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Perceptual Ratings of Nonword Repetitions by Deaf Children after Cochlear Implantation: Correlations with Measures of Speech, Language and Working Memory[1]

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Perceptual Ratings of Nonword Repetitions by Deaf Children after Cochlear Implantation: Correlations with Measures of Speech, Language and Working Memory

Abstract. Seventy-six profoundly deaf children with cochlear implants completed a nonword repetition task. The children were presented with 20 nonword auditory patterns over a loudspeaker and were asked to repeat them aloud to the experimenter. All of the children were deaf before the age of 36 months. At the time of testing the children were between 8 and 9 years old. All but three of the children used a Nucleus 22 implant with the SPEAK coding strategy at the time of testing. Two of the children used a Clarion device and one child used a Nucleus 24 implant at the time of testing. The duration of implant use for all children was between 4 and 7.5 years. All of the children in this study produced a repetition response to at least 15 of the 20 target nonwords. The children's responses were recorded on digital audiotape and then played back to 240 normal-hearing adult listeners for accuracy judgments. Normal-hearing listeners rated the accuracy of the children's imitation responses against the original target models using a 7-point scale. The perceptual ratings of the children's nonwords were strongly correlated with scores on separate independent measures of spoken word recognition, immediate memory span, and verbal rehearsal processes used in phonological working memory, as well as speech production skills. Children who had become deaf at slightly older ages and children who had been deaf for shorter periods of time prior to implantation received higher perceptual ratings. Children whose early linguistic experience and educational environments emphasized oral communication methods also received higher ratings than children enrolled in total communication programs. The findings from this study suggest that individual differences in performance on the nonword repetition task are strongly related to variability observed in the component processes involved in nonword repetition including speech perception, encoding and verbal rehearsal in phonological working memory, and speech production. In addition, a shorter period of deafness prior to implantation and an educational environment emphasizing oral communication may be beneficial to deaf children's ability to develop the robust phonological processing skills that are necessary to accurately repeat novel, nonword stimuli. These skills appear to be related to more complex cognitive processes involved in word learning, vocabulary development, and speech production.

Introduction

The investigation of individual differences in the speech and language skills of deaf children after cochlear implantation has been a major focus of the research program in our laboratory for several years (Pisoni, Cleary, Geers, & Tobey, 2000). We are interested in how the variability in a range of speech and language outcome measures can be accounted for by differences in basic underlying cognitive processing skills such as phonological encoding, short-term storage, verbal rehearsal processes in phonological working memory, and speech production. These basic cognitive processes are assumed to be involved, in one way or another, in all behavioral tasks that require the immediate repetition of an auditory pattern such as a familiar word or a novel phonological nonword pattern.

The nonword repetition task in which a child is asked to immediately repeat back a novel stimulus pattern has been used extensively in recent years by researchers to study the development of phonological working memory in normal-hearing children (e.g., Gathercole, Willis, Baddeley, & Emslie, 1994). More recently, we have also used this methodology to study deaf children with cochlear implants (Cleary, Dillon, & Pisoni, 2002; Dillon & Cleary, 2000). In the present paper, we report data obtained from a nonword repetition task completed by 76 deaf children who use cochlear implants. The results provide several new insights into the relationship between individual variability in the component processes of phonological encoding, storage and speech production, and several traditional outcome measures of the benefit received from a cochlear implant.

Preliminary findings obtained from a small group of children were reported recently in Cleary et al. (2002). In that study, 14 children who had used cochlear implants (Nucleus 22, SPEAK coding strategy) for at least 3.5 years (*M* = 5.5 years) completed a nonword repetition task. Each of their responses was then rated for accuracy by 10 normal-hearing adult listeners on a scale from 1 to 7. We found that the mean ratings received by each child were strongly correlated with other independent measures of word recognition, language comprehension, working memory, speech intelligibility, and speaking rate. These results demonstrate that deaf children with sufficient experience with CIs are able to complete a complex task such as nonword repetition. In addition, the results indicate that the children's performance on this nonword repetition task may predict, at least in part, their performance on other traditional speech and language outcome measures.

The present study addressed the following three questions: First, to what extent is individual variability on the nonword repetition task observed in deaf children after cochlear implantation? Second, is individual variability among children in nonword repetition performance related to individual differences in each of the component processes of speech perception, working memory, verbal rehearsal, and speech production? Third, are the children's demographic characteristics related to their nonword repetition performance? Thus, the primary goal of this study was to replicate our earlier findings by collecting additional perceptual ratings of the nonword repetitions produced by a larger number of deaf children using cochlear implants. The CI users in the original study by Cleary et al. (2002) had all produced a response to each nonword stimulus. The children in the present study included the 14 children in Cleary et al. (2002), and 62 additional children who were somewhat more variable in their response output in the nonword repetition task. The children in the present study produced responses on 75 to 100% of the nonword stimuli. Other than these differences, the procedures were the same.

Methods

Participants

Seventy-six deaf children who use cochlear implants were studied. All of the children were tested at Central Institute for the Deaf (CID) in St. Louis, Missouri in 1999 or 2000 as part of a larger study called "Cochlear Implants and Education of the Deaf Child" conducted by Ann Geers and her colleagues (see Geers et al., 1999). Thirty-eight of the children were participants in 1999 and 39 in 2000. Prior to their inclusion in the larger study at CID, the deaf children were evaluated through intelligence testing to ensure that they fell within a reasonable range of intelligence expected for their chronological age. Only children that met this criterion were tested and included in the present study. Thirty-six of the children were female, and 40 were male.

Table 1 shows a summary of the demographic characteristics of the participants in this study. The mean age at onset of deafness for all children was just over two months (*M* = 2.3, *SD* = 6.4). Most of the children had a congenital profound hearing loss. Only 12 of the children lost their hearing after birth, between the ages of 1 and 36 months (*M* = 14.3*, SD* = 9.7). The duration of deafness before implantation was between 7 and 65 months (*M* = 37.2*, SD* = 13.1). The children's age at implantation was between 1.9 and 5.4 years (*M* = 3.3*, SD* = 1.0). All of the children had used their implants for 3.8 to 7.5 years (*M* =

5.6*,* *SD* = 0.8), prior to testing. At the time of testing, the children's ages ranged from 7.9 to 9.9 years (*M* = 8.9*, SD* = 0.6). Most children were using a Nucleus-22 device with the spectral peak (SPEAK) coding strategy at the time of testing. Several other children had either a Nucleus-24 implant or a Clarion cochlear implant. The number of active electrodes in the devices ranged from 8 to 22 (*M* = 18.4, *SD* = 2.3).

Demographic Variables	***Range***	***Mean***	***Standard Deviation***
Age at Onset of Deafness (in months)	0 - 36	2.3	6.4
Duration of Deafness (in months)	7 - 65	37.2	13.1
Age at Implantation (in years)	1.9 - 5.4	3.3	1.0
Duration of Implant Use (in years)	3.8 - 7.5	5.6	0.8
Chronological Age (in years)	7.9 - 9.9	8.9	0.6
Number of Active Electrodes	8 - 22	18.4	2.3
Communication Mode Score	6 - 30	19.8	7.7

Table 1. Summary of the demographic makeup of the 76 children.

The children were classified into two different groups based on whether they used primarily oral communication (OC) or total communication (TC) strategies. TC is a method utilizing manual signs and lip reading strategies, in addition to speech. The classification was based on scores assigned at five different points in time to evaluate the nature of the children's early experience and communication training programs. The five evaluations were made at: (1) pre-implantation, (2) one year post-implantation, (3) two years post-implantation, (4) three years post-implantation, and (5) at the time of testing (which was the time of their participation in the CID summer program). Scores for each evaluation ranged from "1," signifying a program stressing the use of signs (usually in the form of Signed Exact English (SEE), not American Sign Language (ASL)) and lipreading strategies to "6," representing an oral-only regime. The scores assigned at each evaluation were then summed to determine the communication mode of the CI children at the time of testing. The summed communication mode scores obtained for these 76 children ranged from 6 to 30 (*M* = 19.8, *SD* = 7.7). Children with communication scores of 15 and below were considered to be TC users. Children with communication scores above 15 were considered to be OC users. This classification was made based on the original scoring method in which the lower scores (1-3) most accurately represent TC methods, while higher scores (4-6) most accurately represent oral methods. Twenty-nine of the original 76 children were classified as TC, while the remaining 47 were classified as OC users.

Stimulus Materials

The children were tested with a shortened version of the Children's Test of Nonword Repetition (CNRep; Gathercole et al., 1994; Gathercole & Baddeley, 1996). This nonword repetition test was originally designed to evaluate the phonological working memory skills of normal-hearing and typically developing children. The 40 original nonwords in the CNRep are all phonotactically permissible patterns that could be real words in English. The test items used in the present study included a subset of 20 nonwords, selected from the 40 stimuli originally developed by Gathercole et al. (1994). These 20 stimuli were chosen because they elicited more variability in performance scores when tested on a sample of young, normal-hearing children (Carlson, Cleary, & Pisoni, 1998). The 20 stimuli are listed in Table 2, along with their phonetic transcriptions. The final set of 20 nonwords included five words each at syllable lengths of 2, 3, 4, and 5. The full set of stimuli for the CNRep was previously recorded in our laboratory by a female speaker of American English.

Number of Syllables	Target Nonword Orthography	Target Nonword Transcription
	ballop	ˈbæ.ləp
	prindle	ˈprɪn.dl̩
2	rubid	ˈruˌbɪd
	sladding	ˈslæ.diŋ
	tafflist	ˈtæ.flɪst
	bannifer	ˈbæ.nəˌfɚ
	berrizen	ˈbɛ.ɹəˌzɪn
3	doppolate	ˈdɑ.pəˌle͡ɪt
	glistering	ˈglɪ.stɚ.iŋ
	skiticult	ˈskɪ.ɾəˌkʌlt
	comisitate	kəˈmi.səˌte͡ɪt
	contramponist	kənˈtɹæm.pəˌnɪst
4	emplifervent	ɛmˈplɪ.fɚˌvɛnt
	fennerizer	ˈfɛ.nɚˌa͡ɪ.zɚ
	penneriful	pəˈnɛ.ɹəˌfʌl
	altupatory	ælˈtu.pəˌtɔ.ri
	detratapillic	diˈtræ.ɾəˌpɪ.lɪk
5	pristeractional	ˈprɪ.stɚˌæk.ʃə.nl̩
	versatrationist	ˈvɚ.səˌtɹe͡ɪ.ʃəˌnɪst
	voltularity	ˈvɑl.tʃʊˌlɛ.ɹəˌti

Table 2. The 20 nonwords used in the current study (adapted from Gathercole et al., 1994).

Procedure

Before any of the nonwords were presented, the children were told that they would hear some "funny, made-up sounding" words. They were also told that they would have to repeat each stimulus clearly out loud after they listened to it. The nonwords were then presented in random order to the children, one at a time, at approximately 70 db SPL through a tabletop loudspeaker (Cyber Acoustics MMS-1). The speaker was directly facing the children at a distance of approximately one and a half feet. If a child made the request, the sound level was increased to a comfortable level.

All of the children included in this study produced a verbal response to at least 15 of the 20 nonword stimuli. Figure 1 shows the frequency distribution of the number of nonword repetition responses completed by the children. Of the 76 children, 24 produced a response to each of the 20 target stimuli, 19 children produced 19 responses, 12 children produced 18 responses, 10 children produced 17 responses, 3 children produced 16 responses, and 8 children produced 15 responses.

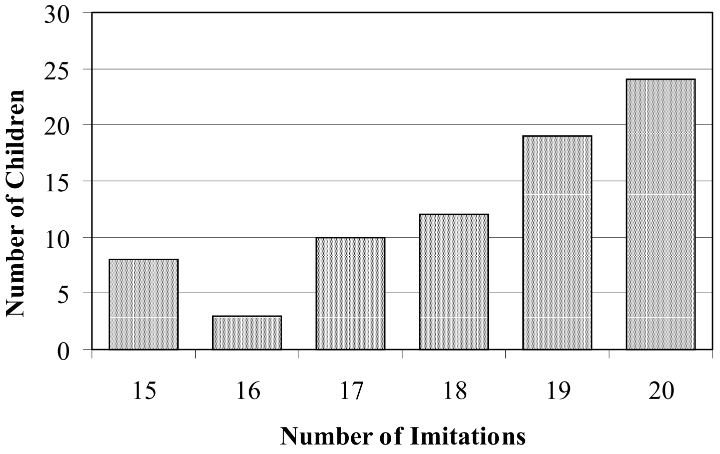

Figure 1. Frequency distribution of the number of nonword imitation responses produced by the 76 children (*M* = 18.36, *SD* = 1.63).

The children's nonword repetition responses were recorded onto digital audiotape (DAT; Sony Walkman TCD-D8) via a uni-directional headset cardioid condenser microphone (Audio-Technica ATM75). This equipment did not physically or mechanically interfere with the function or placement of the cochlear implant. The audio recordings were then digitized and transferred to computer files using the CoolEdit 96 (Syntrillium Software Corporation, 1996) digital waveform editing program. Each utterance was stored as an individual sound file.

All utterances were then edited and compiled together to make 24 different stimulus lists. The test lists were designed so that each list included the entire recorded data set of responses obtained from six different children. Each list included all of the utterances of one child who had produced a response to all 20 of the nonwords. Additionally, the data from five more children who produced a response to fewer than 20 stimuli were included to complete each list. The additional children assigned to each list had produced either 19, 18, 17, 16, or 15 utterances. By this method, no two children who had completed the same number of repetitions were included in a single test list. Thus, a complete list included 105 nonword repetitions produced by six children.

Given the distribution of the number of responses per child, it was necessary to include some children who did not complete all 20 utterances in more than one list so that every list would include 105 utterances. The lists were balanced in this way to insure that the adult listeners heard responses from several children whose set of imitation responses ranged from 15 to 20 utterances. In our earlier study, only children who had produced a response to all 20 of the stimuli were included (Cleary et al., 2002).

The test lists were then played back to normal-hearing adults who were asked to judge the accuracy of the nonword repetition responses produced by the children. Two-hundred-forty normal-hearing adult listeners, obtained from the Indiana University Psychology 101 Subject Pool, were asked to provide accuracy ratings for the CI children's imitations of the nonwords. All participants were monolingual native speakers of American English. They reported no history of a speech or hearing disorder at the time of testing. In addition, all subjects reported having no prior experience listening to the speech of the deaf or hearing impaired. After completing the perceptual rating task, the subjects received credit for the undergraduate psychology course in which they were currently enrolled.

Ten subjects heard each of the 24 test lists, so that each child was rated by at least 10 listeners. On each test trial, the listener first heard the target model stimulus pattern that had been presented to the deaf children for repetition. After hearing the model, the listeners then heard the imitation of that nonword stimulus produced by one of the children. The model stimulus and the child's response were separated by a one second interval of silence.

The order of presentation of the test trials was randomized within a list. Each listener completed two testing blocks using the same set of stimuli. Each block was randomized. Using this procedure, each nonword repetition was rated twice within the experiment by the same listener. Perceptual ratings were given according to a 7-point Likert scale between 1 and 7. The bottom of the scale, "1," was meant to represent a nonword repetition that "totally fails to resemble the target utterance." A score of "7" corresponded to nonword repetitions that were considered by the listeners to be "perfectly accurate renderings of the target utterance, ignoring differences in pitch." Listeners pressed buttons on a seven-button response box to record their judgments. The response box was interfaced to a PC that presented the stimuli to the listeners over high quality headphones (Beyer Dynamic, DT100) and recorded their responses. No feedback was provided during the experiment.

In addition to providing nonword repetition responses for this study, the children also completed a range of other tests designed to assess their speech perception, language, and literacy skills. To evaluate their spoken language comprehension skills, the Test of Auditory Comprehension of Language - Revised (TACL-R; Carrow-Woolfolk, 1985) was given. To evaluate their open-set speech perception and word identification skills, the children were tested using the Lexical Neighborhood Test (LNT; Kirk, Pisoni, & Osberger, 1995). Word identification skills were also measured through open-set sentence repetition using the Bamford-Kowal-Bench (BKB) test (Bench, Kowal, & Bamford, 1979). The Word Intelligibility by Picture Identification test (WIPI; Ross & Lerman, 1979) was used to measure closed-set word recognition skills. Speech feature discrimination was measured using the VIDSPAC (Boothroyd, 1997). The VIDSPAC is a video game test of speech feature contrast perception that was specifically designed for use with hearing-impaired children.

In addition to these traditional outcome measures, forward and backward digit spans were obtained using the Wechsler Intelligence Scale for Children, Third Edition (WISC-III; Wechsler, 1991) to obtain estimates of the capacity of immediate memory. Forward digit span was used as a measure of the children's phonological working memory (Pisoni & Geers, 2000). Backward digit span was used to measure more complex, controlled cognitive processing abilities, or 'executive function' (see Engle, 2002; Lezak, 1983; Li & Lewandowsky, 1995; Rosen & Engle, 1997).

Two speech production measures were also available from another component of the larger CID project. Speech intelligibility scores were obtained using the McGarr Sentence Intelligibility Test (McGarr, 1981). This test contains a set of 3-, 5-, and 7-syllable sentences that are used to elicit spoken utterances from the children. These speech samples were later played back to normal-hearing adult listeners who were asked to transcribe the sentences. These transcription scores provide an objective measure of speech intelligibility. Duration measurements of these test sentences were also used to provide estimates of speaking rate. The duration measurements and the speech intelligibility scores for the McGarr sentences were made by researchers at the Callier Advanced Hearing Research Center at the University of Texas, Dallas, under the direction of Dr. Emily Tobey.

Results

Perceptual Ratings. As mentioned earlier, all of the listeners rated each stimulus item twice during the experiment, once during the first block of test trials and a second time during an additional block. A comparison of the accuracy ratings obtained in each block provided a way to assess the reliability of the perceptual ratings within listener. In order to compare performance in the two blocks, all of the nonword ratings provided by an individual listener in each block were averaged to compute the mean rating provided by each listener per block. The mean ratings in the first block ($M = 2.96$, $SD = .48$) were highly correlated ($r = +.87$, $p <.001$) with the mean ratings in the second block ($M = 2.98$, $SD = .55$). The difference between blocks was not significant.

We also calculated the mean rating per child for each block by averaging the ratings of all imitations produced by an individual child. The mean rating per child in the first block ($M = 3.05$, $SD = 1.12$) was also strongly correlated ($r = +.99$, $p < .001$) with the mean rating per child in the second block ($M = 3.07$, $SD = 1.07$). The mean rating per child for the first block was not significantly different from the mean rating for the second block. Because the perceptual ratings in block one were not different from the ratings in block two, when averaged across either listener or child, the following results are based only on the accuracy ratings provided by the listeners during the first block of trials.

As in our earlier report of nonword repetition in deaf children using cochlear implants (Cleary et al., 2002), we found a wide range of variability in the mean accuracy ratings given to the children by the group of normal-hearing listeners. The distribution of the mean ratings scores assigned to the 76 children is shown in Figure 2. Very few children received ratings at floor on this task, nor did any children receive ratings at the ceiling level, indicating that this perceptual rating task provided a sensitive measure of nonword repetition performance for this particular group of children.

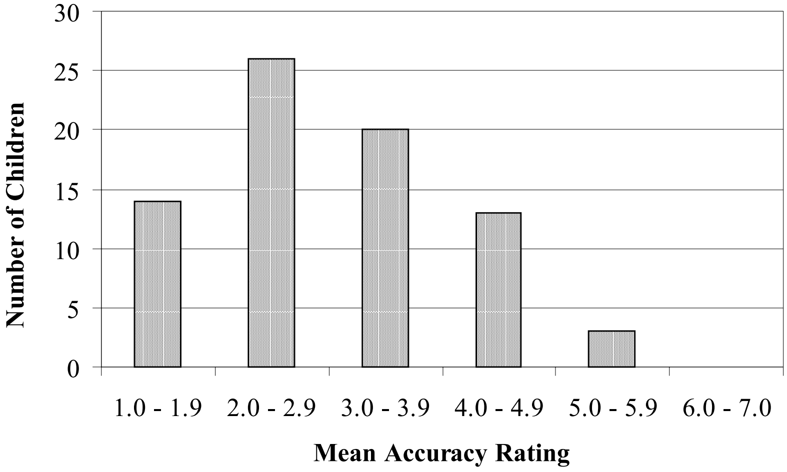

Figure 2. Frequency distribution of mean perceptual rating assigned to each child (N = 76) on a scale of “1” to “7” ($M = 3.05$, $SD = 1.12$)

Figure 3 shows a summary of the mean perceptual ratings of the OC and TC children’s nonword imitations. When the mean perceptual ratings of the children’s nonword imitations were summarized and divided into two separate groups, according to communication mode, a t-test revealed that the nonword responses from the OC children ($M = 2.46$, $SD = .96$) were rated significantly higher ($t(74) = -4.49$, $p <.001$) than the nonword responses from the TC children ($M = 1.40$, $SD = 1.05$). This finding demonstrates an effect of early auditory and linguistic experience on nonword repetition performance. The children’s ability to reproduce a novel nonword stimulus pattern is better when, over time, the use of oral language has been encouraged over the use of manual sign and lip reading in their educational environment.

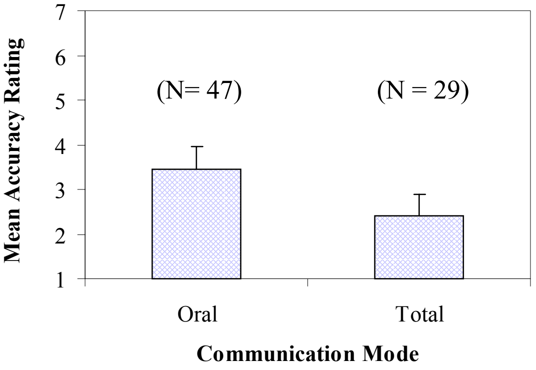

Figure 3. Mean perceptual rating of nonword imitations by OC and TC children. Error bars represent the standard error.

The mean perceptual rating for each of the 20 nonword patterns was also calculated based on the individual ratings of each response to that nonword. Figure 4 shows the mean perceptual ratings of the all the nonwords. The imitations of 2- and 3-syllable nonwords received higher ratings than the imitations of 4- and 5-syllable nonwords. An Analysis of Variance (ANOVA) revealed a significant main effect of syllable length on perceptual rating score (*F*(19) = 4.38, $p < .05$). Post-hoc Tukey tests revealed that imitation responses to 2- and 3-syllable target nonwords were each rated significantly higher than imitation responses to 5-syllable target nonwords (*p*'s = .05). This pattern may reflect the linguistically poorer imitations of the longer nonwords caused by their greater demands on phonological working memory (see also Carter, Dillon, & Pisoni, in press). In addition, the pattern of results shown in Figure 4 is consistent with findings that normal-hearing children's ability to accurately imitate shorter nonwords exceeds their ability to accurately imitate longer nonwords (Gathercole, 1995).

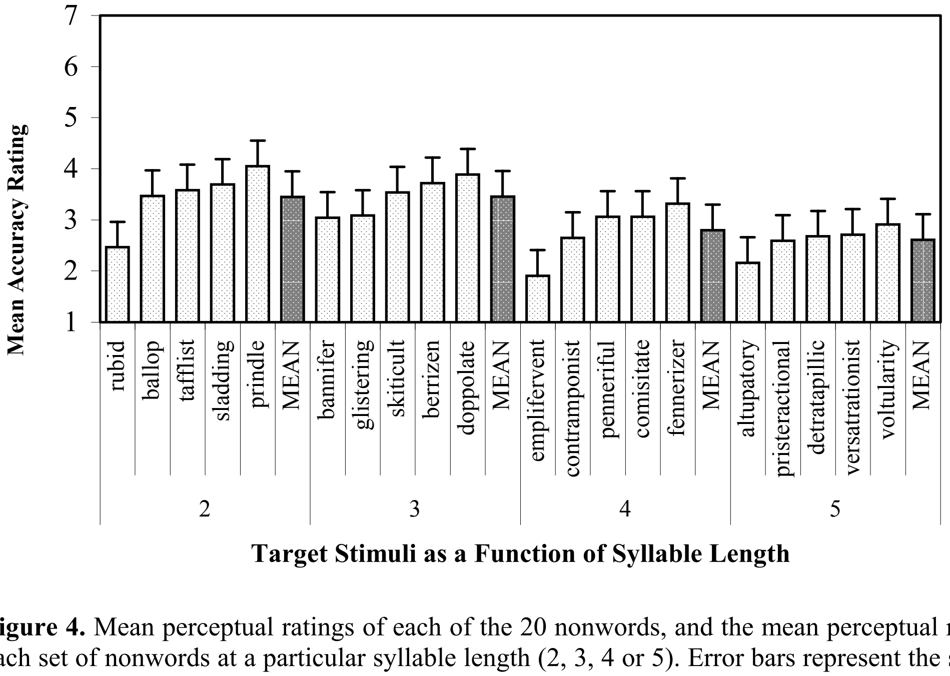

Figure 4. Mean perceptual ratings of each of the 20 nonwords, and the mean perceptual rating of each set of nonwords at a particular syllable length (2, 3, 4 or 5). Error bars represent the standard error.

Correlational Analyses. In order to investigate the extent to which the children's nonword repetition responses were related to their demographic characteristics and their scores on other measures of phonological encoding, immediate memory, verbal rehearsal, and speech production, we carried out a set of correlational analyses. A summary of the demographic correlations is shown in Table 3. The duration of time that the children had used their implants and their age at the time of testing were not significantly correlated with the nonword perceptual ratings. This is not surprising because these two factors were controlled in this study and the group was relatively homogeneous in terms of these two variables. Age at implantation was also not correlated with the perceptual ratings. The lack of correlation could indicate that there is no significant benefit of earlier implantation, or simply that children implanted at a later age had 'caught up' with the earlier-implanted children after four to five years of implant use. The absence of a correlation between age at implantation and nonword repetition performance could also be due to the relative homogeneity of this group of children who were part of the original experimental design.

Demographic Variables	Correlation *r* values
Age at onset of deafness	+.32**
Duration of deafness	- .26*
Age at implantation	- .12
Duration of cochlear implant use	+.06
Age at time of testing	- .13
Degree of exposure to oral-only communication	+.51***
Number of active electrodes in implant	- .31
Gender	- .14

Table 3. Correlations between nonword repetition perceptual ratings and demographic variables of the deaf children using cochlear implants. $*p < .05$, $**p < .01$, $***p < .001$

Despite being a relatively homogeneous group in terms of chronological age, age at onset of deafness was positively correlated with the nonword ratings ($r = +.32$, $p < .01$). Children who lost their hearing at older ages tended to produce nonwords that received higher nonword ratings. This finding suggests that the more opportunity a child has to hear, prior to the onset of deafness, the better their performance will be on tasks involving phonological processing skills such as the nonword repetition task. Duration of deafness was negatively correlated with the perceptual ratings ($r = -.26$, $p < .05$). This finding indicates that children who were deaf for shorter periods of time, prior to implantation, tended to produce nonword utterances that received higher ratings. In addition, we also found that the amount of exposure to oral-only communication was strongly correlated with the nonword perceptual ratings ($r = +.51$, $p < .001$). This relationship demonstrates that oral-aural experiences, promoting the production and perception of spoken language, contribute to phonologically-based tasks such as nonword repetition. The number of active electrodes in the children's implant was not significantly correlated with the nonword perceptual ratings.

Although the nonword repetition task appears on the surface to be simple and straightforward, performance on this task actually reflects the contribution of a number of component subprocesses including initial sensory coding and perception, encoding in working memory, verbal rehearsal, as well as speech articulation and motor control processes in speech production. To examine the contribution of these subprocesses, we also ran correlations between the nonword perceptual ratings and the scores on several standard outcome measures and cognitive processing measures. We expected that the correlations might provide insight into which, if any, skills involved in nonword repetition are indicative of overall performance.

As shown in Table 4, the simple bivariate correlations between the perceptual ratings and several measures of phonological encoding and word recognition (WIPI, LNTe, LNTh, mLNT, and TACL-R) were quite strong and highly significant (*r*'s = +.74, +.77, +.73, +.73, +.50, respectively; *p*'s < .001). In addition, word recognition measured through open-set sentence repetition was related to the nonword ratings. The Bamford-Kowal-Bench (BKB) test was also positively correlated to the perceptual ratings ($r = +.83$, $p < .001$). The children's scores on the VIDSPAC, a measure of speech feature discrimination, were also highly correlated with the perceptual ratings ($r = +.41$, $p < .001$). Similarly, the children's immediate memory span (as measured by the WISC forward digit span task) was significantly correlated with the ratings of their nonword repetitions ($r = +.57$, $p < .001$). The children's performance on the backwards digit span task, however, was not significantly correlated with the perceptual ratings, which is consistent with previous findings that forward and backward digit span tasks measure fundamentally different processes (Lezak, 1983; Li & Lewandowsky, 1995; Rosen & Engle, 1997).

The McGarr intelligibility scores were also strongly correlated with the perceptual ratings of the nonword responses ($r = +.73$, $p <.001$). That is, the intelligibility of children's speech in meaningful sentences was correlated with their performance on the nonword repetition task. In addition, the McGarr durations at all sentence lengths were negatively correlated with the perceptual ratings. The 7-syllable sentences were the most strongly related to the perceptual ratings because they likely provide a better measure of speaking rate than the shorter sentences ($r = -.77$, $p < .001$). Children who spoke more slowly (i.e., had longer sentence durations) on the McGarr task produced poorer imitations of the nonwords.

To control for the known effects of several of the mediating demographic variables, we also ran an additional set of correlations that partialled out the children's age at onset of deafness and duration of deafness. The results of these partial correlations are also shown in Table 4 in the middle column. The similarity of the *r*-values for the bivariate correlations and the partial correlations indicates that these particular demographic variables had little, if any, effect on the values of the simple bivariate correlations.

Because we found a significant correlation between the children's communication mode scores and their mean perceptual ratings (shown in Table 3), we also ran another set of partial correlations in which the children's age at onset of deafness, duration of deafness, and communication mode scores were partialled out. These results are shown in the far right-hand column of Table 4. The correlation between the perceptual ratings and the word recognition measures, the phonetic feature discrimination measure, the forward digit span, and the speech production measures were all slightly lower than the other two sets of correlations shown in Table 4. This decrease in correlations indicates that the children's mean perceptual ratings were more closely related to their communication mode scores than to their other demographic characteristics. This is further support for the finding that children whose educational environments placed greater emphasis on oral communication received higher mean accuracy ratings for their nonword repetitions.

Although the simple bivariate correlation between the perceptual ratings and the WISC-III backward digit span scores was not significant, these two variables were moderately correlated after we controlled for age at onset of deafness and duration of deafness. This correlation suggests that while age at onset of deafness and duration of deafness are related to the development of phonological working memory, these two variables are not related to the abilities used to perform more complex executive functions indexed by the backward digit span task, such as planning and organizing a problem solving strategy.

Outcome and Process Measures of Performance	Correlation *r*-values Bivariate	 Partial 1	 Partial 2
Word Recognition			
Word identification, closed-set, pointing response			
Word Intelligibility by Picture Identification (WIPI)	+.74***	+.74***	+.68***
Word identification, open-set, spoken repetition			
Lexical Neighborhood Test, Easy Words (LNTe)	+.77***	+.78***	+.71***
Word identification, open-set, spoken repetition			
Lexical Neighborhood Test, Hard Words (LNTh)	+.73***	+.73***	+.64***
Word identification, open-set, spoken repetition			
Lexical Neighborhood Test, Multisyllabic Words (mLNT)	+.73***	+.72***	+.65***
Sentence identification, open-set repetition of target sentence			
Bamford-Kowal-Bench (BKB)	+.83***	+.84***	+.78***
Language Comprehension			
Closed set, receptive language comprehension of words and sentences			
Test of Auditory Comprehension of Language-Revised (TACL-R)	+.50***	+.51***	+.52***
Phonetic Feature Discrimination			
Perception of speech pattern contrasts			
Video Game for Assessing Speech Pattern Contrasts (VIDSPAC)	+.41***	+.42***	+.31**
Working Memory			
Forward Digit Span			
Wechsler Intelligence Scale for Children (WISC-III) Auditory Digit Span Subtest, Forward Recall of Digit-Name Lists	+.57***	+.53***	+.46***
Backward Digit Span			
Wechsler Intelligence Scale for Children (WISC-III) Auditory Digit Span Subtest, Backward Recall of Digit-Name Lists	+.19	+.24*	+.20
Speech Production			
Speech Intelligibility			
McGarr Sentence Intelligibility Test	+.73***	+.74***	+.66***
Speaking Rate			
McGarr Mean Duration of 3-Syllable Sentences (log, msec)	-.54***	-.53***	-.41***
McGarr Mean Duration of 5-Syllable Sentences (log, msec)	-.71***	-.72***	-.65***
McGarr Mean Duration of 7-Syllable Sentences (log, msec)	-.77***	-.77***	-.71***

Table 4. Correlations between nonword repetition perceptual ratings and speech-language measures. Simple bivariate correlations are shown in the left-hand column. Partial correlations controlling for age at onset and duration of deafness are shown in the middle column. Partial correlations controlling for age at onset, duration of deafness, and communication mode are shown in the right-hand column. $*p < .05$, $**p < .01$, $***p < .001$

Discussion

With regard to the first question that motivated this study, we found a great deal of variability among deaf children with cochlear implants on the nonword repetition task. This variability was revealed by the wide range of perceptual ratings provided by normal-hearing adult listeners. The range of accuracy ratings indicates that the nonword repetition task and perceptual ratings of children's responses were appropriate methods for studying this group of children.

Addressing our second question, we found that individual differences among children in each of the component subprocesses of speech perception, working memory, and speech production were strongly reflected in the nonword repetition scores obtained from the rating procedure. Strong and highly significant correlations were found between the perceptual ratings of the nonword responses and several other measures of word recognition and language comprehension (WIPI, LNTe, LNTh, mLNT, BKB, and TACL-R), working memory (WISC-III forward digit span subtest), speech intelligibility (McGarr Sentence Intelligibility), and speaking rate (McGarr sentence durations). The simple bivariate correlation between the perceptual ratings and the WISC-III backward digit span scores was non-significant, which supports previous findings in the literature suggesting that backward digit span measures different cognitive processes than forward digit span (Li & Lewandowsky, 1995; Lezak, 1983).

In regard to our third question, we found that age at implantation was not significantly correlated with the children's nonword repetition performance. However, two other demographic variables were significantly correlated with the perceptual ratings of the children's imitations, age at onset of deafness and duration of deafness prior to implantation. These two correlations suggest that early exposure to sound and experience hearing and using spoken language are crucial because these activities have subsequent effects on the development of phonological processing skills, language development, and speech production.

In addition to these demographic variables, we found that greater exposure to an exclusively oral educational environment had a significant and beneficial impact on the children's ability to imitate the novel phonological patterns used in the present study. We believe this is a clinically significant finding, because it suggests that oral communication methods may provide deaf children who use cochlear implants with a distinct cognitive processing advantage in learning new vocabulary and developing robust spoken language skills. Passive exposure to speech and spoken language, without explicit analysis and conscious manipulation of the internal structure of these sound patterns, may not be sufficient to develop robust phonological and lexical representations of spoken words and fluency of speech production, especially in children with hearing impairments who routinely receive degraded input signals from their parents and teachers in the language-learning environment.

Phonological Analysis Skills

Deaf children who use cochlear implants may need to be actively engaged in a wide range of activities that involve spoken language processing in order to develop automaticity and automatic attention strategies that can be carried out rapidly, without conscious effort or increased processing resources. This may be one important and direct benefit of oral-only education programs. The excellent spoken language skills acquired by children in oral-only programs may reflect development of explicit phonological analysis skills, permitting the child to engage in active perceptual processing strategies. These phonological analysis skills include processing activities such as "decomposition" of a speech pattern into a sequence of discrete phonological units and then "reassembly" of those individual units into sequences of highly coordinated gestures that serve as input to motor control processes used in speech production.

Explicit phonological coding skills of this kind may result in increases in the speed and efficiency of constructing phonological representations of spoken words in short-term memory. Recovering and maintaining the structural description of a novel phonological pattern in speech perception and then reconstructing the same phonological pattern again in speech production may be fundamental to establishing permanent links between speech perception and production. These complementary links may then lead to further development of highly automatized sensory-motor articulatory programs for covert verbal rehearsal and phonological coding in working memory. Thus, the superior phonological processing skills of oral deaf children using OC may simply be a natural byproduct of the extensive emphasis on speech and spoken language skills in oral-only educational environments. The phonological analysis skills gained from experience and activities in oral-only environments may account for why oral-only children consistently display better scores on a wide range of outcome measures of speech and language than children from TC environments.

The results of this study revealed relatively large and consistent effects of early experience on nonword repetition performance in deaf children who use CIs. But exactly how does the early sensory and linguistic experience in the language learning environment affect a deaf child's information processing skills after receiving a cochlear implant? This is a fundamental research question that clearly touches on much broader topics such as learning, memory, and cognition. Although it has been well documented over the years that a deaf child's communication mode plays an important role in the development of speech and oral language skills following implantation (Kirk, Pisoni, & Miyamoto, 2000; Osberger, Robbins, Todd, & Riley, 1994; Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000; Tait, Lutman, & Robinson, 2000), there has been little discussion of the underlying neural and cognitive mechanisms responsible for these differences in performance.

Oral vs. TC Environments

Numerous studies have reported that deaf children immersed in oral-only programs do much better on a range of oral language tasks than deaf children who are in TC programs (Kirk et al., 2000; Osberger et al., 1994; Svirsky et al., 2000). Such studies show that oral-only children perform better than TC children on tests assessing speech feature discrimination, comprehension, spoken word recognition, receptive and expressive language, and speech intelligibility. Why does this difference occur? What factors are responsible for the better performance of oral-only children? Can we provide a theoretically motivated explanation of these differences that is consistent with what we know about speech and language development?

As described earlier, among other findings, we found that the nonword repetition scores were strongly correlated with digit span scores. However, this result was highly selective in nature and was only observed for the forward digit span scores and not the backward scores. This pattern of results suggested that early oral experience in the language learning environment may influence phonological coding and rehearsal processes in short-term memory but may not affect controlled attention and executive functions that are used for active processing in working memory (Lezak, 1983; Li & Lewandowsky, 1995; Rosen & Engle, 1997).

We also found that the nonword repetition scores were negatively correlated with speaking rate, which can be taken as an index of the speed of covert verbal rehearsal that is used to maintain phonological representations in working memory. Children from oral-only environments not only received higher nonword repetition ratings in this study, but in previous studies, they also displayed longer forward digit spans, and faster speaking rates than the children from TC environments (Burkholder, this volume; Pisoni & Cleary, in press). These results suggest a common locus in the information processing system for the effects of early experience on speech and language development. This locus appears to be associated with the verbal rehearsal mechanism that is used to maintain phonological representations of sound patterns in short-term memory.

Why do children from TC environments consistently perform worse on a wide range of speech and language outcome measures than the children in Oral environments? Several reasons can be offered to explain the differences in performance between the two groups of children. These factors may provide some insights into how the nature of the child's early sensory experience and activities affects the speed and efficiency of the underlying processing mechanisms that are used in a range of behavioral tasks. First, children in TC environments routinely use simultaneous communication. For these children, speech is combined with some form of manual communication such as Signed Exact English (SEE). One consequence of using simultaneous communication is that the rate of articulation and verbal rehearsal and the transfer of linguistic information are much slower than using speech alone without any manual signs (Bellugi & Klima, 1997; Emmorey, 2002).

A second reason for the poorer performance of TC children may be due to competition between speech and manual communication for controlled attention and limited processing resources of short-term memory. Under simultaneous communication, speech and sign do not specify the same gestures and common underlying articulatory events. The information from the two input modalities is not congruent as it is when a listener sees the talker's lips and hears his speech under auditory-visual presentation conditions. Moreover, because the child is looking at the talker's hands, lip reading is not the primary means of providing complementary phonetic information about the speech signal. Thus, little, if any, additional facilitation is gained from the visual input; if anything there are strong reasons to support the argument that competition and inhibition result from the presentation of two divergent input signals (see Doherty-Sneddon, Bonner, & Bruce, 2001; Tyler, 1993).

These observations about multimodal speech perception are consistent with several recent findings showing interference and inhibition effects of manual communication skills in TC children who are learning oral language via their cochlear implant (Bergeson, Pisoni, & Davis, in progress). In TC children, knowledge and use of manual language competes with the dominant mode of processing speech, via the auditory sensory modality. Differences in input modality between sign language and speech make it difficult for TC children to integrate common gestural information across the two sensory modalities. This information "mismatch" increases the processing load on the working memory system that plays an important role in language comprehension and word recognition (Baddeley, Gathercole, & Papagno, 1998). Thus, it is not surprising that TC children generally show lower scores on a variety of speech and language assessments that measure auditory-only or auditory and visual language processing skills.

Third, it is possible that deaf children who receive cochlear implants have hearing parents who often do not have an expert knowledge of signs and manual communication. This is a reasonable assertion given that about 90 percent of deaf signers without cochlear implants are estimated to have had exposure to atypical signing (Woll et al., 2002). One consequence of atypical signing exposure is that the language model that deaf children in a TC environment experience is likely to be incomplete or impoverished (see Kluwin, 1981). This means that some TC children may not get exposed to robust experiences of manual sign and may have difficulties decoding the morphology and syntax of the language.

Finally, it is also possible that the differences in early speech and language experience after implantation between the TC and oral-only children may produce several different effects on the initial encoding of speech signals and subsequent rehearsal processes used to maintain phonological representations of spoken words in short-term memory. Because TC children have less exposure to speech and spoken language in their early environment after implantation, they may actually have two separate but closely related problems in processing and rehearsing auditory information in short-term memory. The first problem concerns initial encoding and recognition. The lack of exposure to speech may affect the development of automatic attention and the speed with which speech signals can be rapidly identified and recoded into phonological representations in short-term memory. As a consequence, TC children may also have difficulty in scanning and retrieving phonological representations of spoken words in short-term memory.

The second problem deals with the verbal rehearsal process that maintains phonological information in working memory. TC children may not only have slower scanning processes but they may also have slower and less efficient verbal rehearsal strategies once phonological information finally gets into short-term memory simply because they have had less experience in producing speech and spoken language. Encoding and retrieval processes that are very fast and highly automatized in normal-hearing children may be much slower and more effortful for deaf children with CIs, particularly those deaf children who use TC methods.

Scanning of Short-Term Memory

The proposal that deaf children with CIs, especially deaf children who use TC, have atypical abilities to verbally rehearse and scan phonological information in short-term memory was recently confirmed in our laboratory by Burkholder (this volume). In a study using McGarr sentence durations and speech timing measures made during WISC-III digit span recall, she found that children with cochlear implants had slower speaking rates and shorter digit spans than their NH peers. Within the group of children with cochlear implants, she found that TC children had much slower speaking rates than OC children but they also had shorter digit spans. Both findings support the hypothesis that the TC children have slower subvocal verbal rehearsal rates, which may contribute to their shorter digit spans and impact other speech and language processing tasks as well.

In addition, Burkholder (this volume) found that the CI children displayed longer interword pauses during digit span recall than NH children. Cowan (1992; 1999) has suggested that interword pause times during immediate recall can be used as a measure of scanning or retrieval speed. Therefore, longer interword pauses indicate a slower speed of scanning or retrieving information. Within the CI group, the TC users appear to be scanning items in short-term memory more slowly, because the interword pauses displayed in this group were longer than in the OC group. Thus, in addition to slower verbal rehearsal rates, slower scanning and retrieval speeds are also likely to be responsible for the shorter digit spans observed in the TC users and the poorer performance in a range of other speech and language tasks.

Future Directions

Future research should also consider more closely how verbal rehearsal and scanning of short-term memory operate in the CI population in a variety of other phonological working memory tasks. It would be useful to expand the current study to include speech-timing measures in the CI children's nonword repetitions. Examining speaking rate would aid in determining if the scanning processes involved in completing nonword repetition are also slower in TC children. Based on the present findings that TC children performed worse on nonword repetition than OC children, it is likely that TC children also have slower scanning and retrieval processes. These slower scanning speeds, along with slower subvocal rehearsal speeds, could be related to the TC children's lower nonword accuracy ratings, in addition to the demographic and speech perception variables that were found to be correlated to nonword repetition accuracy ratings in the current study.

Another area for future investigation is related to the finding that the children in this study imitated the shorter nonwords more accurately than the longer nonwords. In light of this finding and previous results showing that the phonological structure of the nonword pattern is related to the children's ability to accurately imitate it (Cleary et al., 2002; Carter et al., in press), future studies of repetition performance involving nonword patterns balanced in terms of stress patterns and phonemic content could provide further insights into the nature of the underlying phonological systems of deaf children after cochlear implantation and how these systems may be different from those of normal-hearing children.

All of these questions would be interesting to study in normal-hearing children as well, using a variety of new experimental techniques. In future work, we are planning to study normal-hearing children in quiet conditions and under conditions using processing strategies designed to simulate the degraded speech signals provided to deaf children by their cochlear implants (Dorman, Loizou, Kemp, & Kirk, 2000; Kaiser & Svirsky, 2002). Simulation studies like these using normal-hearing typically developing children should provide new insights into how the nonword repetition task is carried out. In addition, comparison of the normal-hearing children's performance in simulation studies to the performance of deaf children who use CIs should provide valuable new knowledge about how the absence of sound during early stages of speech and language development affects the speed and efficiency of the phonological processing skills used to rapidly encode, maintain and reproduce novel phonological patterns from working memory.

Conclusions

The results of the present study indicate that deaf children who use cochlear implants demonstrate wide variability in spoken language skills used to imitate novel nonword patterns. The observed differences in performance can be accounted for, in part, by variation in the separate underlying cognitive processes involved in spoken word recognition, comprehension, working memory, and verbal rehearsal speed as indexed by speaking rate. In addition, the efficiency and speed of these cognitive processes seems to be related to the nature of the early auditory and linguistic experiences and activities that the CI users are engaged in after receiving their CIs. This study revealed that deaf children who use oral communication (OC) methods received higher nonword accuracy ratings than deaf children who use simultaneous speech and signing methods (TC). We suggest that the increased amounts of early linguistic experience and processing activities provided to OC users is responsible for their ability to rapidly encode, represent, subvocally rehearse, retrieve, and produce the novel phonological patterns presented to them in a nonword repetition task.

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