Nonword Repetition with Spectrally Reduced Speech: Some Developmental and Clinical Findings from Pediatric Cochlear Implantation

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Abstract

Nonword repetition skills were examined in 24 pediatric cochlear implant (CI) users and 18 normal-hearing (NH) adult listeners listening through a CI simulator. Two separate groups of NH adult listeners assigned accuracy ratings to the nonword responses of the pediatric CI users and the NH adult speakers. Overall, the nonword repetitions of children using CIs were rated as more accurate than the nonword repetitions of the adults. The nonword repetition accuracy ratings from both groups of subjects were correlated with open- and closed-set word recognition scores and forward digit spans. Only the perceptual accuracy scores from pediatric CI users were correlated with measures of speech production accuracy. These results suggest that although the pediatric CI users had more experience and success in perceiving speech under degraded auditory conditions, developmental differences in their memory skills prevent them from performing as well on working memory tasks as mature listeners.

For over a decade, nonword repetition has been a popular task used to assess phonological working memory in a wide range of developmental and clinical populations (Bishop, North, & Donlan, 1996; Briscoe, Bishop, & Norbury, 2001; Edwards & Lahey, 1998; Gathercole, Willis, Baddeley, & Emslie, 1994; Laws, 1998; Sahlen, Reuterskiold-Wagner, Nettelbladt, & Radeborg, 1999) and is assumed to be related to a person's ability to learn novel words from childhood through adult life (Gathercole, 2006). Nonword repetition is assumed to be a more accurate measure of phonological memory than other simple auditory memory tasks such as forward digit span or direct assessments of immediate serial recall because it involves a more complex series of information processing operations. To complete a nonword repetition task, listeners must first accurately perceive and encode a novel linguistic pattern in the absence of any semantic or pragmatic context or lip-reading cues. After encoding, the nonword must then be retained in short-term memory using the subvocal verbal rehearsal component of the phonological loop. Finally, nonword repetition also

requires that listeners reassemble the novel auditory pattern into a fluent spoken response and execute a series of motor commands to the speech articulators. Because of its complexity and the specific information-processing steps it involves, the nonword repetition task has recently emerged as a diagnostic tool used by researchers and clinicians interested in the speech, language, and memory skills of deaf children who use cochlear implants (CIs).

The nonword repetition skills of pediatric CI users have been explored extensively in our laboratory to account more fully for the wide individual differences in speech, language, and other cognitive outcomes in this clinical population (Carter, Dillon, & Pisoni, 2002; Cleary, Dillon, & Pisoni, 2002; Dillon, Burkholder, Cleary, & Pisoni, 2004; Dillon & Pisoni, 2004; Dillon & Pisoni, 2006). Two primary methods have been used to assess pediatric CI users' nonword repetition performance. As an alternative to scoring nonword repetitions as simply correct or incorrect, perceptual accuracy ratings and more detailed linguistic analyses—specifically segmental and suprasegmental accuracy—have been carried out on the nonword repetitions of pediatric CI users.

When scored dichotomously as either correct or incorrect, pediatric CI users' nonword repetition skills appear to be at floor and lack any informative variability (Carter et al., 2002). However, by using segmental and suprasegmental linguistic analyses along with perceptual accuracy ratings, the qualitative characteristics of pediatric CI users' nonword repetition skills have been more fully and accurately documented. In addition, by using these more descriptive and sensitive measures of nonword repetition performance, numerous correlates and predictors of pediatric CI users' nonword repetition skills have been identified. The relationships identified between CI users' nonword repetition performance and cognitive processing variables such as subvocal verbal rehearsal, memory, and reading have provided some valuable insights into the large individual differences in speech, language, and other cognitive outcomes that are frequently observed in this clinical population (Carter et al., 2002; Cleary et al., 2002; Dillon, Burkholder, et al., 2004; Dillon & Pisoni, 2006).

In a small group of 14 pediatric CI users who were able to give a spoken response to each of the nonwords used in the study, Cleary et al. (2002) found substantial variability in the overall perceptual accuracy ratings that naive, normal-hearing (NH) adult listeners assigned to the children's nonword repetitions. They also found that the perceptual accuracy ratings were related to a number of speech perception and production measures after demographic variables were partialled out of the analysis. Both open- and closed-set speech perception scores were positively correlated to the children's nonword repetition ratings. This result confirms that reliable initial auditory encoding of the novel nonword patterns is essential for pediatric CI users to complete the nonword repetition task successfully.

Several speech production measures were also found to be related to pediatric CI users' mean perceptual accuracy ratings (Cleary et al., 2002). Speech intelligibility scores obtained from short sentences spoken by the children were positively correlated with the overall nonword repetition rating that they received. In addition, the durations of these sentences were related to the children's nonword repetition accuracy ratings. Children who articulated the sentences more slowly received lower nonword repetition accuracy ratings. This result suggests a relationship between speaking rate and the ability to repeat novel nonword stimuli from representations in immediate memory.

In a larger study of 76 pediatric CI users who varied in their ability to provide a spoken response for each nonword token, Dillon, Cleary, et al. (2004) confirmed some of the earlier findings from Cleary et al. (2002). They found strong relationships between several speech

perception, speech production, and memory measures and nonword repetition accuracy ratings. Using linear regression, Dillon et al. found that the duration of sentences spoken by the children, which can be taken as an index of subvocal verbal rehearsal speed, was the strongest predictor of nonword repetition ratings. Two other significant predictors of nonword repetition accuracy ratings assigned to the children were scores obtained on the closed-set Word Intelligibility by Picture Identification (WIPI; Ross & Lerman, 1979) test and speech intelligibility ratings obtained from a separate group of adult listeners. Taken together, the results of these two studies indicate a close relationship between speech perception, speech production, and speaking rate measures and nonword repetition accuracy ratings.

Speaking rate may be related to the ability to reproduce a novel nonword pattern not only because it indexes pediatric CI users' abilities to produce speech in a fluent and fluid manner but because it is also an index of subvocal rehearsal speed, that is, the speed at which verbal information can be refreshed within the phonological loop of working memory (Burkholder & Pisoni, 2003; Cowan et al., 1998; Kail & Park, 1994; Pisoni & Cleary, 2003). Because nonword repetition is a phonological working memory task, subvocal verbal rehearsal is a very important and integral process involved in its completion. Similarly, subvocal verbal rehearsal is also an important process that contributes to pediatric CI users' auditory and visual memory spans (Burkholder & Pisoni, 2003; Cleary, Pisoni, & Geers, 2001; Pisoni & Cleary, 2003).

It is not surprising then that auditory memory spans have also been found to be related to the pediatric CI users' nonword repetition accuracy ratings. Cleary et al. (2002) found a strong positive correlation between the pediatric CI users' forward digit spans and their average nonword repetition rating. Children with longer forward digit spans received higher nonword repetition accuracy ratings. The relationship between auditory memory span and nonword repetition has been documented previously in numerous populations of NH children (e.g., Brady, Mann, & Schmidt, 1987; Gathercole & Baddeley, 1989, 1990). In addition, both auditory memory span and nonword repetition abilities have been found to be positively correlated with NH children's vocabulary development, vocabulary size, usage of syntactically complex sentences, and word learning abilities in both native and nonnative languages (Edwards, Beckman, &Munson, 2004; Gathercole & Baddeley, 1990; Service, 1992). For children with a hearing impairment (both CI users and traditional hearing aid users), vocabulary training has actually been found to have a causal, not just correlational, effect of improving speech perception scores (Paatsch, Blamey, Sarant, & Bow, 2005).

Because nonword repetition is predictive of and related to such a critical set of speech and language abilities in NH children, it has been valuable to examine this ability in pediatric CI users as well. The nonword repetition skills of pediatric CI users may help explain some of the large individual differences in speech, language, and other cognitive outcomes that are frequently observed in this population and may provide insight into the processes that these children use while developing language and language-related skills. Several language and language-related skills have been found to be associated with pediatric CI users' nonword repetition accuracy. Two previous studies have shown a positive correlation between pediatric CI users' comprehension of spoken language and nonword repetition skills (Cleary et al., 2002; Dillon, Burkholder, et al., 2004). More recently, Dillon and Pisoni (2006) found that measures of reading and lexical diversity in spontaneous speech samples were strongly correlated with the perceptual accuracy ratings of the nonword repetitions of deaf children using CIs. Taken together, research using perceptual accuracy ratings has indicated that pediatric CI users' nonword repetition skills are strongly linked to a number of speech perception, speech production, memory, and reading skills.

Several of the same measures of speech perception and production and subvocal verbal rehearsal that are related to pediatric CI users' nonword repetition accuracy ratings have also been found to be positively correlated with linguistic analyses conducted on their nonword repetition responses. A suprasegmental analysis of pediatric CI users' nonword responses indicated that both the ability to correctly reproduce primary stress and the appropriate number of syllables was related to speech perception and production scores and subvocal verbal rehearsal (Carter et al., 2002). Children's ability to produce consonants in the nonwords accurately was also related to these three variables (Cleary et al., 2002; Dillon, Cleary, Pisoni, & Carter, 2004). In a more detailed analysis of the segmental accuracy of the children's nonword repetitions, Dillon, Cleary, et al. (2004) also found that several measures of speech perception, production, and memory were strongly correlated with the number of segments reproduced correctly.

In addition to reconfirming which speech and cognitive processes are most predictive of CI implant users' nonword repetition skills, segmental and suprasegmental linguistic analyses have also been very useful in qualitatively describing the nature of these listeners' nonword repetition errors. For example, Carter et al. (2002) found that children using CIs were able to produce the correct number of syllables and the correct stress patterns in nonwords with over 60% accuracy. However, children using CIs have been found to be less accurate in producing individual segments in novel nonword patterns. Several segmental analyses by Dillon, Cleary, et al. (2004) revealed that less than 40% of target consonants were repeated correctly. When target consonants were incorrectly reproduced, it was most often due to a substitution of another consonant. Deletions of target consonants accounted for only 25% of the segmental errors. Despite the inability to produce most segments correctly, the children with CIs reproduced manner, place, and voicing of target consonants correctly over 50% of the time. Reproduction of the correct voicing of consonants was easiest for the CI children, whereas reproducing the correct manner was the most difficult.

Accuracy of nonword imitations was consistent across the various voicing and manner features. However, variability was observed in the reproduction of place features. Coronals were reproduced correctly in nonword responses nearly 70% of the time. However, labials were correct only about half the time and dorsals were only correctly produced 40% of the time. A detailed analysis of substitution errors indicated that labials and dorsals were frequently replaced with coronals (see Dillon, Cleary, et al., 2004).

The assessment of pediatric CI users' segmental accuracy in a nonword repetition task by Dillon, Cleary, et al. (2004) was one of the first to find this pattern of place of articulation errors. Previous research has suggested that children with CIs reproduce labial targets more accurately than other places of articulation (Dawson et al., 1995; Tobey, Geers, & Brenner, 1994). The different pattern of place of articulation errors found in the children's nonword repetitions may have occurred because the nonword repetition task was conducted in auditory-only mode with no visual cues to place of articulation (Dillon, Cleary, et al., 2004). In an audio–visual speech perception task, cues to place of articulation are readily available and likely assist pediatric CI users when they are completing open-set word recognition tasks with familiar words, especially for labial segments (Bergeson & Pisoni, 2004; Bergeson, Pisoni, & Davis, 2003; Lachs, Pisoni, & Kirk, 2001). However, when only auditory information is available and when the test stimuli are unfamiliar nonwords like the ones used in these studies, children with CIs must rely exclusively on their ability to encode the speech signal in its acoustic or auditory form prior to subvocally rehearsing and repeating it.

Although nonword repetition may rely more extensively on the initial auditory encoding of a speech signal than some other speech perception tasks that are closed-set or administered in

live-voice with real words, performance on the nonword repetition task has also been found to be related to pediatric CI users' speech production and working memory skills (Carter et al., 2002; Cleary et al., 2002; Dillon, Burkholder, et al., 2004; Dillon, Cleary, et al., 2004). Thus, one potential problem with linguistic analyses or perceptual accuracy ratings of the nonword repetitions of deaf children using CIs is determining whether the observed performance and errors are primarily related to auditory perception and encoding, to working memory, or to speech production problems. That is, it is uncertain whether the observed nonword repetition errors committed by pediatric CI users are due primarily to perceiving the nonword incorrectly, simply articulating it improperly, or inefficiently rehearsing and maintaining the novel nonword pattern in immediate memory.

Previous studies have documented that pediatric CI users have inefficient subvocal verbal rehearsal processes in auditory, auditory–visual, and visual–spatial working memory tasks (Burkholder & Pisoni, 2003; Cleary et al., 2001). Thus, it is no surprise that inefficiencies in subvocal verbal rehearsal may also carry over to the nonword repetition task. Using linear regression, Dillon, Burkholder, et al. (2004) found that speaking rate, which can be used as an index of subvocal verbal rehearsal speed, was the strongest predictor of CI children's nonword repetition ratings. However, closed-set speech perception and speech intelligibility were also found to be significant predictors of nonword repetition ratings. In addition, the strength of these two predictors was nearly equal. Thus, despite identifying subvocal verbal rehearsal speed as the primary predictor of nonword repetition accuracy, the relative contributions of speech perception and speech production still remain unclear.

One way to attempt to investigate the impact of speech perception and production problems on pediatric CI users' nonword repetitions is to study nonword repetition performance in listeners with normal hearing and normal speech production who are exposed to auditory conditions similar to those experienced by pediatric CI users. Using an acoustic simulation that models the input of CIs provides a way to compare nonword repetition performance in pediatric CI users and listeners with normal hearing and speech production.

The present experiment was designed to identify the locus of the problems that pediatric CI users have with nonword repetition. In this study, the locus of "disruption" on the nonword repetition task for the NH adults listening to speech processed through a CI simulator is already known. The adults' initial perception and encoding of the nonwords is disrupted due to the degraded nature of the stimuli. However, their working memory and speech production are intact and are not disrupted in the nonword repetition task. Alternatively, for the CI children it is not clear whether they primarily have impaired or disrupted speech perception, working memory, speech production, or some combination of these processes. Comparing these two groups may provide further insight into whether speech production is a significant contributor to pediatric CI users' poor nonword repetition skills or whether the differences are primarily perceptual or memory related.

In this study, the relationship between nonword repetition accuracy ratings and measures of speech perception, working memory, and linguistic accuracy (segmental and suprasegmental) of nonword imitations were compared for a group of pediatric CI users and a group of NH adults. In addition, overall accuracy was compared across the two groups on measures of speech perception, working memory, and linguistic accuracy of nonword imitations. It is assumed that comparisons made between NH adult speakers and pediatric CI users will help determine whether speech perception, working memory, or speech production difficulties underlie CI children's performance on the nonword repetition task. NH adults have intact speech production and working memory skills; but in this particular task, they have disrupted perception because they are asked to perceive severely degraded

speech processed through a CI simulator. The pediatric CI users, on the other hand, potentially have disrupted speech perception, working memory, and speech production.

In order to tease apart these causes of the variation in nonword repetition skills of CI users, and more generally their atypical language learning abilities, several comparisons were made between the NH adults and the pediatric CI users. First, patterns of correlations between perceptual accuracy ratings of nonwords and measures of speech perception, working memory, and linguistic measures of the actual nonword productions were compared for the two groups. If the same relationships between these language processing skills and nonword repetition accuracy ratings are uncovered in these two groups of listeners, it may indicate that developmental and clinical differences do not influence the relationship between the component processes (i.e., encoding, memory, and production processes) used to complete a nonword repetition task under spectrally degraded listening conditions. Second, the actual performance on these language tasks was compared for the two groups. It is presumed that if NH adults and pediatric CI users demonstrate similar patterns of segmental and suprasegmental accuracy in their nonword repetitions that speech perception and working memory rather than speech production play a more critical role in pediatric CI users' nonword repetitions skills.

A second goal of this study was to confirm the validity of this method of CI simulation. Similar patterns of nonword repetition errors in NH adults listening to spectrally degraded speech and in pediatric CI users would suggest that acoustic simulations of CIs do sufficiently model the acoustic input heard by CI users and are therefore useful when studying the effects of degraded auditory stimuli on speech perception and other cognitive skills.

Methods

Participants

Twenty-four pediatric CI users and 18 NH adults participated in this study. The children were selected from a larger group of participants who took part in the Central Institute for the Deaf "Cochlear Implants and Education of the Deaf " project in 1999 or 2000 (see Geers & Brenner, 2003). The children were between 8 and 9 years old. All but five were deaf at birth. The average duration of deafness prior to receiving a CI for the children was 3 years. The children had between 4 and 6 years of experience with their CI. The 24 pediatric CI users included in this study were the children who provided a response to all the 20 nonwords (see Dillon, Burkholder, et al., 2004).

The adult participants were native English-speaking undergraduate students aged 18–25 who were enrolled in an introductory psychology course at Indiana University and were given partial course credit for their participation. These participants indicated through self-report that they had no history of speech, hearing, language, or attentional disorders. A short hearing screening was also conducted to confirm that the adult subjects had normal hearing at the time of testing.

Stimulus Materials

Three sets of stimulus materials were used in this study. For the nonword repetition task, the stimuli included 20 nonwords taken from the Children's Test of Nonword Repetition recorded by a female speaker of American English (Gathercole et al., 1994). Table 1 lists the nonwords and their target transcriptions. This set of nonwords is balanced for number of syllables and is the same as was used in previous studies conducted in our laboratory (see Cleary et al., 2002; Dillon, Cleary, et al., 2004).

In addition, two tests of speech perception were included: the Lexical Neighborhood Test (LNT; Kirk, Eisenberg, Martinez, & Hay-McCutcheon, 1999) and the WIPI (Ross & Lerman, 1979). The LNT is an open-set spoken word recognition task. The LNT test contains words that vary in "lexical difficulty." Lexically "easy" words are high-frequency words in sparse lexical neighborhoods (having few phonologically similar words) (LNTe); lexically "hard" words are low-frequency words in dense lexical neighborhoods (LNTh). The WIPI, on the other hand, is a closed-set spoken word recognition task that requires participants to point to a picture that matches the auditory stimulus, thereby placing no demands on the participant's speech production system.

Finally, both forward and backward auditory digit spans (Wechsler, 1991, 1997) were obtained to assess the participants' short-term and working memory skills. Forward digit spans test verbal rehearsal and short-term immediate memory. Backward digit span, on the other hand, is assumed to measure working memory and executive functions.

Prior to presentation to the adult listeners, the nonwords, LNT and WIPI words, and digit span lists were processed offline using a personal computer equipped with DirectX 8.0 and a Sound Blaster Audigy Platinum sound card. The signal processing procedure used for the CI simulation was adapted from real-time signal processing methods developed by Kaiser and Svirsky (2000). The signal was low-pass filtered with a cutoff frequency of 12,000 Hz. A bank of eight filters was then used to simulate the speech processing of an eight-channel CI. The output of each filter modulated noise bands of a higher frequency range than the corresponding filter. This mismatch was designed to represent a frequency misalignment that commonly occurs between the analysis filters of a CI's speech processor and the characteristic frequency of the neurons stimulated by the corresponding electrodes. The amount of frequency mismatch used in this model was equivalent to a 6.5-mm shift within the cochlea. For a more detailed discussion of the frequency shift used in this study, see Harnsberger et al. (2001).

Procedure

Nonword repetition—All listeners were given instructions that they would hear a funny made-up nonword and that they should try to repeat it as accurately as possible. The adult participants were also told that the nonwords would be acoustically degraded. Before hearing and repeating any nonwords in their degraded form, the adult listeners completed nonword repetition with five unprocessed practice nonwords. The degraded nonword stimuli were played in random order to the listeners over a tabletop speaker (Cyber Acoustics MMS-1) at approximately 70 dB(A) SPL.

The nonword repetitions obtained from each of the two groups were played to separate groups of naive, NH adult listeners to obtain "perceptual accuracy ratings" (Burkholder, Pisoni, & Svirsky, 2004; Dillon, Burkholder, et al., 2004). These NH adult listeners met the same qualifications as the NH adult speaker; they were native speakers of English, aged 18–25, and reported no history of speech or hearing disorders. Listeners heard the original target nonwords and then the response of either an adult or child speaker. Listeners were asked to rate how accurate they thought the participants' nonword responses were compared to the original target nonword. Ratings were made based on a 7-point Likert scale in which 1 corresponded to a repetition that "completely failed to resemble the target" and 7 corresponded to "completely perfect rendition of the target." All listeners received partial course credit for their participation.

Speech perception and memory tests—The NH adults completed both the LNT and WIPI speech perception tests prior to nonword repetition and completed different lists of forward and backward digit spans in both degraded and clear auditory conditions after the

nonword repetition task (Burkholder, Pisoni, & Svirsky, 2005). The CI children also completed the LNT and WIPI tests, as well as both forward and backward digit spans. The nonword repetition responses obtained from the children and adults were recorded onto a digital audiotape via a head-mounted microphone (Audio-Technica ATM75).

Linguistic Transcription and Accuracy Scoring

All the adult nonword repetitions were transcribed independently by two phonetically trained listeners (second and third authors) and then compared. Any nonword responses that were composed of real words were not transcribed and were discarded. Consensus was reached on 284/291 (97.6%) of the responses. The remaining 7/291 (2.4%) were transcribed by a third phonetically trained listener in order to resolve any disagreements.

All nonword responses were aligned with the target transcription segment by segment to ensure the maximum continuity between the target and the response. Each segment in the response that corresponded to a segment in the target was coded for accuracy along several segmental dimensions. For consonants, the segments were coded for correct global place of articulation (labial, coronal, dorsal), sonorancy ([±sonorant]), manner (stop, affricate/ fricative, nasal, liquid/glide), and obstruent voicing. For vowels, the segments were coded for correct height (high, mid, low), backness (front, central, back), and roundness (round and unround). In addition to these featural codings, segments were also coded for whether the response segments and the target segments matched along these dimensions simultaneously (whole segment correct). It is important to note that for "whole segment correct," the segments may not actually match exactly. For example, [θ], [s], and [ʃ] were coded as exactly correct because they match for global place (coronal), manner, and voicing.

In addition to segmental coding, nonword responses were coded along several suprasegmental dimensions: correct number of segments, correct number of consonants, correct number of syllables/vowels, and correct stress placement. For the NH adult speakers, correct stress was calculated as follows. If either a primary or secondary stress in the response matched the primary stress in the target word, it was scored as correct. This method of scoring stress was utilized because determining the degree of stress (primary vs. secondary) was difficult in several of the adult responses.

The pediatric CI users' nonword responses were transcribed using similar criteria (Carter et al., 2002). Their nonword responses were not retranscribed for this analysis, but were recoded using the same segmental and suprasegmentals dimensions as the adult NH data to allow better comparison between the adult and child data. The only dimension that was not recoded was stress placement because the original transcription of stress for the child data differed from that of the adult transcriptions. Thus, no comparisons were made between the two groups of speakers for stress placement.

Results

Figure 1 displays the adults' and children's performance on the open- and closed-set speech perception tasks. Several analyses of variance (ANOVAs) were carried out to assess differences between listener groups and lexical difficulty. A repeated-measures ANOVA on the open-set LNT with lexical difficulty (easy vs. hard) as a within-subjects factor and listener group (CI children vs. NH adults) as a between-subjects factor revealed a main effect of lexical difficulty ($F(1, 40) = 18.02$, $p = .000$). Lexically easy words were identified better than the lexically hard words. The main effect of listener group was also significant ($F(1, 40) = 83.99$, $p = .000$). The CI children had much better LNT word recognition scores than the adults. The interaction was not significant ($F(1, 40) = 2.95$, $p = .094$). A one-way ANOVA of the CI children's and NH adults' closed-set WIPI scores revealed no significant

differences between the two groups ($F(1, 40) = 1.92$, $p = .174$). Taken together, these two tests revealed that in closed-set word recognition tasks, the two groups of listeners exhibited no significant differences, whereas they did in the open-set task. Interestingly, the children with CIs performed better than the NH adults on the LNT test.

Figure 2 shows the participants' performance on a forward and backward digit span task. The adults' digit span data reflect their performance on the digit span task when it was administered with auditory tokens processed through an acoustic simulation of a CI. A repeated-measures ANOVA was conducted to determine the effects of digit span recall condition and listener group. A main effect of recall condition was found ($F(1, 40) = 59.29$, $p = .000$). As expected, forward digit spans were higher than backward digit spans. The main effect of listener group was also significant ($F(1, 40) = 36.41$, $p = .000$). Digit span scores obtained from adults listening to the acoustic simulation of the CI were higher than the children's digit span scores. The interaction was not significant.

Figure 3 displays the mean perceptual accuracy ratings assigned to each listener group based on the number of syllables in the nonwords. A repeated-measures ANOVA was conducted to determine the effect of syllable number and listener group. A main effect of syllable number was found ($F(3, 40) = 9.53$, $p = .000$). The effect of listener group was also significant ($F(1, 40) = 10.65$, $p = .002$). The children's nonword repetition accuracy ratings were higher than the adults. The interaction of syllable number and listener group also reached significance ($F(3, 40) = 15.09$, $p = .000$). This interaction indicates that the children's nonword repetition accuracy ratings decreased as the number of syllables in the nonwords increased. However, the adults' ratings remained constant across different word lengths.

Table 2 lists the results of bivariate correlations conducted using the listeners' nonword repetition accuracy scores, speech perception measures, and digit spans. The children's nonword repetition accuracy ratings were highly correlated with both the closed- and open-set speech perception tests. Children with higher scores on the LNTe, LNTh, and WIPI received higher nonword repetition accuracy ratings. The children's nonword repetition ratings were also strongly correlated with forward digit span scores, but not with backward digit span scores. This same pattern of results was obtained in the adults, although the magnitudes of the correlations were smaller. Positive correlations were found between the nonword repetition ratings and the three measures of speech perception, as well as between the ratings and the forward digit spans. As with the children, the correlations with backward digit span were weaker and did not reach significance.

Several one-way ANOVAs were carried out on the linguistic analyses of the repetition responses in order to assess the differences in the accuracy in reproductions of the two groups. The results of these ANOVAs are presented in Table 3. The only variables that yielded significant differences between the two groups were obstruent voicing, vowel height, and vowel rounding. The CI children were more accurate in reproducing vowel height, whereas the NH adults were more accurate in reproducing obstruent voicing and vowel rounding. No other linguistic dimensions exhibited significant differences.

Table 4 lists the results of bivariate correlations conducted using the listeners' nonword repetition accuracy scores and the measures obtained from linguistic analysis of the nonword repetitions. Several differences between the two groups emerged when examining the correlations between linguistic measures and perceptual accuracy ratings. Although the CI children's nonword rating scores were found to be highly correlated with 10/11 of the linguistic measures, the adults' nonword accuracy ratings were only correlated with one of the 11 linguistic measures.

Discussion

Several interesting and novel results emerged from the present analyses conducted on the nonword repetitions of pediatric CI users and NH adults listening to an acoustic simulation of a CI. Overall, the CI children had better spoken word recognition scores than the NH adults. This result would initially suggest that the deaf children with CIs performed better on the speech perception tests because they had more experience listening to spectrally degraded speech and/or because the spectrally mismatched speech that the adults were listening to was more degraded than the input from the children's devices. However, the children only performed better than the adults on the open-set LNT; no significant difference between the groups was found for the closed-set WIPI. This pattern suggests that the adults and children may have used different strategies when choosing responses in the closed-set speech perception task.

The closed-set WIPI is a six-alternative, forced-choice test in which the five response alternatives were all minimal pairs or close neighbors of the target words that were all appropriate for use with children. Carrying out this task requires that listeners make discriminations between words based on the perception of fine acoustic–phonetic detail. The performance on the WIPI suggests that adults and children were able to make fine acoustic–phonetic discriminations. The LNT with hard words requires similar abilities in an open-set format because hard words have many acoustically similar neighbors. However, pediatric CI users performed much better than adults on this task. This pattern of results suggests that in the forced-choice task, adults may have used a global pattern recognition strategy and linguistic knowledge to choose the correct response alternative. The adults' decision strategies and their more extensive linguistic knowledge and experience may have compensated for their overall poor speech feature discrimination abilities when they were completing the closed-set task. It is likely that the higher performance of CI children on the open-set test occurred because the children have more experience listening to a degraded speech input through their CI. A reviewer points out that the pediatric CI users may have previously been administered the open-set LNT words, causing an increase in their performance.

Developmental differences in working memory processes may also underlie the differences observed in the digit spans between the pediatric CI users and NH adults listening to the acoustic simulation of a CI. Given that the pediatric CI users showed a tendency for better speech perception scores than the adults, it is unlikely that errors in speech perception were the primary cause of the children's poorer performance on the digit span task. In addition, earlier studies have found that pediatric CI users have shorter visual–spatial memory spans than NH children in a task in which no spoken response is required (Cleary et al., 2001). These two findings suggest that speech perception and speech production problems are not the primary cause of pediatric CI users' shorter memory spans. Rather, slower memory processing strategies such as subvocal verbal rehearsal and scanning for these items in working memory may be the major factors contributing to the relatively short digit spans of pediatric CI users (Burkholder & Pisoni, 2003).

However, in NH adults listening to an acoustic simulation of a CI, it has been suggested that perceptual encoding errors, rather than memory processing errors, are responsible for shorter digit spans in spectrally degraded conditions (Burkholder et al., 2005). Taken together, the previous findings and the current results suggest again that adults' extensive linguistic experience and their more mature processing strategies can be used to compensate for perceptual and encoding difficulties that are the result of listening to spectrally degraded speech in speech perception or immediate serial recall tasks. Similarly, the present results

suggest that the delayed memory processing strategies of pediatric CI users are not sufficient to compensate for auditory encoding problems.

The comparisons between the adults' and children's nonword repetition perceptual accuracy ratings also provide support for this proposal. Pediatric CI users' nonword repetition accuracy ratings were significantly higher than those assigned to the NH adults listening to the acoustic simulation of the CI. Moreover, the effect of syllable length was observed only in the children. The children's mean nonword repetition accuracy ratings decreased as the number of syllables in the nonwords increased. This suggests that limitations in the children's ability to rehearse and retain longer nonword sequences in phonological working memory is responsible for the syllable-length effect (Carter et al., 2002; Dillon, Burkholder, et al., 2004). Future studies comparing NH children with pediatric CI users will help to determine whether the syllable-length effect is purely age related or a result of encoding. The children's repetitions of the shorter nonwords may have been rated as more accurate than the adults' simply because the children had much more experience listening to degraded input. That the children's ratings decrease to that of the adults' for longer words further suggests that limitations to working memory are responsible for the syllable-length effects.

Similar interpretations of the nonword repetition syllable-number effect in NH children have been proposed by Gathercole et al. (1994). In addition, when NH adults complete the nonword repetition task in clear listening conditions using unprocessed speech signals, they also demonstrate a syllable-number effect as a result of increased memory load (Gupta, Mac-Whinney, Feldman, & Sacco, 2003). The lack of the syllable-number effect with the NH adults listening to an acoustic simulation of a CI suggests that difficulty in encoding the degraded speech stimuli may have blocked or inhibited the used of normal phonological memory processes that contribute to the syllable-number effect. In addition, the current group of NH adults may have shown no evidence of the syllable-length effect because their nonword repetition performance and ratings were simply near or at floor. This floor effect may have resulted because the adults in this study had very little experience listening to spectrally degraded speech compared to the pediatric CI users who have used their implant for several years before this study. In addition, the adults may have performed poorly because of the large spectral mismatch used in the acoustic model of the CI that made the task perceptually harder.

Despite having what appears to be near-floor performance and a reduced role of phonological working memory in the nonword repetition task, the NH adults' nonword repetition accuracy ratings were correlated with several speech perception measures and with their forward digit span. The same pattern of correlations observed in the adults listening to the acoustic simulation of the CI was also observed in the pediatric CI users. This is an important finding because it suggests that the pediatric CI users used the same fundamental component processes to carry out nonword repetition that NH adults use. They do not approach the task in a nonstrategic or random manner. This finding may have implications for how pediatric CI users approach other tasks such as novel word learning (Houston, Carter, Pisoni, Kirk, & Ying, 2002). Because nonword repetition requires some of the same basic processing skills that novel word learning makes use of, the present results suggest that pediatric CI users may have more typical word-learning mechanisms than previously thought. The relationship between word learning and several measures of language processing has been shown to be causal, further indicating the link between lexical properties and speech processing (Paatsch et al., 2005).

This current set of results is also interesting in light of earlier findings that in clear listening conditions both NH children and adults demonstrate a relationship between immediate serial

recall and nonword repetition (Gupta et al., 2003). This study replicates these findings in pediatric CI users and NH adults listening to an acoustic simulation of a CI and suggests that being exposed to degraded auditory stimuli in these tasks does not cause this relationship to be atypical or dysfunctional.

The correlations observed between the accuracy ratings and the measures of speech perception and working memory in both groups indicate that listeners who have better perception and working memory perform better on the nonword repetition task. Previous work has shown that CI children's speech intelligibility scores, as measured by transcriptions of short sentences, also correlates with nonword repetition accuracy (Cleary et al., 2002). In this study, the measures of speech production that we obtained were based on linguistic analysis and coding of actual productions scoring for both segmental and suprasegmental contrasts.

The lack of a correlation between any of the linguistic measures and the perceived accuracy of the nonword responses for the NH adults may be due to the lack of variability observed for both the linguistic measures and the perceived accuracy ratings. The NH adults were actually rated as having less accurate nonword responses than the children. This may be due to the fact that the adult responses were generally slow, labored, and disfluent, a fact not reflected in the linguistic transcriptions. Thus, the adult perceived accuracy ratings may have exhibited a floor effect and therefore less variability than the child data. We would expect that speakers who display poor articulation of nonwords would be rated as reproducing the target nonword less accurately as we found in the child data. However, there may simply have been insufficient variability in the adult data to capture this.

Another explanation for the difference in the ratings between the children and the adults may be due to the different expectations of speech production for children vs. adults. Raters may have been more lenient in rating the children's productions simply because they are children. A future study with NH children's nonword repetitions could determine the validity of such a claim. Furthermore, the adults' nonword productions were often disfluent and therefore the ratings may have been lower because the raters may have attended more to general naturalness than to differences in linguistic accuracy. A future study in which speakers produce multiple repetitions of a nonword stimulus in order to get more fluent imitations may eliminate this problem.

Because the linguistic production measures were not found to be significantly different for the CI children and the NH adults, this suggests that the CI children overall have good speech production skills. This finding is consistent with previous results showing that speech production skills do not independently contribute to the variance observed in the nonword repetition task (Dillon, Burkholder, et al., 2004). The absence of any differences in production accuracy between the CI children and NH adults suggests that perception and working memory are the primary loci for variation observed in the nonword repetition task for CI children. The lack of differences in the nonword responses further suggests that the acoustic simulation used here may sufficiently model the acoustic input heard by CI users. However, if both NH adults and CI children are basing their productions entirely on knowledge of phonotactics, segmental frequencies, and/or transitional segmental probabilities rather than on acoustic or spectral qualities, then other degradations of the input signal should produce similar results in the nonword repetition responses. This remains to be tested in future research.

Conclusions

In this study, NH adults performed better than the children with CIs on tasks that required more advanced/developed working memory (digit span). The children with CIs, however, performed better on the open-set speech perception task, probably because of their greater experience in listening to degraded input. The atypical and delayed working memory skills of the CI children were also visible in the interaction between word length (number of syllables) and the perceptual accuracy ratings. Children were rated as less accurate when producing longer rather than shorter nonwords. The lack of a syllable-length effect for the adults could either reflect their better working memory skills or a floor effect of the perceptual accuracy ratings. When comparing the production accuracy (as measured by the various linguistic measures), no differences between the two groups of participants emerged, suggesting that their productions are comparable. Taken together, these results suggest that the locus of the difficulty in performing a nonword repetition task in CI children appears to be related to early perception and lies in memory and verbal rehearsal skills needed to maintain a representation in immediate memory. In other words, difficulties in performing this task are due to developmental differences.

If we consider the patterns of performance, the adults and the children often showed similar results. The perceptual accuracy ratings data for the CI children were found to be correlated with measures of speech perception (WIPI and LNT), short-term memory (forward digit span), and speech production (linguistic accuracy). Children with better performance on each of these components were rated as producing more accurate nonword imitations. The adults showed these same patterns of performance for the speech perception and working memory tasks but not for the linguistic variables. The lack of a correlation with the linguistic measures reflected a floor effect that may be due to disfluent productions which were rated more poorly than the children's. The similarity of the nonword repetition scores for the CI children and NH adults suggests that the same basic component information processing operations are involved in the completion of the nonword repetition task.

Acknowledgments

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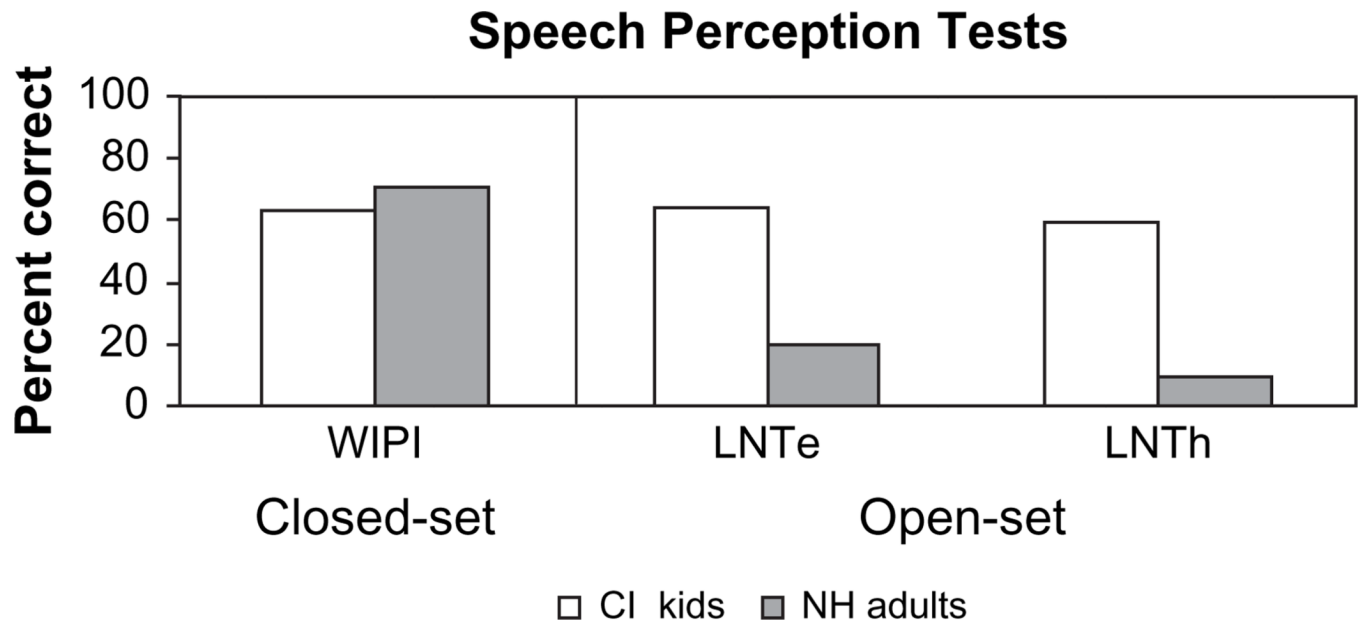Wechsler, D. Wechsler Adult Intelligence Scale—III. San Antonio, TX: The Psychological Corporation; 1997.

Speech Perception Tests

Figure 1.
Performance on closed- and open-set speech perception tests by pediatric CI users and NH adults listening to an acoustic simulation of a CI.
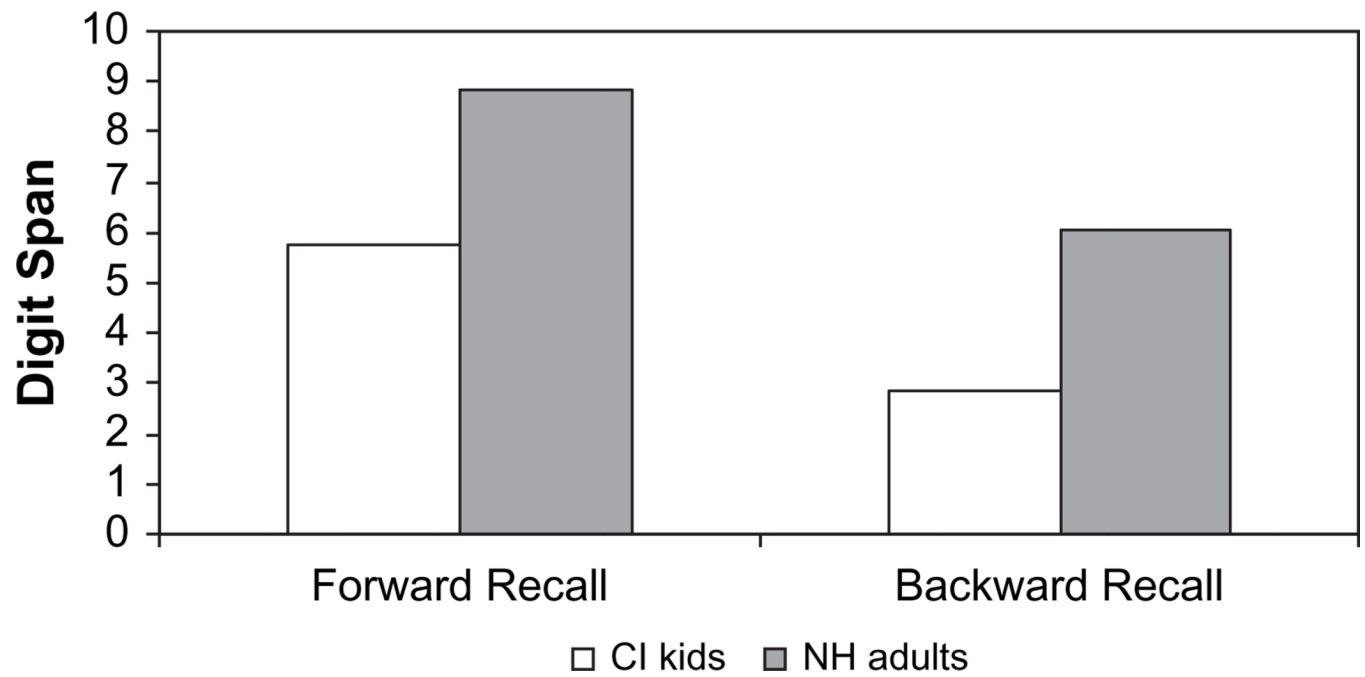
Figure 2.
Forward and backward digit span scores of pediatric CI users and NH adults listening to an acoustic simulation of a CI.
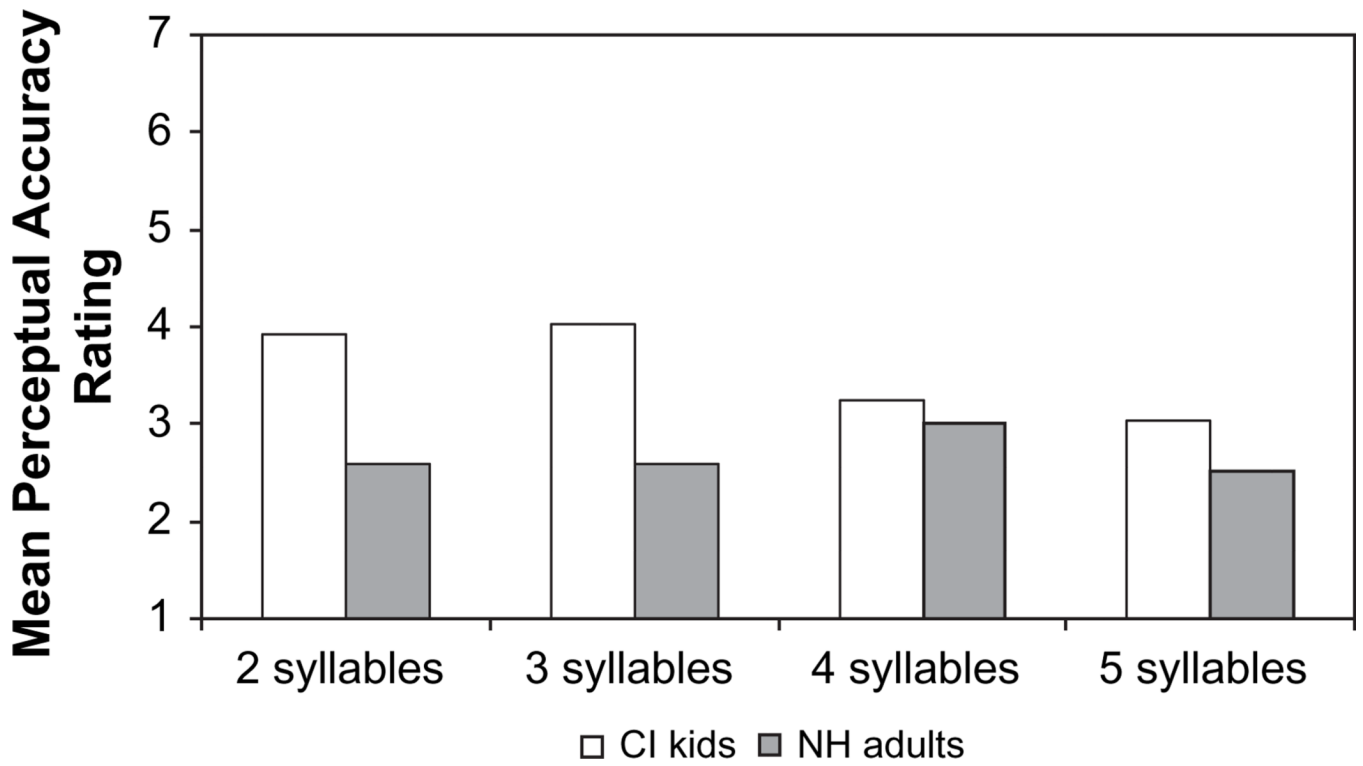
Figure 3.
Mean perceptual accuracy ratings assigned to pediatric CI users and NH adults when repeating nonwords with 2, 3, 4, and 5 syllables.

Table 1

Nonawords used in this study (adapted from Gathercole et al., 1994)

Number of syllables	Target nonword orthography	Target nonword transcription
2	ballop	ˈbæ.ləp
	prindle	ˈprɪn.dəl
	rubid	ˈru.bɪd
	sladding	ˈslæ.ɾɪŋ
	tafflist	ˈtæ.fləst
3	bannifer	ˈbæ.nə.fɚ
	berrizen	ˈbɛ.rə.zən
	doppolate	ˈda.pə.ˌlet
	glistering	ˈglɪ.stɚ.rɪŋ
	skiticult	ˈskɪ.ɾə.ˌkʌlt
4	comisitate	kə.ˈmi.sə.ˌtet
	contramponist	kən.ˈtræm.pə.ˌnɪst
	emplifervent	ɛm.ˈplɪ.fɚ.ˌvɛnt
	fennerizer	ˌfɛ.nɚ.ˈraɪ.zɚ
	penneriful	pə.ˈnɛ.rə.fəl
5	altupatory	æl.ˈtu.pə.ˌtɔ.ri
	detratapillic	di.ˈtræ.ɾə.ˌpɪ.lək
	pristeractional	ˌprɪ.stɚ.ˈræk.ʃə.nəl
	versatrationist	ˈvɚ.sə.ˌtre.ʃə.nɪst
	voltularity	ˈval.t͡ʃə.ˌlɛ.rə.ti

Table 2

Bivariate correlations between the adults' and children's nonword repetition perceptual accuracy ratings and several speech perception tests and digit spans

	Perceptual accuracy ratings	
	CI kids	**NH adults**
LNT (easy words)	**.71** (<.001)	**.62** (.006)
LNT (hard words)	**.67** (<.001)	*.54* (.022)
Word intelligibility by picture Identification	**.69** (<.001)	*.57* (.013)
Forward digit span	**.77** (<.001)	*.56* (.016)
Backward digit span	.39 (.063)	.05 (.834)

Note. *P*-values are provided in parentheses. Correlations with a *p*-value of .01 are considered significant (Bonferroni correction = .05/5). Significant correlations are indicated in bold. Correlations that approach significance are indicated in italics.

Table 3

Results of one-way ANOVAs comparing the average percent correct performance of CI kids and NH adults along several linguistic measures

		Means		
		CI kids	**NH adults**	*p*-Value
Suprasegmentals	Number of syllables/vowels	64% (17)	74% (8)	.082
	Number of consonants	32% (18)	30% (12)	.736
	Number of segments	29% (19)	25% (13)	.441
Segmentals	Place of articulation	77% (12)	73% (4)	.302
	Sonorancy	83% (8)	86% (4)	.271
	Manner	75% (11)	74% (5)	.690
	Obstruent voicing	**77% (11)**	**83% (4)**	.048
	Vowel height	**71% (9)**	**63% (7)**	.004
	Vowel backness	67% (10)	67% (9)	.903
	Vowel rounding	**87% (5)**	**92% (4)**	.004

Note. Standard deviations are provided in parentheses. Significant differences are indicated in bold.

Table 4

Bivariate correlations between the adults' and children's nonword repetition accuracy ratings and several linguistic measures

		Perceptual accuracy ratings	
		CI kids	NH adults
Supra-segmentals	Number of syllables/vowels	**.75** (<.001)	.28 (.262)
	Number of consonants	**.66** (<.001)	−.08 (.741)
	Number of segments	**.70** (<.001)	.07 (.783)
	Correct stress placement	**.60** (.002)	.23 (.360)
Segmentals	Place of articulation	**.82** (<.001)	−.32 (.189)
	Sonorancy	**.80** (<.001)	.04 (.863)
	Manner	**.81** (<.001)	.22 (.382)
	Obstruent voicing	**.74** (<.001)	−.02 (.944)
	Vowel height	**.82** (<.001)	**.75** (<.001)
	Vowel backness	**.60** (.002)	.20 (.426)
	Vowel rounding	.30 (.152)	−.07 (.773)

Note. *P*-values are provided in parentheses. Correlations with a *p*-value of .0045 are considered significant (Bonferroni correction = .05/11). Significant correlations are indicated in bold.