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Nonword Repetition by Children With Cochlear Implants: Accuracy Ratings From Normal-Hearing Listeners

Caitlin M. Dillon, Rose A. Burkholder, Miranda Cleary, and David B. Pisoni
Indiana University, Bloomington

Abstract

Seventy-six 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. The children's responses were recorded on digital audiotape and then played back to normal-hearing adult listeners to obtain accuracy ratings on a 7-point scale. The children's nonword repetition performance, as measured by these perceptual accuracy ratings, could be predicted in large part by their performance on independently collected measures of speech perception, verbal rehearsal speed, and speech production. The strongest contributing variable was speaking rate, which is widely argued to reflect verbal rehearsal speed in phonological working memory. Children who had become deaf at older ages received higher perceptual ratings. Children whose early linguistic experience and educational environments emphasized oral communication methods received higher perceptual ratings than children enrolled in total communication programs. The present findings suggest that individual differences in performance on nonword repetition are strongly related to variability observed in the component processes involved in language imitation tasks, including measures of speech perception, speech production, and especially verbal rehearsal speed in phonological working memory. In addition, onset of deafness at a later age and an educational environment emphasizing oral communication may be beneficial to the children's ability to develop the robust phonological processing skills necessary to accurately repeat novel, nonword sound patterns.

Keywords

cochlear implants; children; nonword repetition; working memory; communication mode

Numerous studies of the speech and language skills of hearing-impaired children who use cochlear implants (CIs) have been completed in recent years. Researchers have found that many pediatric CI users show improvement on a variety of speech and language skills after implantation, as indexed by measures of word and sentence recognition and speech perception (e.g., Blamey, Sarant, et al., 2001; Geers, Brenner, & Davidson, 2003); speech feature production and speech intelligibility (e.g., Blamey, Barry, et al., 2001; Brown & McDowell, 1999; Chin & Kaiser, 2002; Langereis, Bosman, van Olphen, & Smoorenburg, 1999; O'Donoghue, Nikolopoulos, Archbold, & Tait, 1999; Tobey, Geers, & Brenner, 1994); language (e.g., Brinton, 2001; Geers, Spehar, & Sedey, 2002; Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000); and literacy (Watson, 2002). Several factors have been shown to play a contributing role in the degree to which implantation benefits a child's speech and language performance, such as the child's age at implantation (Kileny, Zwolan, &

Ashbaugh, 2001; Kirk, Miyamoto, Ying, Perdew, & Zuganelis, 2002; Richter, Eißele, Laszig, & Löhle, 2002) and the extent to which oral communication is emphasized in the child's educational environment (Geers et al., 2002; Waltzman, Roland, & Cohen, 2002), among others (see Geers & Brenner, 2003). In general, children who become deaf at a later age, receive an implant before the age of 4 or 5 years, and use oral communication methods tend to demonstrate greater postimplantation benefit in terms of speech and language-processing skills. However, children with CIs display an extraordinary amount of individual variability, which has yet to be fully explained (Pisoni & Cleary, 2003).

The investigation of individual differences in the speech and language skills of children with CIs has been a major focus of our research program for several years (see Pisoni, 2000; Pisoni & Cleary, 2003; Pisoni, Cleary, Geers, & Tobey, 2000). We are interested in how the variability in a wide range of speech and language outcome measures can be accounted for by differences in basic underlying information-processing skills such as phonological encoding, the short-term storage capacity of phonological working memory, and the verbal rehearsal processes used to circumvent capacity limitations in phonological working memory. These processes are assumed to be basic components that are 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 immediately repeats back a novel stimulus pattern has been used widely in recent years to study the expressive language skills of children with language impairment (e.g., Sahlén, Reuterskiöld-Wagner, Nettelbladt, & Radeborg, 1999); the development of phonological awareness and working memory in normal-hearing children (e.g., Gathercole, 1995; Gathercole, Willis, Baddeley, & Emslie, 1994; Metsala, 1999); children with Down syndrome (Laws, 1998); and children with mild-to-moderate sensorineural hearing loss (SNHL; Briscoe, Bishop, & Norbury, 2001). In addition, nonword repetition has been used as a process-dependent (as opposed to knowledge-dependent) task in a study of task effects on language performance by children from ethnic majority versus minority groups (Campbell, Dollaghan, Needleman, & Janosky, 1997). The effect of variations in nonword stimulus presentation, such as the presence of gestural visual cues, also has been studied in both normally developing children and children with specific language impairment (Ellis Weismer & Hesketh, 1993). Research also has demonstrated that nonword repetition is related to word learning and working memory skills in children with brain lesions (Gupta, 2003) and neurologically intact adults (Gupta, MacWhinney, Feldman, & Sacco, 2003).

In studies of normal-hearing children, researchers have found that nonword repetition performance is related to vocabulary development (Gathercole, Willis, Emslie, & Baddeley, 1992; Metsala, 1999); sentence comprehension (Montgomery, 1995); and reading ability (Roodenrys & Stokes, 2001). Briscoe et al. (2001) found that a group of nineteen 5- to 10-year-old children with mild-to-moderate SNHL performed more poorly on a nonword repetition task than a normal-hearing control group. Within the SNHL group, a subgroup of children with phonological impairments were compared with a subgroup of children who did not have phonological impairments. The children with phonological impairments tended to have significantly lower scores on measures of vocabulary but not on measures of language or literacy. This finding demonstrates a link between nonword repetition and vocabulary acquisition in mild-to-moderately hearing-impaired children. Thus, profoundly hearing-impaired pediatric CI users' performance on a nonword repetition task may also be related to their speech perception, word recognition, vocabulary-learning, and, even more generally, language-learning abilities.

While nonword repetition is inherently a speech production task, it is crucially different from other speech production tasks that involve the use of real words. Speech production tasks that require the production of words that are in the child's vocabulary or *mental lexicon* make use of items for which the child has already formed a phonological representation (see Goldinger, Pisoni, & Luce, 1996). Hence, such tasks measure the child's ability to reproduce a word with the advantage of accessing that word and its preexisting phonological representation in his or her mental lexicon. The nonword repetition task, on the other hand, involves the production of novel phonological patterns that the child has never heard.

Thus, in a nonword repetition task, the child cannot rely on a preexisting phonological representation to repeat the nonword; instead, she or he must immediately construct a new phonological representation, based on a single exposure to the novel auditory stimulus that she or he perceived, and then translate or reassemble that newly formed representation into an articulatory output in speech production. For a child whose means of auditory perception is a CI, it is conceivable that the nonword repetition task would be too difficult with only a single exposure to the nonword. The investigation of a child's ability to accurately complete a nonword repetition task is of special interest, however, because it may provide some new insights into the underlying linguistic processes used by the child when learning to say new words.

In the present study, we do not directly address whether nonword repetition performance correlates with vocabulary learning or, longitudinally, with the development of speech and language outcomes. Instead, we focus on the relationship between nonword repetition performance and scores on other speech and language measures, seeking insight into the possibility that nonword repetition performance may be a good index of pediatric CI users' long-term vocabulary, speech, and language acquisition. Preliminary findings obtained from a small group of children with CIs were reported recently by Cleary, Dillon, and Pisoni (2002). In that study, 14 children who had used CIs (Nucleus-22; spectral peak [SPEAK] coding strategy) for at least 3.5 years ($M = 5.5$ years) completed a nonword repetition task. Their responses were recorded and played back to listeners. Each of their responses was then rated for accuracy on a scale from 1 to 7 by 10 normal-hearing adults. We found that the mean ratings received by each child were strongly correlated with other independent measures of spoken word recognition, language comprehension, working memory, speech intelligibility, and speaking rate. These preliminary results demonstrated that children who have sufficient experience with CIs are able to accurately complete a complex task such as nonword repetition. However, the small group of CI users analyzed in the study by Cleary et al. (2002) was an above-average group because they 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 had more variable nonword repetition responses. The children in the present study produced responses for 75% to 100% of the nonword stimuli. Other than these differences, the procedures were the same.

Nonword repetition may appear to be simple at first glance, but it is in fact a complex information-processing task that involves the rapid execution and coordination of several underlying linguistic processing skills. For children with CIs, we expected this task to be particularly difficult. To accurately repeat a nonword stimulus in our study, it is necessary for the child to accurately complete the following subprocesses: (a) perceive a completely novel sound pattern in auditory-only mode without the aid of speech reading, pragmatic context, or semantic content; (b) hold and verbally rehearse the novel sound pattern in immediate phonological memory; and (c) reassemble and translate the perceived novel sound pattern into an articulatory program to produce speech.

For a child to produce a response to a nonword stimulus, all three of these steps (which in themselves involve subcomponents that are outside the scope of this article) must be completed rapidly with some minimum level of accuracy. In the present study, we were interested in examining pediatric CI users' nonword repetition performance in terms of their ability to perform each of these subcomponents. We therefore examined the relative contribution of independently collected measures of each of the subcomponent skills in determining the children's nonword repetition performance (as measured by listeners' perceptual ratings).

Clearly, a participant will not be able to complete a nonword repetition task if he or she is unable to perceive and encode the stimulus, both as an acoustic signal and an abstract phonological pattern. This subcomponent of nonword repetition depends on the participants' *speech perception* skills. In the present study, an independent measure of speech perception and phonological encoding skill was available in the form of scores on the Word Intelligibility by Picture Identification Test (WIPI; Ross & Lerman, 1979), which requires the child to select a picture that matches an auditory target word. In this test, the target words are familiar, and only a pointing response is required, thereby placing few to no demands on phonological working memory or speech production.

Just as crucially, nonword repetition is predicated on the participant's ability to subvocally rehearse and maintain the perceived stimulus pattern in immediate memory as it is translated into an articulatory pattern and produced as speech. The participant's ability to hold and subvocally rehearse a nonword stimulus depends on two subcomponents of the phonological working memory, as discussed extensively by Baddeley (2001, 2003). One subcomponent is the "temporary storage system [that holds] memory traces over a matter of seconds" (Baddeley, 2003, p. 191). One of the most widely used measures of this memory system's storage capacity is forward digit span. Forward digit span is a measure of how accurately a listener is able to immediately recall a list of digits in the correct order as list length is increased over a number of trials (Baddeley, Thompson, & Buchanan, 1975; Schofield & Ashman, 1986; Wechsler, 1991). In the present study, we used forward digit spans (Wechsler Intelligence Scale for Children–III [WISC–III]; Wechsler, 1991; described below) as a measure to assess the "temporary storage system" subcomponent of phonological working memory.

The initial memory traces in this temporary storage system are thought to decay rapidly unless maintained by the second subcomponent of phonological working memory, the "subvocal rehearsal system" (Baddeley, 2003, p. 191). The rate at which items are subvocally (or verbally) rehearsed in phonological working memory is widely accepted to be reflected in the speaking rates of both children and adults. In numerous studies, it has been found that faster speaking rates are strongly correlated with longer memory spans (Baddeley et al., 1975; Cowan et al., 1998; Hulme & Tordoff, 1989; Kail & Park, 1994; Schweikert, Guentert, & Hersberger, 1990). According to Baddeley et al. (1975), this relationship exists because as the rate of overt speech and subvocal verbal rehearsal speed increases, the number of times lists of verbal information can be refreshed in the short-term memory store also increases, thereby facilitating recall of items in immediate memory.

Pediatric CI users have also been found to exhibit a robust relationship between speaking rate and memory span, suggesting that speaking rate is an accurate reflection of their subvocal verbal rehearsal rates as well (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2003). In the present study, durations of seven-syllable McGarr sentences (McGarr, 1981; Tobey, Geers, Brenner, Altuna, & Gabbert, 2003) were used as a measure of speaking rate (longer durations indicate slower speaking rates), argued to be an index of subvocal or verbal rehearsal, the second component of phonological working memory.

Finally, if a participant is unable to produce the component sounds and phonotactic patterns of English, she or he will not be able to complete the nonword repetition task. Because children with CIs demonstrate a wide range of individual variability in speech production skills in a variety of tasks (e.g., Tobey et al., 2003), we could not assume that the children's speech production abilities were independent of their ability to complete the nonword repetition task. Thus, in the present study, we used the children's speech intelligibility scores as an independent measure of their speech production skills (McGarr, 1981, as described below; Tobey et al., 2003).

In this study, we were interested in whether experienced pediatric CI users would be able to use their speech perception, immediate phonological memory, and speech production skills online to accurately reproduce novel auditory-only nonword patterns, after hearing the stimulus only once. If a child demonstrated that she or he possessed at least the minimal information-processing skills necessary to complete most of the test trials in this task, we were then interested in the relative roles of the component processes (speech perception, the two memory subcomponents, and speech production) in the completion of the nonword repetition task. Our study was designed to answer the following question: What can we observe about the relative importance of CI users' speech perception, phonological memory, and speech production systems from nonword repetition performance? Our answers to this broad question may serve to inform further research regarding the relationship between nonword repetition performance and vocabulary, speech, and language acquisition in children who use CIs. In the present study, we specifically addressed the following questions.

1. Could children who are deaf and use CIs complete the nonword repetition task? In other words, could they provide responses to the nonword stimuli, or was this task much too difficult for them to carry out?
2. If the children provided responses, were their responses produced with some measurable variation in levels of accuracy, or were most of the responses "at floor" in terms of accuracy?
3. Was our measure of accuracy based on perceptual ratings an internally reliable measure? That is, were the within-listener ratings consistent, and were the between-listener ratings consistent?
4. If the children's nonword responses were produced with a measurable range of accuracy, was their nonword repetition performance correlated with the traditional demographic variables of age at onset of deafness, duration of deafness, age at implantation, duration of CI use, chronological age at time of testing, communication mode, number of active electrodes, and/or gender?
5. Similarly, if the children's nonword responses were produced with a measurable range of accuracy, did the children's speech perception skills, working memory capacity and verbal rehearsal speed, and speech production skills contribute equally to the individual variability in nonword repetition performance, or did some component skills contribute more than others?

Method

Participants

Eighty-eight children with CIs participated in a nonword repetition task. Twelve of these children were excluded from the present analyses because they produced a response to less than 75% of the nonword stimuli or because a technician error resulted in less than 75% audiotaped responses. Thus, 76 children who use CIs were studied. Thirty-six of the children

were female; 40 were male. All of the children were tested at Central Institute for the Deaf (CID) in St. Louis, MO, 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 (Geers & Brenner, 2003). Thirty-eight of the children were participants in 1999, and 38 were participants in 2000.

The mean age at onset of deafness for the 76 children in the present study was just over 2 months ($M = 2.3$, $SD = 6.4$). Most children (64) had a profound congenital 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 children's 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 CIs for 3.8 to 7.5 years ($M = 5.6$, $SD = 0.8$), before testing. At the time of testing, the children's ages ranged from 7.9 to 9.9 years ($M = 8.9$, $SD = 0.6$). Seventy-four children were using a Nucleus-22 device with the SPEAK coding strategy at the time of testing. One child used a Nucleus-24, and 1 child used a Clarion CI. The number of active electrodes, which is dependent on the child's implant map and the particular device, ranged from 8 to 22 ($M = 18.4$, $SD = 2.3$).

The children were classified into two different groups based on whether they used primarily oral communication (OC) or total communication (TC) strategies (Geers & Brenner, 2003). TC methods emphasize the use of English-based sign systems (usually not American Sign Language) and lipreading strategies, in addition to speech. The classification was based on parental report scores, which evaluated the nature of the children's early experience and communication training programs for five different points in time: (a) preimplantation, (b) 1-year postimplantation, (c) 2 years postimplantation, (d) 3 years postimplantation, and (e) time of testing (i.e., the time of their participation in the CID summer program). Scores for each evaluation ranged from 1 (signifying a program stressing the use of sign, usually in the form of SEE, 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. Twenty-nine of the 76 children were classified as TC users, 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 & Baddeley, 1996; Gathercole et al., 1994). The CNRep was originally designed to evaluate the phonological working memory skills of normal-hearing, 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 1, along with their phonetic transcriptions. The final set of 20 nonwords included 5 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 (see Carlson et al., 1998).

Procedure

Before any of the nonwords were presented, the children were told they would hear “funny, made-up sounding” words. They were also told they would have to repeat each stimulus clearly out loud after hearing it. The nonwords were presented in a different random order to each child, one at a time. Root-mean-squared amplitudes of the stimuli were equated before presentation. The stimuli were presented through a computer at a calibrated level of 70 dB SPL to a loudspeaker (Cyber Acoustics MMS-1) approximately 1.5 ft from the child. At the specific request of a few children, the sound level was increased slightly to a more comfortable level.

All of the children included in this study produced a verbal response to at least 15 of the 20 nonword stimuli. Of the 76 children, 24 produced a response to all 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.

The children’s nonword repetition responses were recorded onto digital audiotape (DAT; Sony Walkman TCD-D8) via a unidirectional headset cardioid condenser microphone (Audio-Technica ATM75). The audiotapes were segmented and down-sampled at a rate of 22 kHz with 16-bit quantization and appropriate anti-aliasing filtering using the CoolEdit (1996) digital waveform editing program. Each utterance was then stored as an individual sound file for later playback.

The children’s utterances were compiled into sets, which were played back to groups of normal-hearing adults who were asked to judge the accuracy of the nonword repetition responses produced by the children. The listeners were normal-hearing adults obtained from the Indiana University Psychology 101 participant pool. 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 listeners reported having no prior experience listening to the speech of the deaf or hearing impaired. After completing the perceptual rating task, the listeners received credit in the undergraduate psychology course in which they were currently enrolled.

On each test trial, the listener first heard the target model stimulus pattern that had been presented to the CI users for repetition. After hearing the model, the listeners then heard the imitation of that nonword stimulus produced by 1 of the children. The model stimulus and the child’s response were separated by a 1-s interval of silence. The listeners could not alter the volume of the stimuli, nor were they able to repeat the playback of any stimulus.

The listeners were asked to provide accuracy ratings for the CI children’s imitations of the nonwords. Perceptual accuracy ratings were given according to a 7-point Likert scale ranging from 1 (*totally fails to resemble the target utterance*) to 7 (*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 all the stimuli to the listeners over high-quality headphones (Beyer Dynamic, DT100) at 70 dB SPL and recorded their responses. No feedback was provided at any time during the experiment.

Each listener heard all of the utterances produced by 6 different children. A pilot study indicated that children who produced fewer responses (e.g., 15 rather than 20) tended to receive lower ratings overall. Therefore, it was necessary to balance the set of children that each listener heard according to the number of responses provided by the children. Thus, each listener heard all utterances produced by 6 children who had each produced a different total number of responses (15, 16, 17, 18, 19, and 20). In this way, each listener heard 105

different utterances. In addition, each utterance was rated twice within the experiment by the same listener. That is, each listener completed two test blocks using the same set of 105 stimuli in each block. The order of presentation of the utterances was randomized within each block.

Each child was rated by at least 10 listeners. To have 10 different listeners rate each of the 24 children who had produced 20 responses, we had 24 groups of listeners with 10 listeners in each group. Thus, the number of listeners was 240. Each of the 10 listeners in a given group provided ratings of the same 105 utterances produced by the same 6 children.

In addition to producing nonword repetition responses for this study, the children completed a range of other tests designed to assess their speech and language skills as part of the larger study at CID. We used these tests to examine the relative contribution of the component processes (discussed above) to nonword repetition performance.

We measured the children's speech perception skills with the WIPI (Ross & Lerman, 1979). The WIPI is a closed set task in which the participating child is asked to listen to a word spoken live by the task administrator. A six-alternative set of pictures is presented to the child on each trial, and the child is asked to point to the picture of the spoken word. Because the child is asked to provide a pointing response, scores on the WIPI depend on speech perception as opposed to speech production skills.

Forward digit spans, obtained by means of the WISC-III (Wechsler, 1991), provided a measure of the capacity subcomponent of the children's phonological working memory (Pisoni & Cleary, 2003; Pisoni & Geers, 2000). For the forward digit span task, the participating child was asked to listen to and repeat lists of digits out loud. The lists were spoken live-voice by an administrator at a rate of approximately one digit per second. The first list was two digits in length. If the child correctly repeated either one of two lists presented at a given length, then the list length was increased by one. The child received 1 point for each list he or she repeated correctly. No partial credit was assigned.

Duration measurements of the children's productions of McGarr sentences (McGarr, 1981) were used to provide estimates of speaking rate (see Pisoni & Cleary, 2003; Pisoni et al., 2000), which is understood to be an index of subvocal or verbal rehearsal, the second component of phonological working memory (Baddeley et al., 1975; Cowan et al., 1998; Hulme & Tordoff, 1989; Kail & Park, 1994; Schweikert et al., 1990). Each McGarr sentence was presented to each child in written form as well as spoken and/or signed form (depending on the child's preferred communication mode; Tobey et al., 2003). The children were asked to say each sentence out loud as clearly as possible. Their responses were recorded, digitized, and stored in individual wave files. The McGarr sentences include 12 three-syllable sentences, 12 five-syllable sentences, and 12 seven-syllable sentences. Duration measurements of the 12 seven-syllable sentences were used to obtain a measure of speaking rate in the present study.

Finally, speech intelligibility scores served as a measure of the children's speech production skills. The intelligibility scores were based on the children's productions of the 36 McGarr sentences (described above). As described by Tobey et al. (2003), the sound files containing the children's sentence productions were played back to judges who were naive to the speech of people who are deaf. Each judge was permitted to listen to each audio file only once. Judges were asked to orthographically transcribe the sentences that they heard. Each child's intelligibility score was based on the percentage of key words in the 36 sentences that were correctly transcribed by the judges. Each judge heard only one sentence produced by any given child. Each of the 36 sentences produced by a given child was played back to three different judges. Thus, each child's overall intelligibility was based on 108 judgments

(36 sentences $\times$ 3 judges each), each provided by a different judge. A speech production measure such as a phonological inventory was not available for this group of children.

Results

Reliability of the Perceptual Ratings

We examined the reliability of the ratings both within listener and between listeners. As mentioned earlier, all of the listeners rated each stimulus item twice during the experiment, once during the first block and a second time during another block. A comparison of the accuracy ratings obtained in each block allowed assessment of the reliability of the perceptual ratings within a listener. To compare 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 ($M = 2.96$, $SD = 0.48$) were strongly correlated ($r = .87$, $p < .001$) with the mean ratings in the second block ($M = 2.98$, $SD = 0.55$). The difference in mean ratings between blocks was not significant. In addition, for each of the 240 listeners, we calculated a pairwise correlation between the rating provided in response to each stimulus in the first block ($n = 105$) and the rating provided in response to the same stimulus in the second block. In other words, we calculated intralister, interblock reliability for the ratings provided in response to individual stimulus items. Because this analysis included a large number of correlations (240), we corrected for Type I error using the Bonferroni method of dividing the desired α ($p < .01$) by the number of correlations (240) to determine the required α for statistical significance. The corrected α was $p < (.01/240)$, which is $p < .00004$. Of these correlations, 239 were statistically significant ($p < .00004$ for 239 correlations; $p = .00305$ for 1 correlation). Of the correlations, 95% (228 out of 240) were .60 or greater, and 65% (157 out of 240) were .80 or greater.

As stated earlier, there were 24 groups of 10 listeners, and each listener within a group heard the same set of utterances. To determine whether the mean ratings provided by each of the 10 listeners within a group were significantly different from the mean ratings provided by all other listeners within their group, we calculated Cronbach's alpha. This statistic is used to measure internal consistency, by finding the reliability coefficient for the correlations between each logically possible pair of listeners within a group. Cronbach's alpha for each group (all α s $\geq .94$) indicated that the listeners provided mean ratings that were similar to the other listeners within their group. That is, the listeners within a group seemed to have based their ratings on similar characteristics of the nonword repetitions. This result indicates that the ratings provided by our listeners in this task would be replicable if other groups of listeners participated in this same task. In summary, we found that the results of the nonword rating task were highly reliable both within listener and between listeners.

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, indicating that children who received low ratings in the first block also received low ratings in the second block (and vice versa).

The following results are based only on the accuracy ratings provided by the listeners during the first block of trials, because the perceptual ratings in this block were not different from the ratings in Block 2 when averaged across either listener or child.

Variability

As in our earlier preliminary report of nonword repetition in children who use CIs (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. Figure 1 contains the distribution of the mean ratings assigned to the 76 children. No children received ratings at the ceiling level, and only 6 children received a mean rating below 1.5, which could be considered floor level, on this task.

Correlations With Demographic Characteristics

To investigate the extent to which the children's nonword repetition responses were related to their demographic characteristics, we carried out a set of correlational analyses. Because several correlations were included in our analysis, we again corrected for Type I error using the Bonferroni method of dividing the desired α ($p < .05$) by the number of correlations (7) to determine the required α for statistical significance. The corrected α was $< (.05/7)$, or $< .007$.

A summary of the correlations with traditional demographic measures is shown in Table 2. The children's duration of deafness, age at implantation, duration of CI use, and age at the time of testing were not significantly correlated with the nonword perceptual ratings. We also found that the number of active electrodes in a child's CI was not significantly correlated with the perceptual ratings. A t test revealed no significant difference between the mean perceptual rating for the boys ($M = 1.91$, $SD = 1.04$) and that for the girls ($M = 2.21$, $SD = 1.18$).

Despite being a fairly homogeneous group, the children's age at onset of deafness was positively correlated with the nonword repetition ratings ($r = .32$, $p < .007$). Children who lost their hearing at older ages produced nonwords that received higher nonword ratings than children who lost their hearing at younger ages. In addition, we found that the amount of exposure to oral-only communication methods (as measured by the children's communication mode scores) was correlated with the nonword perceptual ratings ($r = .51$, $p < .007$). Children whose communication mode scores were higher tended to receive higher nonword repetition ratings.

Degree of Exposure to Oral Communication

After finding that degree of exposure to oral communication was significantly correlated with nonword repetition performance, we decided to look more closely at this demographic variable. Figure 2 summarizes 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 divided into two groups according to communication mode, as described above, and analyzed separately, a t test revealed that the nonword responses from the OC children ($M = 3.46$, $SD = 0.96$) were rated significantly higher, $t(74) = 4.49$, $p < .001$, than were the nonword responses from the TC children ($M = 2.40$, $SD = 1.05$).

Relative Contribution of Subprocesses

Although the nonword repetition task appears on the surface to be relatively simple, performance on this phonologically based imitation task actually reflects the contribution of a number of different component subprocesses including initial sensory coding and perception, maintenance in working memory, and verbal rehearsal in working memory, as well as speech articulation and motor control processes used in speech production. To examine the relative contribution of these subprocesses to nonword repetition performance, we carried out a multiple stepwise regression analysis (Cohen & Cohen, 1983). The children's nonword repetition ratings were used as the dependent variable. The children's

scores on four measures—the WIPI (speech perception), forward digit span (working memory capacity), durations of McGarr seven-syllable sentences (the inverse of speaking rate, an index of verbal rehearsal rate), and McGarr intelligibility (speech production)—were included among the set of predictor variables.

We excluded from the regression analysis 7 children who were outliers either because their performance on most of the speech and language measures was below chance (1 child) or because they differed markedly from the majority of the other children in terms of age at onset of deafness. Specifically, the 6 children who became deaf after the age of 1 year were excluded from the regression analysis. The remaining 69 children were included in the regression analysis. Table 3 shows the correlations between these 69 children's nonword repetition ratings and the demographic variables. The non-significant correlation between age at onset of deafness and the nonword repetition ratings indicated that the removal of the 7 children effectively controlled for the effect of age at onset of deafness.

We also found that degree of exposure to oral communication was significantly correlated with nonword repetition ratings, but the large numbers of children in each communication mode group made it unreasonable to control for this variable by removing children from the regression analysis. Therefore, we included the children's communication mode scores as a fifth independent variable in the regression analysis. The group of 69 children included 42 OC users and 27 TC users.

The 69 children's raw scores on the WIPI ranged from 12 to 88 ($M = 55.68$, $SD = 19.29$). Their forward digit span scores ranged from 2 to 9 ($M = 5.07$, $SD = 1.39$). The children's mean McGarr seven-syllable sentence durations ranged from 1,791 to 8,232 ms ($M = 3,341$ ms, $SD = 1,290$ ms), and their McGarr intelligibility scores ranged from 4 to 98 ($M = 70.48$, $SD = 25.03$).

Following established statistical procedures for the fitting of a regression model, we transformed all raw scores for each variable (WIPI scores, forward digit spans, McGarr sentence durations, McGarr intelligibility scores, and communication mode scores) into standardized scores (z scores). Thus, the results of the regression model provided the standardized coefficients (β coefficients), which represent the linear relation between the dependent variable (ratings) and the independent variables, regardless of units of measurement. Standardized beta coefficients allow comparison across the independent variables in terms of the extent to which they each contribute to the variance in the dependent variable. In a regression model, a 1 SD change in an independent variable will result in a change in the dependent variable (ratings) that is equal to ($\beta \times SD_{\text{ratings}}$), which is the independent variable's standardized coefficient (β) multiplied by the standard deviation of the dependent variable (see Cohen & Cohen, 1983).

We found that forward digit span was not a significant contributor to the variation in nonword repetition ratings, $t(68) = 0.76$, $p = .45$. As shown in Table 4, however, the results of the regression model indicated that the four remaining independent variables each contributed significantly to variation in nonword repetition ratings. Degree of exposure to oral communication contributed to the variance to a lesser degree than did the other contributing variables ($\beta = .155$, $p < .05$). Two of the other independent variables, speech perception skills (as measured by the WIPI scores; $\beta = .291$, $p = .001$) and speech production skills (as measured by the McGarr intelligibility scores; $\beta = .284$, $p < .01$), accounted for about equal amounts of the variance in non word repetition ratings. The strongest contributing variable in the analysis was speaking rate, a measure reflecting verbal rehearsal speed (as measured by the McGarr seven-syllable sentence durations; $\beta = -.339$, p

< .001). Overall, these variables accounted for 77% of the variance ($R^2 = .770$) in the children's nonword repetition scores.

Discussion

The present article reports data obtained from a nonword repetition task completed by 76 children who use CIs. As expected, we found significant variability among the children. The variability in performance was evident from the wide range of perceptual ratings obtained from normal-hearing adult listeners. The range and reliability of the accuracy ratings indicated that the nonword repetition task and perceptual ratings of the nonword responses were appropriate methods for studying this group of children. In addition, the range of variability in ratings, with few children at floor level and no children at ceiling level, indicated that this perceptual rating task provided a sensitive measure of nonword repetition performance for this particular group of children.

The reliability of the accuracy ratings among listeners within each group indicated that listeners attended to similar characteristics of the children's nonword responses. The listeners may have based their ratings, at least in part, on their perception of the suprasegmental characteristics and consonant segment characteristics of the children's nonword repetition responses. For example, in a study of 24 of these same children, Carter, Dillon, and Pisoni (2002) found that they tended to produce the correct number of syllables and primary stress placement in response to shorter target nonwords than to longer target nonwords. In terms of consonant accuracy, the children tended to produce target coronal consonants correctly more often than target consonants with other places of articulation (Cleary et al., 2002; Dillon, Cleary, Pisoni, & Carter, 2004; Dillon, Pisoni, Cleary, & Carter, 2003). Listeners may have attended to such characteristics as syllable number and consonant feature accuracy when providing their perceptual accuracy ratings of the children's nonword repetition responses.

Our finding that nonword repetition performance was correlated with age at onset of deafness suggests that the more exposure a child has to auditory input, before the onset of deafness, the better her or his performance will be on tasks involving phonological processing skills such as nonword repetition. We also found that nonword repetition performance was strongly correlated with communication mode and that the mean accuracy ratings of the OC group were significantly higher than those of the TC group. These findings indicate that oral-aural experiences and activities, which promote and emphasize the production and perception of spoken language, contribute to the underlying linguistic skills used in phonologically based processing tasks such as nonword repetition. The children's ability to reproduce a novel nonword stimulus pattern was better when, over time, the use of oral language had been encouraged and emphasized compared with the use of manual sign and speech in their educational environment. This finding may have clinical significance because it suggests that oral communication methods may provide children who use CIs with a significant linguistic processing advantage. Passive exposure to speech and spoken language, without explicit analysis and conscious manipulation of the internal phonological structure of sound patterns of language, may not be sufficient to develop robust phonological and lexical representations of spoken words and promote close coupling between speech perception and speech production.

However, the present findings regarding the effects of communication mode must be interpreted cautiously, because a pediatric CI user's placement in OC or TC environments is not randomly determined. Children whose auditory and articulation abilities do not allow effective oral communication are often more likely to be placed in TC programs to learn manual methods of communication. Thus, the children who use TC in our study may have

had significantly poorer speech and language abilities even before implantation (see also Bergeson, Pisoni, & Davis, 2003; Svirsky, Chin, Miyamoto, Sloan, & Caldwell, 2002). Recent findings have indicated that while children in OC programs tend to demonstrate better performance on a wide range of speech and some language measures, some early-implanted children in TC programs may have better receptive and expressive spoken vocabulary scores (Connor, Hieber, Arts, & Zwolan, 2000), and both groups of children tend to improve at similar rates on speech, vocabulary, and language measures. As the TC children in our study gain additional experience with their CIs over time, it is possible that they may reach the same average levels of performance as the OC children.

A substantial amount of the variance observed in nonword repetition performance could be accounted for by the children's degree of exposure to oral communication and their performance on separate tasks measuring the underlying component processes involved in nonword repetition: the WIPI (a speech perception measure), durations of seven-syllable McGarr sentences (an index of speaking rate), and McGarr sentence intelligibility (a speech production measure). The strongest contributing factor predicting the variation in nonword repetition performance was the children's mean durations for their productions of the McGarr seven-syllable sentences. These durations are an inverse index of the children's speaking rates, which are understood to reflect verbal rehearsal speed in phonological working memory. Thus, we found that the children's mean McGarr sentence durations, which are thought to reflect one component of phonological working memory (verbal rehearsal rate), were the strongest contributor to the variation in nonword repetition performance. On the other hand, the children's digit spans, which are thought to reflect another subcomponent of phonological working memory (capacity), did not significantly contribute to the variance in nonword repetition performance when other measures (i.e., speech perception, speech production, and verbal rehearsal rate) were considered.

These findings indicate that individual differences in verbal rehearsal speed appear to contribute more strongly to nonword repetition performance in children with CIs than individual differences in memory capacity (considered without reference to rehearsal speed). Verbal rehearsal speed in phonological working memory, as indexed by speaking rate, accounts for a substantial portion of the variance in nonword repetition scores in the CI users who participated in the present study. Although our results must be interpreted with some caution due to moderate intercorrelation among the independent variables, these results suggest that digit spans, as simple measures of memory capacity, do not fully capture a particular aspect of processing in phonological working memory that is critical to individual differences in nonword repetition performance.

Our finding that speaking rate as an index of verbal rehearsal speed is an important contributor to nonword repetition is consistent with the results of a recent study by Burkholder and Pisoni (2003). Burkholder and Pisoni examined speech timing measures of productions made during WISC-III digit span recall and McGarr sentence durations in a subgroup of the children in the present study and in a group of normal-hearing children. They found that children who use CIs had shorter digit spans and slower speaking rates than their normal-hearing age-matched peers. Within the group of children who use CIs, they also found that TC children had shorter digit spans and slower speaking rates than did OC children. Both findings support the hypothesis that the TC children have slower subvocal verbal rehearsal speeds, which may contribute to their shorter digit spans and affect other speech- and language-processing tasks as well (see Fry & Hale, 2000; Salthouse, 1985).

Our finding that age at implantation and age at time of testing were not significantly correlated with nonword repetition performance was not surprising because these two factors were controlled in this study. The group of children was relatively homogeneous in

terms of both of these variables. The lack of significant correlation with age of implantation could indicate that there is no significant benefit of earlier implantation. It could also indicate simply that children implanted at a later age had “caught up” with the earlier-implanted children after 4 to 5 years of implant use.

Finally, the results of the present study suggest two particular areas for future research. The first area deals with educational and reading achievement, which is a major concern of researchers and families of children with CIs (see Geers, 2003). Because the skills used in nonword repetition appear to be closely related to reading achievement in normal-hearing children who are either normally developing or who have expressive phonological disorders (e.g., Larrivee & Catts, 1999), it may be useful to study the relation between nonword repetition performance and both reading readiness and reading skills in children who have CIs. Second, in the present study, the individual phonological segments and within-item sequences of these segments in the nonword patterns were probably familiar due to the child’s ambient language (see Storkel, 2000, 2001, 2003). Thus, although each nonword was a novel phonological pattern and had no status as a word in the child’s lexicon, it is possible that nonword repetition performance in the present study was facilitated by phonotactic probability. Additional research should investigate the development of phonotactic awareness in children with CIs and its relationship to nonword repetition performance and novel word learning.

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Figure 1.

Frequency distribution of mean perceptual rating assigned to each child ($N=76$) on a 7-point Likert scale ranging from 1 (*totally fails to resemble the target utterance*) to 7 (*perfectly accurate renderings of the target utterance, ignoring differences in pitch*).

Figure 2.

Mean perceptual rating of nonword imitations by the oral-only communication ($n = 47$) and total communication ($n = 29$) groups of children. Error bars represent standard error.

Table 1

The 20 target nonwords used in the current study.

Orthography	Transcription
Two syllables	
ballop	'bæ.ləp
prindle	'p.rɪn.dl
rubid	'ru.bɪd
sladding	'slæ.dɪŋ
tafflist	'tæ.flɪst
Three syllables	
bannifer	'bæ.nə.fə
berrizen	'be.rə.zɪn
doppolate	'dɑ.pə.leɪt
glistering	'glɪ.stə.ɪŋ
skiticult	'skɪ.rə.kʌlt
Four syllables	
comisitate	kə.'mi.sə.teɪt
contramponist	kən.'tɹæm.pə.nɪst
emplifervent	em.'plɪ.fə.vənt
fennerizer	'fe.nə.əɪ.zə
penneriful	pə.'ne.rə.fʌl
Five syllables	
altupatory	æl.'tu.pə.tə.ri
detratopillic	di.'tɹæ.rə.pɪ.lɪk
pristeractional	'pɪ.stə.ək.ʃə.nəl
versatrationist	'və.sə.tɹeɪ.ʃə.nɪst
voltularity	'vɒl.tʃʊ.le.rə.ti

Note. Adapted from Gathercole et al. (1994) and Gathercole and Baddeley (1996).

Table 2

Correlations between nonword repetition perceptual ratings and demographic variables of 76 hearing-impaired children using cochlear implants.

Demographic variable	<i>r</i>
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
No. active electrodes in implant	-.03
Degree of exposure to oral-only communication	.51 *

*
 $p < .007$.

Table 3

Correlations between nonword repetition perceptual ratings and demographic variables of 69 hearing-impaired children using cochlear implants.

Demographic variable	<i>r</i>
Age at onset of deafness	-.07
Duration of deafness	-.16
Age at implantation	-.18
Duration of cochlear implant use	.13
Age at time of testing	-.13
No. active electrodes in implant	-.05
Degree of exposure to oral-only communication	.58*

*
 $p < .007$.

Table 4

Results of the regression model fit to the nonword repetition ratings of 69 pediatric cochlear implant users ($R^2 = .770$).

Contributing factors to nonword repetition performance	β
Verbal rehearsal speed in working memory: Speaking rate McGarr mean duration of 7-syllable sentences (log, milliseconds)	-.339***
Speech perception: Word identification, closed-set, pointing response Word Intelligibility by Picture Identification test	.291***
Speech production: Speech intelligibility McGarr sentence intelligibility	.284**
Degree of exposure to oral-only communication Communication mode score	.155*

* $p < .05$.

** $p < .01$.

*** $p < .001$.