prelingually deaf children may begin to improve during the first year after implantation and, on some measures, continue to improve over at least 3 years of CI use. Because we did not have sufficient data to analyze children following greater lengths of CI use, we cannot say whether this improvement levels off or continues to increase with greater CI use. Given the previous findings of Quittner et al. and Smith et al., we would expect continued improvement in CPT performance as a function of CI use until the deaf children are, on average, performing equally to normal-hearing children. We did not find a significant interaction between chronological age and length of CI use to suggest a critical period for development of sustained visual attention skills. We did not find any significant effects for the demographic, medical, or audiological variables on CPT performance.

Our correlational analysis revealed a significant relation between false alarm rate on the school-age CPT and vocabulary knowledge as assessed by the PPVT in prelingually deaf children who had used a CI for two years. No other relations were uncovered involving the speech perception, language, or speech intelligibility measures. These findings suggest that individual differences in sustained visual attention abilities may explain some portion of the variability of vocabulary acquisition, but not other aspects of speech and language development, in prelingually deaf children with CIs.

Experiment II

Methods

Participants. Experiment II was also a retrospective analysis of longitudinal clinical data gathered at the Indiana University School of Medicine Cochlear Implant Program. Participants included a younger group of 47 prelingually deaf children who received CIs by 9 years of age. The medical, audiological, and demographic characteristics of the sample are summarized in Table 5.

Medical	**Etiology**	**3 genetic, 13 meningitis, 31 unknown**
	Ear of Implantation	**24 right, 19 left**
Audiological	**Mean Pure Tone Average (n=29) (dB HL)**	**110.1 (6.162)**
	Mean Number of active electrodes	**19.8 (3.42)**
	Mean Age of implantation (yrs.)	**4.80 (1.34)**
Demographic	**Gender**	**21 female, 26 male**
	Communication mode	**22 OC, 25 TC**
	Mean non-verbal IQ (n=18)	**104.1 (15.28)**

Table 5. Medical, audiological, and demographic characteristics of participants in Experiment I (standard deviations in parentheses)

Testing protocols in this experiment were identical to the previous study. Children were tested once every 6-12 months until two years post-implantation. Interval data were collapsed into one of three intervals: pre-implant, one year post-implant, and two years post-implant. As in the previous experiment, not all children were tested on all measures at each interval. The numbers of children who were tested at each interval are shown in Table 2.

Procedures. The preschool CPT is recommended for use in normal-hearing children from 3-5 years of age (Gordon et al.). This 6-minute CPT task uses the same testing apparatus and visual stimuli as the school-age CPT described previously. In this new task, children were also required to monitor a stream of visually presented numbers presented at 1-second intervals. In contrast to the school-age CPT, however, the preschool CPT required children to only respond whenever a "1" appeared on the screen. This CPT version is easier than the school-age task because children are not required to remember the previously presented number when the target appears. Therefore, the preschool CPT has a lower working memory load than the school-age CPT. The results were scored in the same manner and dependent variables for sustained visual attention were computed as described previously for Experiment I.

The same five traditional speech and language outcome measures used in Experiment I were also used as outcome measures in this second experiment. However, in this younger population of children, we did not have a sufficient sample size with 2 years of CI use to carry out correlations with scores obtained at this interval. Therefore, in Experiment II, we only examined relations between measures obtained after 1 year of CI use.

Results

To test for independent effects of chronological age and length of implant use, we constructed a model using the SAS Mixed Procedure described earlier.

Preschool CPT performance of prelingually deaf children with CIs compared to normative sample. Although the preschool CPT is recommended and normed for children from 3-5 years of age, a number of children were older than 5 at the time of testing. The most stringent criteria for calculating percentile scores would be to exclude those children who were older than 5 years old. However, this would leave us with a very small group of children to compare to the normative samples. Therefore, we made the judgment to report normative scores for children who were 6 years old or younger at the time of testing, although these data should be interpreted with caution and are included only for descriptive purposes. Table 6 shows the percentile means for hit rate and false alarm rate at each interval along with the number of participants who were normed at each interval. These data suggest that, like the older deaf children in Experiment I, deaf children with CIs performed poorly on the preschool CPT compared to the normative sample. The highest mean normative scores, 38th and 20th percentile for hits and false alarms respectively, were found in children who had used their CI for two years.

Gordon Test	CI Use (Years)	Percentile mean (SD)
Hit Rate	0 (n=19)	20.6 (25.6)
	1 (n=25)	20.2 (23.3)
	2 (n=19)	38.5 (36.1)
False Alarms	0 (n=19)	13.8 (14.8)
	1 (n=25)	22.7 (23.0)
	2 (n=19)	25.4 (20.6)

Table 6. Percentile CPT scores at each interval of testing from Experiment II (preschool CPT).

Effects of chronological age and length of CI use. The results obtained from the SAS mixed model revealed significant effects of chronological age on both hit rate (*F*(1, 47.7) = 64.69, *p*=<0.01), and d' (*F*(1, 50.9) = 55.2, *p*=<0.01). Thus, this sample of deaf children with CIs demonstrated an increase in hit rate and increase in perceptual sensitivity as a function of chronological age. No effect of chronological age was found on β or false alarm rate, although the latter just missed significance (*F*(1,51.6) = 3.18, *p*=0.08). Figures 3a-b illustrate the mean hit rate and d' of individual participants plotted as a function of chronological age. In all subsequent analyses with the SAS mixed model, we controlled for the effect of chronological age.

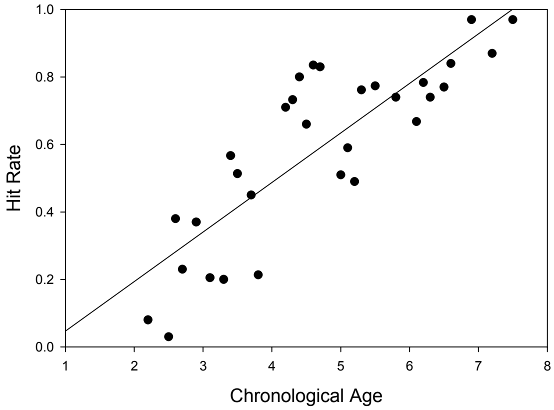

Figure 3a. Hit rate on the preschool CPT as a function of chronological age. Some data points overlap; all individual data points are plotted with a line of best fit.

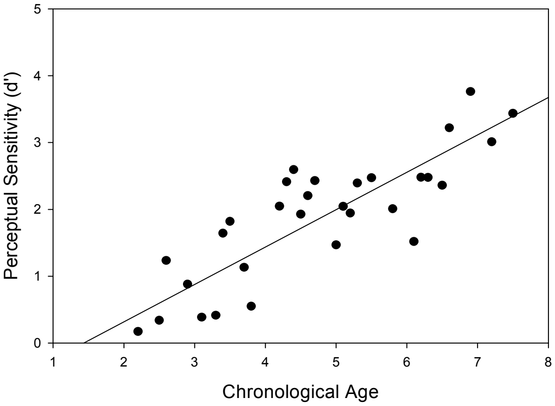

Figure 3b. Perceptual sensitivity (d') on the preschool CPT as a function of chronological age. Some data points overlap; all individual data points are plotted with a line of best fit.

Estimated mean hit rate increased from 0.45 (*SE*=0.05) before implantation to 0.74 (*SE*=0.04) after two years of CI use, a significant effect (*F*(2,47.8) = 11.38, *p* <0.01). A significant effect of length of CI use was also found for mean false alarm rate which decreased from 0.14 (*SE*=0.02) before cochlear implantation to 0.07 (*SE*=0.02) after two years of CI use (*F*(251.3) = 5.55, *p* <0.01). Finally, d' increased from 1.04 (*SE*=0.19) prior to implantation to 2.49 (*SE*=0.17) after two years of CI use, also a significant effect (*F*(2,50.2) = 16.25, *p* <0.01). In contrast, length of CI use did not significantly effect β. Figures 4a-c illustrate the significant effects of length of CI use on preschool CPT performance.

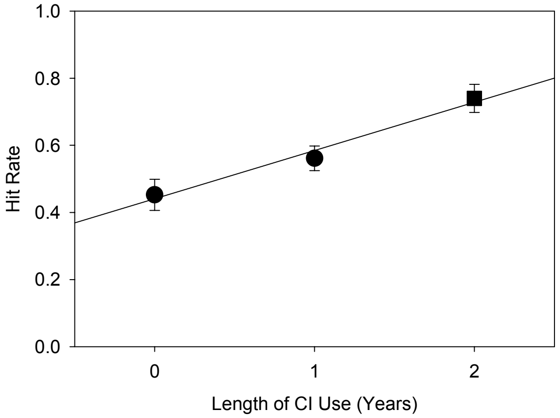

Figure 4a. Hit rate on the preschool CPT as a function of length of CI use. Different shaped data points are used to represent significantly different performance means between different lengths of CI use.

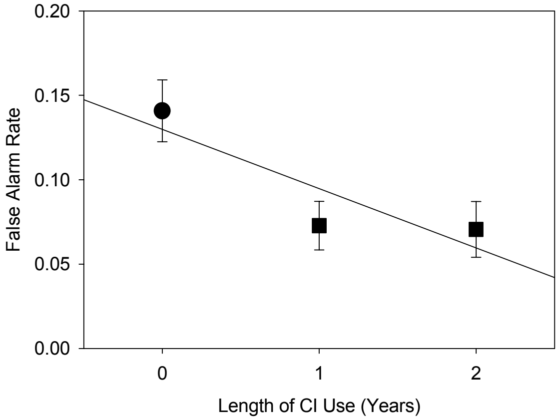

Figure 4b. False alarm rate on the preschool CPT as a function of length of CI use. Different shaped data points are used to represent significantly different performance means between different lengths of CI use.

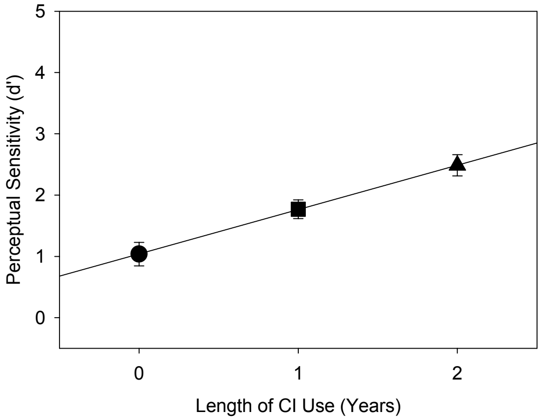

Figure 4c. Perceptual sensitivity (d') on the preschool CPT as a function of length of CI use. Different shaped data points are used to represent significantly different performance means between different lengths of CI use.

Tukey's post hoc analyses were carried out to assess performance differences on the preschool CPT between each post-implant interval. Figure 4a shows that preschool CPT hit rate increased significantly, as a function of length of CI use, between post-implantation years 1 and 2 (Tukey's $p<0.01$), but not between pre-implant and post-implant year 1 although the latter was a trend (Tukey's $p=0.06$). Figure 2b shows that false alarm rate on this task decreased significantly between the pre-implant interval and post-implantation year 1 (Tukey's $p<0.01$), but not between post-implantation years 1 and 2 (Tukey's $p=0.92$). Figure 2c shows that perceptual sensitivity (d') increased significantly from pre-implantation to post-implantation year 1 (Tukey's $p<0.01$) and then again from post-implantation year 1 to post-implantation year 2 (Tukey's $p<0.01$).

Effects of medical, audiological, and demographic variables on preschool CPT performance. No significant effects on preschool CPT scores were found for any of the medical, audiological, or demographic variables with the exception of the number of active electrodes in the implant array. To explore this effect further, we divided the participants into one of two groups, using a median split, at an electrode number of 21. Thus, the two groups consisted of children with a full array of active electrodes and children with less than a full array of active electrodes. Children in the full array group had higher d' scores on the preschool CPT ($F(1,48)=6.79$, $p<0.05$) and a higher hit rate ($F(1,43.9)=4.03$, $p=0.05$) than children who had less than 22 electrodes. Not only does this effect remain significant when we split at lower electrode numbers, but the significance p values become even lower suggesting that the effect is likely carried by those children with electrode numbers far lower than 21. However, because we found electrode number to be skewed toward higher numbers, we only present the findings using a median split.

Correlations between preschool CPT scores and speech and language outcome measures. We computed bivariate correlations between each preschool CPT measure and each of the speech and language outcome measures using scores obtained at one year post-implantation. As shown in Table 7, significant correlations ($p<0.05$) were found between expressive and receptive language (RDLS) and hit rate (r's $=0.48$ and 0.52, respectively). No other significant correlations were found between preschool CPT scores and speech/language outcome measures. We conducted two univariate regression analyses with RDLS receptive and expressive scores as dependent variables, CPT hit rate as the independent variable, and chronological age as a covariate. In this model, the relations between hit rate and RDL expressive and receptive language were no longer significant. Thus, when we controlled for the effects of chronological age, we found no significant relations between the preschool CPT scores and speech and language outcomes in deaf children who had used their CIs for 1 year.

Outcome Measure	**Hit Rate**	**False Alarms**	**d'**	**Beta**
PBK	ns	ns	ns	ns
CP V	ns	ns	ns	ns
CP AV	ns	ns	ns	ns
PPVT	ns	ns	ns	ns
RE	0.517*	ns	ns	ns
RR	0.483*	ns	ns	ns
BIT	ns	ns	ns	ns

Table 4. Bivariate correlations between school-age CPT scores and outcome measures
* *p*= 0.05 level (two tailed)

Discussion

The children in Experiment II, who were all younger than 6 years of age, performed poorly on the preschool CPT compared to the normative sample tested by Gordon et al. Although no study to date has compared the preschool CPT scores of prelingually deaf children to normal-hearing children, our results suggest that atypical development of sustained visual attention in deaf children is detectible by ages 3-6 years old. However, future comparisons between deaf and normal-hearing children on the preschool CPT will help to confirm this interpretation.

As we showed in Experiment I for the older children, scores on the preschool CPT improved as a function of length of CI use. Over two years of CI use, prelingually deaf children showed an increase in hit rate, decrease in false alarm, and an increase in perceptual sensitivity when the effect of chronological age was partialled out. While the decrease in false alarm rate on the preschool CPT leveled off after one year of CI use, the hit rate did not increase until after 1 year of use. Perceptual sensitivity, d', increased significantly at each interval of CI use. Given the earlier findings of Quittner et al. and Smith et al., we would expect continued improvement in CPT performance as a function of CI use until the deaf children are, on average, performing at levels that are comparable to normal-hearing children.

We did not observe any effects of the medical, audiological, or demographic variables on preschool CPT scores except for the number of active electrodes. This is the first report of an effect for the number of active electrodes on the development of visual attention skills in children with CIs. Our sample size and skewed distribution of electrode number do not allow us to determine whether this finding was carried by a small number of children who have fewer active electrodes than most of the children. Other studies have found that only a relatively small number of electrodes (less than 12) is required to achieve maximal speech perception scores with CIs or CI simulations (Dorman, Loizou, Kemp, & Kirk, 2000; Friesen, Shannon, Baskent, & Wang, 2001).

There are at least two reasons why some children with CIs may not have a full array of active electrodes. First, some of these children may have had partial insertions due to anatomic cochlear abnormalities such as a Mondini malformation. Secondly, during programming it is sometimes necessary to deactivate electrodes which are functioning inappropriately (stimulating the facial nerve, requiring a disproportionate large amount of current, not working at all). Thus, it is hard to determine precisely whether the effect we found is due to the actual number of stimulation points in the cochlea, or to some other confounding variable associated with a lower number of electrodes.

Our correlational analysis of the data in Experiment II revealed no significant relations between the preschool CPT scores and the speech perception, language, vocabulary, or speech intelligibility measures when we controlled for chronological age. These findings demonstrate that individual differences in sustained visual attention abilities and speech/language outcomes do not share a significant amount of variance. However, our correlations were obtained from scores at 1 year post-implantation. This is admittedly quite early in terms of assessing speech/language benefits with a cochlear implant. It is possible that relations between CPT performance and speech/language skills would emerge if we were to test children with 4 or more years of implant experience. Indeed, this is a research area for future exploration.

General Discussion

Experiments I and II investigated the development of sustained visual attention skills of prelingually deaf children who used cochlear implants. Overall, our results are consistent with the earlier findings of Quittner et al. and Smith et al. which showed that the sustained visual attention skills of prelingually deaf children are atypical compared to normal-hearing children. The effect of CI use on CPT performance, independent from chronological age, suggests that auditory experience leads to a gradual maturation of sustained attention skills over a period of years. Although we did not find direct evidence for a critical period for sustained visual attention development as suggested by Quittner et al.'s and Smith et al.'s data, the lack of an interaction between length of CI use and chronological age in our study does not disprove their critical period hypothesis. It is possible that the age ranges of children in the present study fell within a critical period during which CI experience influenced sustained visual attention development. Further research on the sustained visual attention skills of our youngest and oldest children with CIs may reveal evidence of a critical period.

We found little evidence to suggest that demographic, medical, and audiological variables influenced CPT performance, and did not find any interactions of these variables with the effect of length of CI use. Therefore, the impact of early auditory experience appears to shape the development of cognitive processing in the visual modality. Moreover, sustained visual attention abilities display some degree of plasticity and ability to reorganize in the presence of the cross-modal auditory input provided by a CI. However, the underlying neural and cognitive processes responsible for deaf children's atypical CPT performance, and for the effect of CI use, have yet to be sufficiently defined.

The hypothesis proposed by Quittner et al. and Smith et al. was that early auditory deprivation leads to remodeling of visual attention processes. Reasoning that deaf children are required to utilize vision to monitor their environment, Quittner et al. and Smith et al. argued that visual attention processes in these children would reorganize and adapt to maintain a wide spatial focus rather than a narrow, task-specific focus such as a CPT. In describing their "division of labor" hypothesis, Smith et al. suggested that normal-hearing children learn to sustain focused visual attention with a remarkable degree of acuity in part because of their ability to utilize auditory signals to detect environmental events. Because many environmental events may occur outside the field of visual attention, audition frees the visual system from utilizing capacity-demanding resources to detect these events.

However, the CPT used in the present and earlier studies does not explicitly assess selective allocation of visual attention. In selective attention experiments, distracting stimuli are used to test for effects on visual target processing time or accuracy (Parasnis, Samar, & Berent, 2003). Although selective attention may be useful in any task requiring concentration (there are almost always small sounds/events occurring in the environment), we do not know to what degree these abilities play a role in performance on sustained attention tasks. To test the predictions of the division of labor hypothesis, therefore, the appropriate type of task is a selective attention task.

The Gordon Diagnostic System includes a task called the distractibility CPT (Gordon et al., 1996). This task is similar to the previous CPTs (which we will call vigilance CPTs for distinction) except for the addition of two additional streams of numbers which appear to the right and left of the original number sequence. Participants are instructed to ignore these two additional number sequences and focus only on the numbers which appear in the center of the display. By comparing performance on the distractibility CPT with the vigilance CPT, the ability of a subject to selectively attend to the center display can be measured.

Mitchell and Quittner (1996) administered both the distractibility and vigilance CPTs to a population of normal-hearing children and prelingually deaf children with CIs. They found that prelingually deaf children scored lower on average than the normal-hearing children on both CPTs. The authors computed a distraction decrement score by subtracting each subject's score on the distractibility CPT from their score on the vigilance CPT. Mitchell and Quittner reported that prelingually deaf children with CIs showed greater mean distraction decrements than the normal-hearing children. Thus, prelingually deaf children with CIs were less able to ignore the distracting numbers which flanked the stimulus stream of interest. This finding is consistent with Smith et al.'s prediction that selective visual attention skills of prelingually deaf children develop atypically compared to those of normal-hearing children.

A number of visual information processing studies conducted with prelingually deaf adults have revealed compelling evidence that auditory deprivation leads to reorganization of visual attention processes (Bavelier, Brozinsky, Tomann, Mitchell, Neville, & Liu, 2001; Bavelier, Tomann, Hutton, Mitchell, Corina, Liu, & Neville, 2000; Neville & Lawson, 1987a, 1987b, 1987c; Proksch & Bavelier, 2002; Rothpletz, Ashmead, & Tharpe, 2003). In general, the findings of these electrophysiological, functional magnetic resonance imaging (fMRI), and behavioral studies have demonstrated that deaf adults, compared to normal hearing adults show evidence for increased processing of peripheral visual stimuli and wider spatial distribution of selective attention. The deaf adults in these studies appeared to have developed a visual system geared toward processing a wider spatial area than typically observed in normal hearing participants (Proksch & Bavelier, 2002).

The deaf adult participants in these experiments typically use American Sign Language (a manual language which is linguistically distinct from any spoken language). Therefore, several studies have tested normal hearing adults who learned ASL at an early age (due to having deaf parents) to control for effects of acquiring a manual language. The effect of ASL fluency itself has not turned out to be significant, suggesting that the reorganization of peripheral visual processing and selective attention results from auditory deprivation (Bavelier et al., 2001; Neville et al., 1987c; Proksch & Bavelier, 2002).

These studies of visual processing in deaf adults do not tell us at what age this visual reorganization occurs. However, the results reported by Mitchell and Quittner with the distractibility CPT showing that deaf children were more distractible than normal-hearing children do suggest that some reorganization occurs in deaf children by the school-age years. Furthermore, if deaf children are processing a wider part of their visual world than normal-hearing children, this might lead to atypical performance on the vigilance CPT as well (although this task is not a selective attention task). Given the capacity limitations of young children, these additional processing demands might be responsible for the poor performance of prelingually deaf children on the tasks in this study and the earlier studies of Quittner et al. and Smith et al.

Presumably, the effect of auditory experience on the development of sustained and selective visual attention reflects some degree of cortical reorganization. Studies of cross-modal plasticity have found evidence to suggest that cortical areas normally responsible for auditory processing can be recruited and reorganized for visual processing. In an early study, Rebillard, Carlier, Rebillard, and Pujol (1977) reported increased visual evoked responses in the primary auditory cortex of congenitally deafened cats compared to normal-hearing cats. Their findings were taken as evidence for recruitment of unused auditory cortex by visual cortical functions. Although a more recent study of congenitally deaf cats failed to demonstrate cross-modal recruitment of primary auditory cortex (Kral, Schroder, Klinke, & Engel, 2003), other evidence has been found for cross-modal plasticity in secondary auditory areas.

Finney and colleagues (Finney, Clementz, Hickok, & Dobkins, 2003; Finney, Fine, & Dobkins, 2001) have employed neuro-imaging techniques to demonstrate visual evoked activity in the auditory cortex of prelingually deaf adults. In particular, increased activity Brodmann's areas 41, 42, and 43 in deaf adults compared to normal-hearing adults when participants processed visual motion stimuli (Finney et al., 2001). This visually-evoked activity in the auditory cortex of deaf adults occurs rapidly after stimulus presentation, suggesting that it results from cross-modal recruitment of auditory cortex by visual thalamic afferents (Finney et al., 2003).

Lee and colleagues (Lee, Lee, Oh, Kim, Kim, Chung, Lee, & Kim, 2001; Oh, Kim, Kang, Lee, Lee, Chang, Ahn, Hwang, Park, & Koo, 2003) have found PET evidence that cross-modal recruitment of auditory cortex may have important consequences for speech/language outcomes in prelingually deaf children with CIs. These authors found a negative predictive relationship between the degree of pre-implant auditory cortex metabolism and post-implant speech perception scores. Children with less auditory metabolism (an indication of cross-modal recruitment) demonstrated better outcomes with their CI. The results reported by Lee et al. and Oh et al. suggest that cross-modal reorganization is one cortical mechanism which may be responsible for shaping the speech perceptual processes of deaf children with CIs. However, it is not clear whether cross modal recruitment of auditory cortex plays a role in the observed atypical visual processes of deaf children and adults. Relations between cross-modal recruitment of auditory cortex and visual attention processes have not yet been reported and may prove to be a promising area for future research.

The effect of CI use on sustained visual attention skills of deaf children, and their atypical skills relative to normal-hearing children, might be due to additional factors other than cross-modal reorganization. An alternative hypothesis is that these findings may reflect underlying deficiencies in processing of verbally-encoded visual stimuli in deaf children. Because visually presented numbers were likely to be verbally-encoded by the deaf children in our study, we would expect that verbal fluency would play a role in CPT performance. Several recent studies of working memory capacity in prelingually deaf children with CIs have reported evidence that verbal encoding and rehearsal skills are also atypical in these children.

Prelingually deaf children with CIs have been shown to have impaired immediate recall for sequences of stimuli regardless of modality of presentation (Cleary, Pisoni, & Geers, 2001; Dawson, Busby, McKay, & Clark, 2002; Pisoni & Cleary, 2003). Compared to normal-hearing children, prelingually deaf children with CIs display reduced overall span (number of items they can recall) for auditory presentation of numbers (Pisoni & Cleary, 2003), visual presentation of colored lights (Cleary et al., 2001), auditory presentation of color names (Cleary et al., 2001), and for auditory color names and lights presented together (Cleary et al., 2001). Dawson et al. tested deaf children with CIs on a number of immediate recall tasks using either auditory or visually-presented stimuli. They found impairments in deaf children on the auditory tasks as well as on some of the visual tasks. Dawson et al. found that, on the visual tasks which employed stimuli which could be verbally encoded or named, deaf children showed shorter spans than normal-hearing children. However, they did not show impairments in recall of visual stimuli which could not be easily verbally encoded. Taken together these studies suggest that verbal encoding of stimuli is impaired in young deaf children regardless of whether these stimuli are heard, seen, or both.

The CPTs used in the present study utilized visually-presented numbers, stimuli which can be verbally encoded by our participants. Therefore, deficits in verbal encoding of these stimuli may have played a limiting role in the performance of deaf children on the CPT. In other words, the deaf children might have normal visual attention mechanisms, yet have difficulty encoding and processing stimuli into phonological representations. Indeed, phonological storage and sub-vocal rehearsal of stimulus representations via the phonological loop have been shown to protect stimulus representations in working memory from time-related decay (Baddeley, Gathercole, & Papagno, 1998). Studies which manipulate use of the phonological loop by participants have shown that deaf children do not take advantage of this mechanism to the same degree as normal-hearing children (Chincotta & Chincotta, 1996; Pisoni & Cleary, 2003). Therefore, the CPT used in this and other studies may be biased against prelingually deaf children with atypical verbal encoding skills.

To date, only two studies of sustained visual attention in normal hearing adults and prelingually deaf adult ASL users have utilized CPTs in which stimuli were unlikely to be verbally encoded. Dittmar, Berch, and Warm (1982) used a CPT which required 45 minutes of visual monitoring of a light-bar which executed a string of paired movements. The detection task was to respond when the degree of movement differed between the two paired movements. Dittmar et al. reported that deaf adults showed greater performance on this task than normal hearing adults, a result which initially appears to contradict the present results. However, the visual processing required by this task is clearly different from the current CPT because visual detection of movement differences does not involve or require verbal encoding. Thus, differences in CPT performance between deaf and normal hearing individuals may depend on the type of visual stimulus used, and whether or not this stimulus is verbally encoded.

Recently, Parasnis et al. (2003) reported CPT results obtained from prelingually deaf adult ASL users and normal hearing adults. Their CPT used visually-presented geometrical shapes as stimuli and the task was to detect a certain type of shape based on whether the object had a hole toward its top or bottom. In contrast to Dittmar et al.'s findings, Parasnis et al. reported deficits in performance of deaf adults compared to normal-hearing participants. It is unclear to what degree the geometric stimuli were verbally encoded (for instance as, "top" or "bottom"). If we assume that verbal encoding was utilized by participants in Parasnis et al.'s task, then their results appear consistent with the current and earlier studies by Quittner et al. and Smith et al. which found deficits in deaf children's' abilities on a CPT which used numbers as stimuli. Future work on sustained visual attention skills of deaf children with CIs should include tasks which are not likely to induce or encourage verbal encoding.

In summary, we have proposed two general mechanisms to explain the effect of a CI on the sustained visual attention skills of deaf children. One possible explanation is that visual attention processing is altered by cross-modal auditory experiences obtained during a period of auditory deprivation and is reorganized after implantation. A second possible explanation is that atypical phonological encoding and verbal rehearsal skills, which result from a period of early auditory deprivation begin to improve after cochlear implantation. Both processes may interact to affect CPT performance in deaf children, and certainly other explanations for the current and previous findings may exist. Future research into sustained visual attention skills of deaf children with CIs should utilize tasks which do not contain stimuli which can be easily named or encoded phonologically. Testing of these children on tasks of selective attention may help to define the nature of reorganization of visual attention resulting from auditory experience. In parallel to these studies, future work on the longitudinal development of the phonological loop in deaf children may provide valuable information as to how the processing and storage of visual stimuli may be altered by early auditory experience. Finally, the testing of children from a wide range of ages may reveal critical periods during which the development of these cognitive processes may be altered by auditory deprivation and cochlear implantation.

We did not find evidence to suggest that the skills assessed by the CPT were closely related to speech and language acquisition with CIs, although we did find one relationship between the school-age CPT and vocabulary knowledge. However, before we make the conclusion that sustained visual attention skills do not partially explain individual differences in audiological outcomes of these children, it would be important to examine relations between CPT and speech/language scores after longer intervals of CI use. Relations may emerge after many years of implantation which we were not able to detect in this study. Therefore, more research on CPTs and other laboratory measures of sustained visual attention are needed to fully assess the clinical usefulness of these measures for deaf children with cochlear implants.

References

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

Barkley, R. (1991). The ecological validity of laboratory and analogue assessment methods of ADHD symptoms. *Journal of Abnormal Child Psychology, 19*(2), 149-178.

Bavelier, D., Brozinsky, C., Tomann, A., Mitchell, T., Neville, H., & Liu, G. (2001). Impact of early deafness and early exposure to sign language on the cerebral organization for motion processing. *Journal of Neuroscience, 21*, 8931-8942.

Bavelier, D., Tomann, A., Hutton, C., Mitchell, T., Corina, D., Liu, G., et al. (2000). Visual attention to the periphery is enhanced in congenitally deaf individuals. *Journal of Neuroscience, 20*, RC93.

Blamey, P., Sarant, J., Paatsch, L., Barry, J., Bow, C., Wales, R., et al. (2001). Relationships among speech perception, production, language, hearing loss, and age in children with impaired hearing. *Journal of Speech Language and Hearing Research, 44*, 264-285.

Chincotta, M., & Chincotta, D. (1996). Digit span, articulatory suppression, and the deaf: a study of the Hong Kong Chinese. *American Annals of the Deaf, 141*, 252-257.

Cleary, M., Pisoni, D., & Geers, A. (2001). Some measures of verbal and spatial working memory in eight- and nine-year-old hearing-impaired children with cochlear implants. *Ear and Hearing, 22*, 395-411.

Conners, C. (2000). *Conners' CPT II for Windows*. North Tonawanda, NY: Multi-Health Systems.

Dawson, P., Busby, P., McKay, C., & Clark, G. (2002). Short-term auditory memory in children using cochlear implants and its relevance to receptive language. *Journal of Speech Language and Hearing Research, 45*, 789-801.

Dittmar, M., Berch, D., & Warm, J. (1982). Sustained visual attention in deaf and hearing adults. *Bulletin of the Psychonomic Society, 19*, 339-342.

Dorman, M., Loizou, P., Kemp, L., & Kirk, K. (2000). Word recognition by children listening to speech processed into a small number of channels: data from normal-hearing children and children with cochlear implants. *Ear and Hearing, 21*, 590-596.

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

Finney, E., Clementz, B., Hickok, G., & Dobkins, K. (2003). Visual stimuli activate auditory cortex in deaf subjects: evidence from MEG. *Neuroreport, 14*, 1425-1427.

Finney, E., Fine, I., & Dobkins, K. (2001). Visual stimuli activate auditory cortex in the deaf. *Nature Neuroscience, 4*, 1171-1173.

Forbes, G. (1998). Clinical utility of the test of variables of attention (TOVA) in the diagnosis of attention-deficit/hyperactivity disorder. *Journal of Clinical Psychology, 54*, 461-476.

Friesen, L., Shannon, R., Baskent, D., & Wang, X. (2001). Speech recognition in noise as a function of the number of spectral channels: comparison of acoustic hearing and cochlear implants. *Journal of the Acoustical Society of America, 110*, 1150-1163.

Fryauf-Bertschy, H., Tyler, R., Kelsay, D., & Gantz, B. (1992). Performance over time of congenitally deaf and postlingually deafened children using a multichannel cochlear implant. *Journal of Speech Language and Hearing Research, 35*, 913-920.

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

Geers, A., Nicholas, J., & Sedey, A. (2003). Language skills of children with early cochlear implantation. *Ear and Hearing, 24*, 46S-58S.

Gordon, M., McClure, F., & Aylward, G. (1996). *The Gordon diagnostic system (GDS) instruction manual & interpretive guide* (3 ed.). Dewitt, NY: Michael Gordon, PhD.

Green, D., & Swets, J. (1966). *Signal detection theory and psychophysics*. New York: Wiley.

Greenberg, L. (1991). *T.O.V.A. interpretation manual*. Minneapolis, MN.

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

Kirk, K. (2000). Cochlear implants: new developments and results. *Opinion in Otolaryngology Head and Neck Surgery, 8*, 415-420.

Kral, A., Schroder, J., Klinke, R., & Engel, A. (2003). Absence of cross-modal reorganization in the primary auditory cortex of congenitally deaf cats. *Experimental Brain Research, 153*, 605-613.

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

Mitchell, T., & Quittner, A. (1996). Multimethod study of attention and behavior problems in hearing-impaired children. *Journal of Clinical Child Psychology, 25*, 83-96.

Miyamoto, R., Osberger, M., Robbins, A., Myres, W., & Kessler, K. (1993). Prelingually deafened children's performance with the nucleus multichannel cochlear implant. *Amercian Journal of Otology, 14*, 437-445.

Miyamoto, R., Svirsky, M., Kirk, K., Robbins, A., Todd, S., & Riley, A. (1997). Speech intelligibility of children with multichannel cochlear implants. *Annals of Otology Rhinology Laryngology Supplement, 168*, 35-36.

Neville, H., & Lawson, D. (1987a). Attention to central and peripheral visual space in a movement detection task: an event-related potential and behavioral study. I. Normal hearing adults. *Brain Research, 405*, 253-267.

Neville, H., & Lawson, D. (1987b). Attention to central and peripheral visual space in a movement detection task: an event-related potential and behavioral study. II. Congenitally deaf adults. *Brain Research, 405*, 268-283.

Neville, H., & Lawson, D. (1987c). Attention to central and peripheral visual space in a movement detection task. III. Separate effects of auditory deprivation and acquisition of a visual language. *Brain Research, 405*, 284-294.

Niparko, J., Kirk, K., Mellon, N., McConkey-Robbins, A., Tucci, D., & Wilson, B. (2000). *Cochlear Implants: Principles & Practices*. Philadelphia, PA: Lippincott Williams & Wilkins.

Oh, S., Kim, C., Kang, E., Lee, D., Lee, H., Chang, S., et al. (2003). Speech perception after cochlear implantation over a 4-year time period. *Acta Oto-Laryngologica, 123*(2), 148-153.

Osberger, M., Miyamoto, R., Zimmerman-Philips, S., Kemink, J., Stroer, B., Firszt, J., et al. (1991). Independent evaluation of the speech perception abilities of children with the Nucleus-22 channel cochlear implant system. *Ear and Hearing, 12*, S66-80.

Osberger, M., Robbins, A., Todd, S., & Riley, A. (1994). Speech intelligibility of children with cochlear implants. *Volta Review, 96*, 169-180.

Parasnis, I., Samar, V., & Berent, G. (2003). Deaf adults without attention deficit hyperactivity disorder display reduced perceptual sensitivity and elevated impulsivity on the Test of Variables of Attention (T.O.V.A.). *Journal of Speech Language and Hearing Research, 46*, 1166-1183.

Parasuraman, R. (1998). *The Attentive Brain*. Cambridge, MA: MIT Press.

Pastore, R., Crawley, E., Berens, M., & Skelly, M. (2003). "Nonparametric" A' and other modern misconceptions about signal detection theory. *Psychonomic Bulletin & Review, 10*, 556-569.

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

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

Proksch, J., & Bavelier, D. (2002). Changes in the spatial distribution of visual attention after early deafness. *Journal of Cognitive Neuroscience, 14*, 687-701.

Quittner, A., Smith, L., Osberger, M., Mitchell, T., & Katz, D. (1994). The impact of audition on the development of visual attention. *Psychological Science, 5*, 347-353.

Rebillard, G., Carlier, E., Rebillard, M., & Pujol, R. (1977). Enhancement of visual responses on the primary auditory cortex of the cat after an early destruction of cochlear receptors. *Brain Research, 129*, 162-164.

Reynell, J. K., & Huntley, M. (1985). *Reynell Developmental Language Scales* (2nd ed.). Windsor, UK: NFER-Nelson.

Rosvold, H., Mirskey, A., Sarason, I., Bransome, E., & Beck, L. (1956). A continuous performance test of brain damage. *Journal of Consulting and Clinical Psychology, 20*, 343-350.

Rothpletz, A., Ashmead, D., & Tharpe, A. (2003). Responses to targets in the visual periphery in deaf and normal hearing adults. *Journal of Speech Language and Hearing Research, 46*, 1378-1386.

Sarant, J., Blamey, P., Dowell, R., Clark, G., & Gibson, W. (2001). Variation in speech perception scores among children with cochlear implants. *Ear and Hearing, 22*, 18-28.

Schafer, J., & Graham, J. (2002). Missing data: our view of the state of the art. *Psychological Methods, 7*, 147-177.

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

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

Tharpe, A., Ashmead, D., & Rothpletz, A. (2002). Visual attention in children with normal hearing, children with hearing aids, and children with cochlear implants. *Journal of Speech, Language, & Hearing Research, 45*, 403-413.

Tobey, E., Geers, A., Brenner, C., Altuna, D., & Gabbert, G. (2003). Factors associated with development of speech production skills in children implanted by age five. *Ear and Hearing, 24*, 36S-45S.

Tyler, R., Fryauf-Bertschy, H., Kelsay, D., Gantz, B., Woodworth, G., & Parkinson, A. (1997). Speech perception by prelingually deaf children using cochlear implants. *Otolaryngology Head and Neck Surgery, 117*, 180-187.

Wolfinger, R., & Chang, M. (1995). *Comparing the SAS GLM and MIXED procedures for repeated measures.* Paper presented at the Proceedings of the Twentieth Annual SAS Users Group International Conference, Orlando, Florida.