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Imitation of nonwords by hearing impaired children with cochlear implants: suprasegmental analyses

ALLYSON K. CARTER, **CAITLIN M. DILLON**, and **DAVID B. PISONI**
Department of Psychology, Indiana University, Bloomington, IN 47405, USA

Abstract

In this study, we examined two prosodic characteristics of speech production in 8–10-year-old experienced cochlear implant (CI) users who completed a nonword repetition task. We looked at how often they correctly reproduced syllable number and primary stress location in their responses. Although only 5% of all nonword imitations were produced correctly without errors, 64% of the imitations contained the correct syllable number and 61% had the correct placement of primary stress. Moreover, these target prosodic properties were correctly preserved significantly more often for targets with fewer syllables and targets with primary stress on the initial syllable. Syllable and stress scores were significantly correlated with measures of speech perception, intelligibility, perceived accuracy, and working memory. These findings suggest that paediatric CI users encode the overall prosodic envelope of nonword patterns, despite the loss of more detailed segmental properties. This phonological knowledge is also reflected in other language and memory skills.

Keywords

cochlear implants; hearing impaired children; nonword repetition; prosody; phonological processing; speech production

Introduction

Research on the speech production skills of paediatric cochlear implant (CI) users has shown that while they perform more poorly than normal-hearing children on a wide range of tasks, their speech and language performance improves significantly after receiving a cochlear implant. Previous studies have largely centred on segmental and featural aspects of children's phonological systems. For example, in terms of segments, hearing-impaired children with CIs tend to produce vowels more accurately than consonants (Tye-Murray, Spencer, Bedia and Woodworth, 1996; Brown and McDowall, 1999; Serry and Blamey, 1999). In terms of features, it has generally been found that stops are produced more accurately than fricatives (Tobey, Geers and Brenner, 1994; Serry and Blamey, 1999) and labials are produced more accurately than non-labials (Tobey *et al*., 1994; Serry, Blamey and Grogan, 1997). Reports regarding the acquisition and accuracy of voicing are not as consistent. In one study, Tobey *et al*. (1994) found that during their first 3 years of implantation, children with CIs improved in their production of voiceless fricatives and both voiced and voiceless stops to a greater degree than voiced fricatives. More recently, Serry and Blamey (1999) reported that paediatric CI users preferred voiced consonants (i.e. they

Address correspondence to the authors at: Speech Research Laboratory, Department of Psychology, Indiana University, Bloomington, IN 47405, USA. allcarte@yahoo.com, cmdillon@indiana.edu, pisoni@indiana.edu.

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emerged earlier and the children acquired more of them) to voiceless consonants. It is possible that production of voicing, more than manner or place, is more dependent on other factors such as the surrounding segmental context or position within the syllable (see Dillon and Cleary, 2000).

Studies of suprasegmenta l aspects of speech production of children who use cochlear implants are fewer in number and primarily concern phonetic properties of speech. For example, Tobey *et al*. (1994) examined children's speech samples using the CID Phonetic Inventory (Moog, 1989), which consists of a set of syllable imitation tasks in which the child is given points based on the number of contexts in which he/she produces particular sounds or suprasegmenta l skills correctly. Specifically, in terms of suprasegmentals, Tobey *et al*. (1994) judged imitations for correctness of duration, intensity, pitch, breath control, and overall voice quality in strings of one to three syllables. Each of these suprasegmental characteristics was given a score based on the number of contexts in which the characteristic attribute was produced correctly. The results reported by Tobey *et al*. showed that children improved in their suprasegmental production accuracy post-implantatio n (see also Kirk and Hill-Brown, 1985; Tobey, Angelette, Murchison, Nicosia, Sprague, Staller, Brimacombe and Beiter, 1991; Tobey and Hasenstab, 1991; Tobey *et al*., 1994). Little is known, however, about the production of word-level suprasegmenta l characteristics, such as stress and syllable structure in these children.

Research with normal-hearing children has shown that an understanding of phonological development is incomplete without detailed investigation of the suprasegmental (i.e. prosodic) aspects of speech production. Between 1.5 and 4.0 years of age, young, normal-hearing children undergo a great deal of phonological development in their speech production skills. In the beginning, they tend to show poor segmental accuracy, often departing from the adult target model in substantial ways (Macken, 1980; Ingram, 1986; Menn and Matthei, 1992). However, it is often observed that they are able to reach adult-like word-level prosodic patterns prior to gaining accuracy on a segmental level (Menn, 1978; Gleitman and Wanner, 1982; Kirk and Hill-Brown, 1985; Stemberger, 1988; Echols, 1993; Peters and Menn, 1993).

One instance of children's accurate prosodic representations with incorrect segmental assignment is the case of segmental substitutions. For example, children's speech error patterns often consist of sound substitutions or sound exchange errors (e.g. 'pasghetti' for 'spaghetti') in which one or more segments are transposed or substituted for others. Another example of the dissociation between prosodic accuracy and segmental accuracy is children's use of filler syllables. Gleitman and Wanner (1982) discuss the early inclusion of stressless syllables in young children's speech, but note that they surface in an 'undifferentiated form' such as a schwa [ə] or other lax vowel. Examples include the production of 'report card' as [ə-poɹt kɑɹ d] (Gleitman and Wanner, 1982) and 'you put' as [ʊ-pʊt] (Peters and Menn, 1993). In each of these cases, the prosodic structure of the target has been correctly reproduced, while the segmental content has been replaced with a simpler sequence of sounds.

These types of utterances, in which the prosodic envelope is retained while segmental composition is simplified, are often treated in terms of different frames, or tiers, of the phonological system. Garrett (1980; 1982), for instance, suggests that sound exchange errors and sound substitution errors are a result of the segmental composition of lexical items being mapped onto an independently represented prosodic frame. Thus, segmental material is reflected distinctly from the prosody in the output.

Other more linguistically oriented models suggest a separation of phonological tiers (Goldsmith, 1976; Menn, 1978; Stemberger, 1988; Echols, 1993). The proposal for a nonlinear relation between phonological levels (feet, syllables, segments, segmental features, etc.) was formalized into Autosegmental Theory by Goldsmith (1976) and developed to explain tonal shift and floating tones (in which vowels and their accompanying tones do not always correspond one-to-one). Autosegmental theory was extended to account for the dissociation between segmental and suprasegmental aspects of children's utterances by Menn (1978), Stemberger (1988) and Echols (1993). According to this approach, children's syllable structure is located on one tier and their segmental content on another, allowing omission of segments but retention of the syllable structure. For example, the notion of separate segmental and syllabic tiers led Echols (1993) to propose that young children's underlying representations may be fully specified at the level of the syllable tier, but only partially specified at the level of the segmental tier, in order to explain the phenomena of segmental substitutions and filler syllables discussed above, as well as reduplications such as [bʌ-bʌ] for 'bunny', in which the initial syllable is repeated as the second syllable (Echols, 1993).

Investigation of the prosodic development of children with CIs may provide new insights into their phonological development and how their development compares to normal developmental processes. The current study was an attempt to further this long-term goal. We examined stress- and syllable-level imitation scores using utterances from a sample of experienced paediatric cochlear implant users. The utterances were obtained from a nonword repetition task. Typically, in a nonword repetition task the child is asked to listen to and immediately repeat back a phonologically permissible sound sequence that has no semantic content. The nonword repetition task is complex because it requires the child to successfully complete multiple auditory, cognitive, linguistic, and articulatory speech-motor processes, without relying on visual cues or previous experience with the stimulus tokens. This type of task taps the same processes that children use in learning new words. Spoken language, including vocabulary, emerges from a basic ability to encode, store, rehearse and reproduce a novel, serial order of sound patterns (Baddeley, Gathercole and Papagno, 1998; Gupta and MacWhinney, 1997). The nonword repetition task allows us to measure how well profoundly hearing-impaired children with CIs are able to acquire certain aspects of English prosodic structure and successfully access and use this prosodic knowledge in reproducing novel sound patterns that could be possible real words in English.

Nonword repetition tasks have been used successfully to study the speech production skills of children with various language-learning difficulties (e.g. Kamhi, Catts,Mauer, Apel and Gentry, 1988; Gathercole and Baddeley, 1990; Edwards and Lahey, 1998; Botting and Conti-Ramsden, 2001; Roodenrys and Stokes, 2001). Although normally developing children have been studied as comparison groups for the children with language disorders (Dollaghan and Campbell, 1998; Weismer, Tomblin, Zhang, Buckwalter, Chynoweth and Jones, 2000; Roodenrys and Stokes, 2001), the nonword repetition task has also been used with normally developing children in studies of vocabulary size, reading abilities, and phonological working memory (see Michas and Henry, 1994; Gathercole, 1995; Metsala, 1999; Adams and Gathercole, 2000, among others).

The version of the nonword repetition task we employed in this investigation was originally designed to study individual differences in phonological working memory in young normal-hearing children (Gathercole, Willis, Baddeley and Emslie, 1994; Gathercole and Baddeley, 1996). We first adopted this procedure in our lab to study individual differences in phonological working memory of normal-hearing children (Carlson, Cleary and Pisoni, 1998), and then extended its use to study the phonological working memory and speech of profoundly hearing impaired children with cochlear implants (Dillon and Cleary, 2000;

Cleary, Dillon and Pisoni, 2002). In the present study, we were specifically interested in using the children's nonword repetition responses to investigate the prosodic characteristics of their speech production skills, that is, to explore their ability to imitate and reproduce the correct number of syllables and stress patterns in nonsense words.

Method

Participants

Twenty-four children who participated in either the 1999 or 2000 Central Institute for the Deaf (CID) 'Cochlear Implants and Education of the Deaf ' project (see Geers, Nicholas, Tye-Murray, Uchanski, Brenner, Crosson, Davidson, Spehar, Torretta, Tobey, Sedey and Strube, 1999) were included in this study. Table 1 shows a summary of the demographic information about the children. The group consisted of 15 males and nine females and ranged in age from 8.2 to 9.9 years (M = 8.8 years). Nineteen children were congenitally deaf; the other five children were 3 years old or younger at the onset of deafness. All of the children had used their cochlear implant for at least 3.8 years (M = 5.4 years), and all used a Nucleus 22 implant with the SPEAK coding strategy at the time of testing. Both oral and total communication modes were represented in the group.

Stimulus materials

The stimuli used for this study were a subset of the 40 nonwords originally developed by Gathercole for the Children's Test of Nonword Repetition (CNRep; Gathercole *et al.*, 1994; Gathercole and Baddeley, 1996). The specific items were selected by eliminating the CNRep nonwords that showed the least amount of variance in scores obtained previously in our lab from a young group of normal-hearing children (Carlson *et al.*, 1998). We also eliminated nonwords that were essentially common real words attached in an unfamiliar manner to a standard affix. The remaining 20 nonword stimuli are shown in table 2. These items were balanced in terms of syllable number: there were five words each, at syllable lengths of two, three, four and five. Each of the target nonwords contained primary stress on either the first or second syllable.

Procedure

Because the nonwords used by Gathercole *et al.* (1994) were originally recorded by a British talker, they were re-recorded in our lab by an adult female talker of American English (Carlson *et al.*, 1998). The tokens were sampled at a rate of 22.05 kHz and stored as individual digital files. The stimuli were presented auditorily to the children via a desktop speaker (Cyber Acoustics MMS-1) at approximatel y 70 dB SPL. The children heard the list of nonwords in random order. They were forewarned that the stimuli would be unfamiliar 'funny' words and were told to imitate and reproduce the items to the best of their ability. Children's responses were recorded via a head-mounted microphone (Audio-Technica ATM75) onto digital audiotape (DAT) using a TEAC DA-P20 tape deck. The utterances on the DAT tapes were later digitised and segmented into individual sound files. Each imitation response was independently transcribed using broad phonemic transcription by the first and second authors. Intertranscriber agreement was 93%, and any disagreements about the transcriptions were resolved by a third transcriber.[1]

Scoring

Imitations were scored for accuracy in three ways. First, the responses were scored for overall phonological accuracy, where overall phonological accuracy meant the child's

[1]We would like to thank Cynthia Clopper for her assistance as the third transcriber.

response was correct in terms of the reproduction of all segmental and suprasegmenta l features of the nonword target pattern, that is, whether the child correctly reproduced all segmental features (place, manner, voice) as well as suprasegmental aspects (syllable number, primary stress placement). For example, an imitation of the nonword ‘bánnifer’ (/bǽ nəfɚ) would have been scored as correct only if the imitation was reproduced as [bǽnəfɚ]. An imitation such as [pǽ nəfɚ], [bænəf ɚ], or [bǽ nfɚ] would have been scored as incorrect. Second, the responses were scored specifically for syllable accuracy, that is, whether the child correctly reproduced the same number of syllables as were present in the target nonword, regardless of segmental content. Third, the responses were scored specifically for primary stress placement, that is, whether the child correctly reproduced the stress pattern that was present in the target. These latter two accuracy scores (the syllable score and the stress score), which assessed children’s ability to correctly reproduce the prosodic characteristics of the target nonword, will be referred to throughout the remainder of the paper as the two prosodic accuracy scores.

Predictions

We predicted that children with cochlear implants would perform poorly on the overall phonological score. This was based on previous findings indicating difficulties in correctly reproducing segments and features of isolated syllables and words (Geers and Tobey, 1992; Sehgal, Kirk, Svirsky, Ertmer and Osberger, 1998; Dillon and Cleary, 2000). However, as noted above, although young normal-hearing children may have some difficulty producing segmentally correct utterances, they are able to produce prosodic patterns that are faithful to the adult target (Menn, 1978; Gleitman and Wanner, 1982; Kirk and Hill-Brown, 1985; Stemberger, 1988; Echols, 1993; Peters and Menn, 1993). Because the profoundly hearing impaired children in our study had three or more years of experience using their cochlear implant, we expected that they would possess a phonological system sufficient for them to produce non-word imitations that resembled the overall prosodic shape of the nonword targets, regardless of their accuracy on a segmental level. Specifically, we predicted that children’s responses would be closer to the target with respect to the overall prosodic envelope than the detailed segmental pattern. Our expectation provided the motivation for the prosodic scoring system we developed.

In addition, we predicted that certain prosodic characteristics of the target patterns would affect children’s performance on the two prosodic accuracy scores in specific ways. First, based on previous findings that overall repetition accuracy scores are higher for imitations of shorter target patterns (e.g. Gathercole, 1995), we predicted that the children in our study would have higher prosodic accuracy scores for shorter nonwords than longer nonword patterns. Children should show higher syllable and stress scores in imitating a nonword like ‘ballop’ than a nonword such as ‘detratapillic’.

Second, both prosodic accuracy scores (syllable and stress) should be higher for targets with primary stress on the initial syllable. The motivation for this prediction was based on earlier accounts of normal-hearing children’s prosodic development (e.g. Demuth, 1995; Gerken, 1996), which suggest that young children produce words that are more prosodically faithful to the adult target if the target begins with a stressed syllable than an unstressed syllable. Thus, children should show higher prosodic scores for their imitation of the nonword ‘fénnerizer’ than for a nonword such as ‘emplífervent’.

Finally, both prosodic accuracy scores should be higher for nonword targets with less syllable complexity (fewer consonant clusters, e.g. ‘ballop’) than patterns with higher complexity (e.g. ‘prindle’). This prediction is based on the findings reported by Gathercole (1995), who showed that imitations of nonwords containing fewer consonant clusters tend to have greater overall accuracy. Therefore, we predicted that nonwords containing fewer consonant clusters would also display higher prosodic accuracy scores. A consonant cluster was scored in two separate ways for this analysis: whether it existed as a cluster across a syllable boundary, or more conservatively, existed as a cluster only within a syllable. For example, the nonword 'contramponist' would have three clusters if scored using the first method (/ntr/, /mp/, /st/), and would have two clusters if scored using the second method (/tr/, /st/).

An additional set of predictions was developed to assess whether individual differences in the component processes of speech perception and production, including working memory, would also be reflected in the children's nonword repetition performance. Success in a nonword imitation task is contingent upon successful performance in encoding, storage in short-term memory, and production of a response. Based on recent findings demonstrating that nonword imitation ability correlates with performance on other speech- and language-relate d behavioural tests (Cleary *et al.*, 2002), we predicted that higher prosodic accuracy scores (syllable and stress) would correlate with better performance on a range of speech perception and word recognition tests that were also collected from the 24 children during their participation in the CID summer programs. These behavioural tests included measures of spoken word recognition, language comprehension, speech intelligibility, speaking rate, and working memory span.

In addition, we also predicted that the syllable and stress scores obtained from the nonword repetition task would be related to a measure of overall perceived accuracy of the children's imitations that was obtained as part of a separate study with 240 native speakers of English who had no previous experience with deaf speech. In this study, ten listeners rated the imitations of each of the 24 children. For each rating, the listeners heard a 'model' target utterance followed by a child's imitation of that model, and gave a goodness rating of that child's imitation using a scale of '1' to '7', in which '1' represented a poor imitation of the model and '7' represented a perfectly accurate imitation. The listeners were only told to rate the child's imitation of the model utterance. They were not given any guidelines as to what to base their goodness ratings on, apart from being asked to ignore differences in pitch between the adult model's voice and the child's voice. We predicted that adults would judge children's imitations of the model target to be more accurate overall when the children's nonword responses had higher prosodic accuracy scores, regardless of the segmental accuracy of the children's utterances.

Results

Accuracy scores

As predicted, the children performed quite poorly on the overall phonological accuracy score. Only 5% of their nonword imitations were produced correctly without any errors in either the segmental or suprasegmenta l domain. Children's individual performance ranged from 0% to 40% correct. However, further examination of the children's responses revealed that this overall score was based primarily on *segmental* errors. Importantly, children correctly reproduced target-like prosodic characteristics much more frequently than target-like segmental properties when the responses were scored for syllable number and stress placement. 48% of the nonword imitations were reproduced with both the correct syllable number and the correct primary stress placement. That is, almost half of the children's nonword repetitions were correct when these two prosodic dimensions were used to score the responses. (Children's individual performance ranged from 25% to 85% correct on these two dimensions.) Moreover, there were some imitations that were correct in terms of only one of the two prosodic characteristics. Of the total number of children's imitations, 64% of the responses were reproduced with the correct number of syllables as the target nonword, and 61% of the responses were reproduced with the correct placement of primary stress. The individual performance for each prosodic score was 35% to 95% and 30% to 85%, respectively. Thus, analysis of the scores using three accuracy measures indicate that these profoundly hearing impaired children are able to reproduce the suprasegmenta l features of the target pattern much better than the segmental components of the nonword patterns.

Prosodic analyses

Number of syllables in the target—Correlations were calculated between the number of syllables in the target pattern and the two prosodic accuracy scores described above (syllable score and stress score) for each of the 20 nonwords (averaged across children). The analysis revealed that the number of syllables in the target pattern was negatively correlated with syllable scores ($r = -0.25$, $p<0.01$). Likewise, the number of syllables in the target was also negatively correlated with stress scores ($r = -0.30$, $p<0.01$). Both correlations confirm our first prediction regarding the reproduction of the prosodic characteristics of the target pattern and indicate that children show more accurate performance on imitation of shorter target nonwords. Specifically, children preserved syllable number and primary stress location in their imitations more often for shorter nonword target patterns than for longer nonword patterns. The more syllables that were present in the target nonword, the less likely the child was to reproduce the correct number of syllables and the correct primary stress pattern of the target nonword.

In order to investigate the types of syllable errors that children made, their nonword imitations were broken down into the per cent of nonword imitations that contained no errors, the per cent of total imitations that contained syllable deletion errors, and the per cent of total imitations that contained syllable addition errors. The results are shown in figure 1. For targets with two, three, or four syllables, the majority of the imitations contained the correct number of syllables. For targets with five syllables, there were many fewer imitations that contained the correct number of syllables than imitations with syllable additions or deletions. Overall, when children failed to reproduce the correct number of syllables, they were more likely to delete syllables (70% of errors) than add syllables (30% of errors), except in the case of target nonwords with two syllables, for which only syllable additions were observed. Moreover, we also found that when a syllable error occurred, the response consisted of the addition or deletion of a single syllable (85% of errors). Only 14% of the syllable errors consisted of the addition or deletion of two syllables, and in one single case, the syllable error consisted of the addition of three syllables. Thus, shorter target nonwords resulted in fewer errors in syllable number. However, when children did produce errors, they tended to omit syllables more often than add syllables.

Stress placement in the target: To assess our second prediction that prosodic accuracy scores would be higher for stress-initial targets than non-stress-initia l targets, we carried out two comparisons. The first was a comparison of the syllable scores for stress-initial targets and non-stress-initial targets. The second was a comparison of the stress scores for stress-initial targets and non-stress-initia l targets. Figure 2 shows a summary of the results of these analyses. A significant difference in syllable scores between targets with primary stress on the initial syllable and targets with primary stress on the non-initial syllable was found, $t(478)=2.7$, $p<0.01$. A significant difference was also found for stress scores, $t(478)=2.3$, $p<0.05$. These two results show that children's imitations retained prosodic properties of targets with initial stress more often than targets with non-initial stress. If the target pattern had initial stress, the corresponding nonword imitations were more likely to contain the correct number of syllables and the correct location of primary stress.

Syllable complexity of the target: Our third prediction, that prosodic accuracy scores would be higher for targets containing fewer clusters, was not confirmed in our analyses.

Specifically, neither the correlation between the number of consonant clusters in a target and syllable scores, nor the correlation between the number of clusters and stress scores, reached significance, for either complexity scoring method (within-syllable or across syllable boundaries). These findings indicate that children were able to reproduce prosodic characteristics equally well for nonwords with more consonant clusters than with fewer clusters, and that target syllable complexity did not affect children's ability to reproduce prosodic structure in these patterns. This may be a reflection in the nonword patterns of a dissociation between syllable-level and segmental-level representations. The presence of consonant clusters may only affect children's performance on imitating the segmental components of those clusters, not children's performance on imitating and reproducing the more global overall prosodic shape of the syllables containing them.

Correlations with other measures of speech and language performance

We were also interested in the extent to which the children's prosodic scores on the nonword imitation task would reflect the contribution of the underlying component processes involved in speech perception, production and working memory. Although the nonword repetition task used in the present study may appear to be relatively simple at first glance, successful imitation of a nonword pattern involves the contribution of several different component processes: auditory and phonological encoding, short-term storage of the target item in working memory, and articulatory planning and speech production at the time of output. In order to be able to imitate and quickly reproduce a nonword pattern on the fly, a child needs to be able to perform well in each of these component processes.

The 24 children in this study also participated in a range of other tasks that were designed to measure their performance on these component processes as part of a larger study at CID (Geers *et al.*, 1999). These scores provided an unusual opportunity to assess the contribution of several of these component processes to performance on the nonword repetition task. To accomplish this, correlations between the children's prosodic accuracy scores on the one hand, and several speech, language, and working memory measures on the other hand, were examined. Table 3 provides a summary of these correlations.

Correlations with word recognition measures: Three measures of spoken word recognition performance were available from CID: the Lexical Neighborhood Test (LNT), Bamford-Kowal-Bench Sentence List Test (BKB) and Word Intelligibility by Picture Identification test (WIPI). The LNT (Kirk, Pisoni and Osberger, 1995) is an open-set test of spoken word identification consisting of 100 monosyllabic words divided into four lists of 25 words each. Two of the lists, the LNT Easy lists, contain words that are 'lexically easy' (i.e. phonetically similar to very few other words) and two of the lists, the LNT Hard lists, contain words that are 'lexically hard' (i.e. phonetically confusable with many other words). Each child was tested on one LNT Easy word list and one LNT Hard word list. Separate percent-words-correct scores were obtained for each list. Scores were also available from the Multisyllabic Lexical Neighborhood Test (MLNT), which is analogous to the LNT, but uses multisyllabic words of two or three syllables. The BKB is an open-set task involving spoken repetition of a target sentence (Bench, Kowal and Bamford, 1979). The WIPI is a closed-set measure of spoken word identification involving a six-alternative pointing response (Ross and Lerman, 1979). The LNT, BKB, and WIPI were all administered using recorded auditory-onl y presentation.

Scores on LNT Easy words were positively correlated with the stress scores and syllable scores, but only the correlation between LNT Easy words and stress scores reached significance (r=+0.57, p<0.01). Likewise, scores on the LNT Hard words were positively correlated with the stress scores and syllable scores, but only the correlation between the

LNT Hard words and stress scores reached significance (r= +0.57, p<0.01). Scores on the MLNT were significantly correlated with both the syllable scores and the stress scores (r= +0.42, p<0.05, r=+0.41, p<0.05, respectively). Likewise, BKB scores were significantly correlated with both of the prosodic accuracy scores (r's=+0.48, p<0.05). Lastly, the correlation between the children's WIPI scores and their syllable scores was significant (r= +0.46, p<0.05), although the correlation between the WIPI scores and their stress scores did not reach significance.

Taken together, these results show that children's ability to imitate the stress pattern and correctly reproduce the number of syllables in a novel nonsense word is related to their scores on several independent word recognition tasks. The findings suggest that the individual differences among the children in terms of their ability to imitate novel patterns is related to differences in their ability to recognize real words, both in open and closed set tasks as well as sentence contexts. The results suggest that the same underlying linguistic processes are being used in each of these component tasks to construct phonological representations.

Correlation with a measure of language comprehension: The battery of tests administered by researchers at CID also included the Test of Auditory Comprehension of Language Revised (TACL-R), a language comprehension measure that was designed to assess children's receptive vocabulary, morphology, and syntax (Carrow-Woolfolk, 1985). In the CID study, the TACL-R was administered using total communication to all children, and an age-equivalency score was obtained for each child. The TACL-R age-equivalent scores were positively correlated with both the children's syllable scores (r=+0.68, p<0.01) and their stress scores (r=+0.30, p<0.05). These results indicate that better performance on the nonword repetition task was associated with higher language comprehension scores in terms of receptive vocabulary, morphology, and syntax. That is, the children's ability to decompose, reassemble and reproduce those specific phonological properties in their own speech production outputs is related to their ability to grasp regularities and patterns in their language environment.

Correlations with speech intelligibility: A measure of speech intelligibility was also obtained from each child as part of the larger study at CID using the McGarr Sentence Intelligibility Test (McGarr, 1983).[2] This test involves eliciting sentences three, five or seven syllables in length. Each child was provided with spoken and/or signed models of each test sentence as well as the printed text and was asked to repeat these sentences aloud as intelligibly as possible. The children's utterances were recorded and later played back to groups of adult naïve listeners who were asked to transcribe the utterances using standard orthography. This procedure provided an objective measure of speech intelligibility (McGarr, 1983).

Significant correlations were found between prosodic accuracy and speech intelligibility for both the syllable scores (r=+0.50, p<0.05) and the stress scores (r=+0.60, p<0.05), indicating that the children who produced more intelligible speech on the McGarr task also tended to correctly reproduce syllable number and primary stress location more often in their nonword imitations.

Correlations with speaking rate: Each child's productions of the McGarr sentences were also submitted to an acoustic analysis. One portion of the acoustic analysis consisted of measuring the duration of each seven-syllable sentence, and calculating an average sentence

[2]The McGarr speech intelligibility and duration measures were provided by Dr. Emily Tobey and her colleagues at Callier Advanced Hearing Research Center at the University of Texas, Dallas.

duration for each child. Prosodic accuracy was negatively correlated with sentence duration. Specifically, mean sentence duration on the seven-syllable McGarr sentences was negatively correlated with syllable scores and stress scores ($r = -0.55$, $p<0.01$, $r = -0.52$, $p<0.01$, respectively). This result was not unexpected, as sentence duration is inversely related to speaking rate. The correlation between the prosodic accuracy scores on nonword repetition and speaking rate is consistent with previous findings showing that children who have slower speaking rates perform more poorly on speech production tasks (Cleary, Pisoni, Kirk, Geers and Tobey, 2000; Pisoni and Cleary, in press). This finding suggests that limitations in phonological processing, coding, and rehearsal may be an important underlying factor leading to both slower speaking rate and poorer performance on a variety of speech and language measures.

Correlations with short-term memory: Measures of the children's forward and backward digit spans were also obtained for each child using the WISC Digit Span Supplementary Verbal sub-test of the Wechsler Intelligence Scale for Children, Third Edition (WISC-III) (Wechsler, 1991). The 'digits forward' task is considered a reliable measure of the encoding, rehearsal, and storage processes involved in short-term memory (Rosen and Engle, 1997; Pisoni and Geers, 2000; Engle, 2002). In contrast, the 'digits backward' task is thought to involve different and more complex processing abilities than the digits forward task, and is frequently used as a measure of 'controlled' cognitive processing, or 'executive function' because subjects have to consciously carry out operations or procedures that make demands on a limited capacity processing system (see Rosen and Engle, 1997; Engle, 2002).

For the digits forward task, a child listens to and repeats lists of digits as spoken live-voice by the experimenter at a rate of approximatel y one digit per second (WISC-III Manual, Wechsler, 1991). Two lists are administered at each list length, beginning with two digits. The list length is increased one digit at a time until the child fails to correctly repeat both lists administered at a given length. The child receives points for correct repetition of each list, with no partial credit allowed. The digits backward task is similar to the digits forward task. The only difference in procedure is that the child is asked to repeat the digits in reverse order from the order in which they were originally presented.

The children's WISC forward digit span scores were found to be positively correlated with both the syllable scores ($r=+0.47$, $p<0.05$) and the stress scores ($r=+0.57$, $p<0.01$). Longer forward digit spans were associated with higher scores on both of the prosodic measures of nonword repetition performance. The correlations between the children's WISC backward digit span scores and their prosodic scores were not significant (syllable scores, $r=+0.14$; stress scores, $r=+0.18$), indicating that backward digit span, unlike forward digit span, is unrelated to the ability to imitate prosodic characteristics of nonwords. This pattern is consistent with previous findings suggesting that forward and backward digit spans measure fundamentally different cognitive processes (see Rosen and Engle, 1997; Engle, 2002).

Correlations with perceptual ratings: The nonword utterances produced by the children were also subjected to a perceptual analysis to obtain objective ratings of speech intelligibility and goodness judgements (for preliminary findings from a related study, see also Cleary *et al.*, 2002). As described above, a perceptual measure of goodness was gathered from 240 adult listeners who heard model target utterances followed by the children's imitation responses and rated them for repetition accuracy on a scale of '1' to '7'. The goodness ratings gathered from that study were averaged across listeners and test items to produce an average composite perceptual rating for each child. We then calculated correlations between these average perceptual ratings and our two prosodic accuracy scores (syllable score and stress score).

The perceptual ratings of the children’s imitations were positively correlated with both of the prosodic scores (syllable score, r=+0.67, p<0.01 and stress score, r=+0.69, p<0.01) indicating that successful reproduction of prosody, that is, imitation of the correct number of syllables and the correct stress pattern of an utterance, is an important underlying phonological factor that influences adult listeners’ perception of CI children’s speech production accuracy in imitating non-word patterns (see also Cleary *et al.*, 2002). These findings suggest that the children’s ability to encode and reproduce the prosodic characteristics of a nonword pattern is linked to listeners’ judgements of how well the speech production of profoundly hearing impaired children with CIs resembles that of a normal hearing adult.

Discussion and conclusions

In this investigation of the prosodic aspects of paediatric cochlear implant users’ nonword imitation skills, we observed a number of related findings that provide some new insights into the underlying phonological skills that profoundly hearing impaired children acquire after cochlear implantation. The children with CIs produced very few responses that matched the nonword target patterns exactly when their utterances were scored in terms of both segmental and prosodic attributes. Only 5% of their nonword imitations were correct by this strict scoring procedure. The children’s performance was markedly lower than the typical performance of their normal-hearing peers who consistently perform near ceiling on the same non-word repetition task (Gathercole *et al.*, 1994; see also Carlson *et al.*, 1998). However, in light of previous studies showing poorer segmental accuracy in the speech production of children with cochlear implants, this finding was not unexpected. Although these children had difficulty reproducing the segmental content of these nonword patterns, they displayed much greater skill in imitating suprasegmenta l properties of the nonwords. As expected, they were able to reproduce the correct number of syllables in the target pattern as well as the primary stress location on almost two-thirds of their nonword imitations. They also achieved significantly higher scores for targets with fewer syllables and with initial stress than for targets with more syllables and non-initial stress. Moreover, about half of the nonword responses contained *both* the correct syllable number and primary stress location, suggesting a knowledge and sensitivity to selected aspects of phonological structure in these nonword patterns.

The children’s performance on the nonword repetition task suggests that they were able to acquire several important aspects of English prosodic structure and successfully access and use this prosodic knowledge in their utterances. The different speech production skills of these children at the suprasegmental and segmental levels lends further support for the proposal of a theoretical framework consisting of separate phonological tiers. It may be the case that during the process of encoding new words profoundly hearing impaired children with CIs are more likely to correctly encode elements on the suprasegmenta l tier than the segmental tier, which requires encoding of much finer phonetic detail. Another possibility is that once the novel sound patterns are encoded, their output representations become more robustly specified at the level of the syllable than the segment. Further studies are necessary in order to make a particular claim as to where in the perception—production system these separate levels exist, but the present results clearly demonstrate a strong and reliable dissociation between segmental and suprasegmental levels in this task.

When children made errors on syllable number, their nonword repetition errors revealed a pattern that was similar to normal-hearing children. That is, normal-hearing children tend to delete syllables in their utterances more often than add them (Demuth, 1995). Taken together with the children’s higher prosodic scores for targets with fewer syllables, this finding may reflect the additional load on short-term phonological memory capacity induced by a greater number of syllables in a temporal or segmental pattern, especially a nonword pattern that has no lexical representation. Further support for this conclusion was provided by the positive correlations observed between the children's prosodic scores and their forward digit spans. Longer digit spans were associated with higher stress and syllable scores, suggesting close links between processing capacity and encoding phonological structure (Gathercole, 1995).

The finding that prosodic performance was better for nonword targets with initial stress than non-initial stress is also consistent with previous findings regarding the English stress system in utterances of young normal-hearing children who are in the process of acquiring language (Demuth, 1996; Gerken, 1996). The majority of English content words have primary stress on the initial syllable (Cutler and Carter, 1987), thus the input that children perceive most often contains stress-initial forms. It is not surprising then that, when given a novel form that may tax the information processing system, children reproduce a stress pattern that is consistent with their prior experience and exposure to sound patterns in their ambient language.

The nonword imitations which erroneously contained a stress-initial syllable, whether it was formed by an omission of a stressless initial syllable, or by a stress-shift, are also similar to normal-hearing children's errors. These patterns are less faithful to the adult target but are more prosodically optimal, with regard to English stress (Demuth, 1995; 1996; Gerken, 1996). One account of this phenomenon, known as Optimality Theory (OT; Prince and Smolensky, 1993), assumes the existence of a set of ranked violable constraints in the child's phonological grammar, which yields his/her output forms. These constraints, while identical in type to those in an adult's grammar, are ranked in a different order for young children, and only over time do they adapt to reflect adult grammars (Demuth, 1995; Gerken, 1996; Pater and Paradis, 1996). At a young age, constraints that reflect common prosodic properties of the English language are ranked higher than constraints of segmental faithfulness to the adult target. This early ordering of constraints thus yields more prosodically optimal word forms in children, at the expense of segmental accuracy. Such an account may be useful for the productions in the current study, although an in-depth discussion of constraints and OT is outside the purview of the present report.

The finding that the complexity of consonant clusters did not affect syllable number or stress accuracy scores is inconsistent with the earlier findings of Gathercole (1995), who reported an effect of consonant clusters on segmental accuracy. However, the present results can be explained by considering differences in the perception of segmental and suprasegmenta l properties of these nonword patterns: the presence of consonant clusters may only affect how well children can perceive and imitate the constituents of those clusters, not how well children can imitate the prosodic shape of the syllables containing them. It is well-known that hearing impaired children with CIs have difficulty perceiving fine phonetic distinctions such as place of articulation and voicing in stop consonants (Miyamoto, Kirk, Todd, Robbins and Osberger, 1995; Chin and Finnegan, 1998).

The correlations between the prosodic scores, and word recognition as well as the language comprehension scores suggest that the underlying linguistic processes that enable a child with a cochlear implant to accurately imitate the prosodic structure of novel patterns are related to his/her real-word recognition and comprehension skills. The presence of correlations between the children's prosodic scores and both the McGarr intelligibility measure and the goodness ratings by naïve adults indicate that preservation of prosody may be an important factor affecting adult listeners' perception of hearing impaired children's speech intelligibility. Similar correlations have been found in previous studies of hearing-impaired children measuring the relationship between speech intelligibility and the correct production of various suprasegmental features: stress placement, number of syllables, syllable groupings, and breath control (Hudgins and Numbers, 1941); stress, intonation and pitch (McGarr and Osberger, 1978); timing and intonation (Gold, 1980); pitch, intensity, and timing (Stoker and Lape, 1980). The correlations between our prosodic accuracy scores and the speaking rate measure are also consistent with previous findings showing that children with faster speaking rates perform better on a range of speech production tasks. Specifically, Pisoni and Cleary (in press) found a positive correlation between speaking rate (as measured by McGarr durations) and WIPI scores, LNT scores, BKB scores, and digit spans for 88 children who participated in the 1998 and 1999 summer programs at CID. Our results showing that children who had higher prosodic accuracy scores in the nonword repetition task also had higher word recognition scores, higher language comprehension scores, higher speaking rates and longer digit spans extend and refine the earlier findings of Pisoni and Cleary (in press). Together, these results suggest that a common underlying source of variance related to phonological processing skills is operative and that these fundamental skills influence children's performance not only on prosodic accuracy of nonword imitations but also on all of these other behavioural tasks.

Taken together, the results of this study demonstrate that the nonword repetition task and the component information processing and linguistic processing that it taps can provide new insights into the speech production skills and underlying linguistic abilities of profoundly hearing impaired children following cochlear implantation. The present findings indicate that experienced paediatric CI users are able to encode the prosodic structure of nonwords that conform to English phonological rules. They are able to reproduce syllable and stress information with relatively high levels of accuracy, despite their difficulty in perceiving and reproducing the fine segmental properties of these novel patterns. The present findings also demonstrate a close correspondence between the children's speech perception, working memory and speech production skills. With further analytic studies of this type using novel information processing tasks, we hope to better understand the relations between perceptual, cognitive, and linguistic skills used in the processing of spoken language, and describe how these fundamental information processing skills develop and change over time in profoundly hearing impaired children following cochlear implantation.

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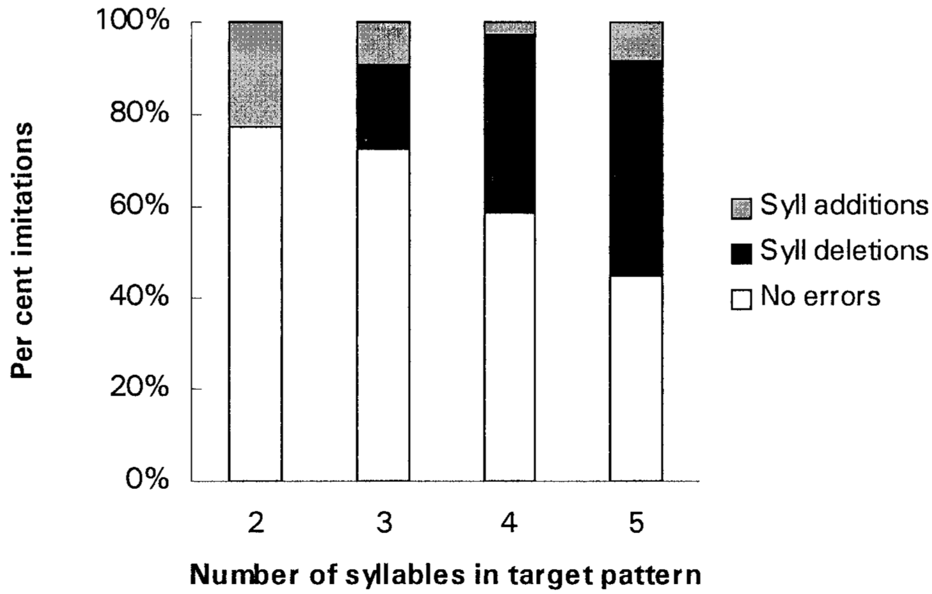

Figure 1.

Percent of nonword imitation responses containing correct syllable count, syllable deletions, or syllable additions.

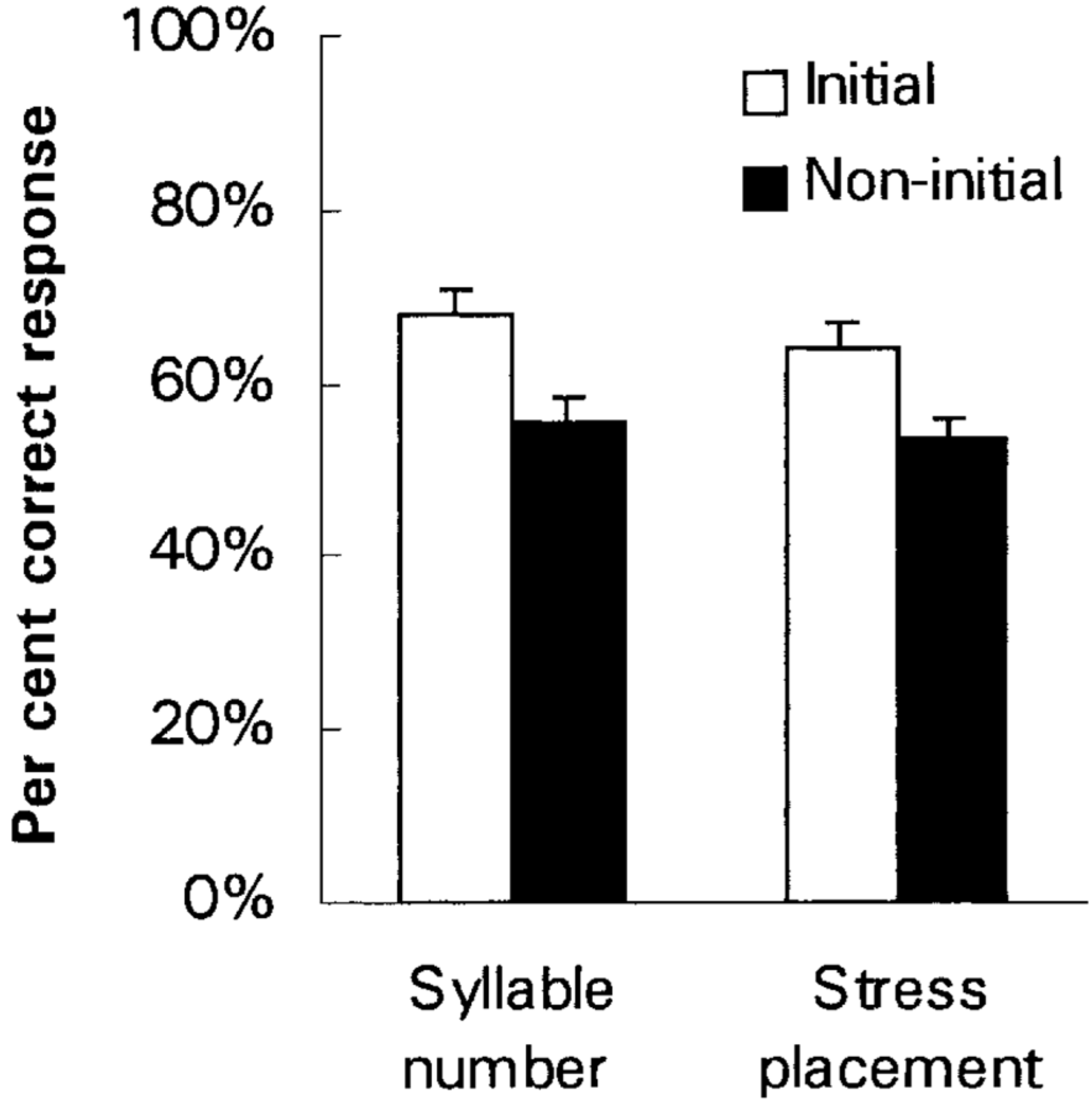

Figure 2.
Mean percent correct as a function of target stress placement (initial syllable or non-initial syllable) and type of accuracy score (syllable or stress). Error bars show standard error.

Table 1

Demographic information for the 24 children (ages and durations in years)

Child ID #	Gender	Age	Age at onset of deafness	Duration of deafness	Duration of CI use
1	M	9.1	0	3.3	5.8
2	M	8.7	0	3.9	4.8
3	M	8.2	0	3.3	5.0
4	M	9.5	0	4.7	4.8
5	F	8.3	0	2.1	6.1
6	M	8.3	0	2.1	6.1
7	F	9.4	3.0	2.0	4.3
8	M	8.2	1.5	0.7	6.0
9	M	8.7	0	4.0	4.8
10	M	9.9	0	4.5	5.4
11	M	9.0	0	3.4	5.6
12	F	8.7	0	2.2	6.5
13	M	9.5	0	2.9	6.6
14	F	8.5	0	3.2	5.3
15	F	8.3	0	2.4	5.9
16	F	8.3	0	3.0	5.4
17	M	8.4	0	3.9	4.5
18	M	8.2	0.8	2.7	4.7
19	M	8.2	2.0	1.7	4.5
20	M	9.0	1.5	1.6	6.0
21	M	9.0	0	2.6	6.4
22	F	8.4	0	3.3	5.1
23	F	9.1	0	5.4	3.8
24	F	9.7	0	3.2	6.5
Means:		8.8	0.4	3.0	5.4

Table 2

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

Number of syllables	Target nonword orthography	Target nonword transcription
	ballop	’bæ.ləp
	prindle	’prɪn. dl̩
2	rubid	’r uˌbɪd
	sladding	’slæ.diŋ
	taffist	’tæ.flɪst
	bannifer	’bæ.n əˌfɚ
	berrizen	’bɛ.r əˌzɪn
3	doppolate	ˈdɑ.pəˌleɪt
	glistering	’glɪ.st#x0025A;.i#x0014B;
	skiticult	’skɪ.#x0027E; əˌ kʌlt
	comisitate	kəˈmi.səˌteɪt
	contramponist	kən’træm.p əˌ nɪst
4	emplifervent	Em’plɪ.fɚ vɛnt
	fennerizer	ˈfɛ.nɚˌaɪ.zɚ
	penneriful	pə’n ɛ.r əˌ fʌl
	altupatory	æl’tu.p əˌ tɔ.ri
	detratapillic	di’træ. ɾ əˌ pɪ.lɪk
5	pristeractional	’prɪ.st ɚˌ æk. ʃə.n l̩
	versatrationist	ʻvɚ.səˌtreɪ.ʃəˌnɪst
	voltularity	vɑl.tʃʊ lɛ.r əˌti

Table 3

The correlation r-values between language measures, working memory measures, and perceptual ratings scores, and each of the prosodic accuracy scores

Measure		Syllable score	Stress score
Word recognition	LNT Easy	+0.38	+0.57**
	LNT Hard	+0.38	+0.57**
	MLNT	+0.42*	+0.41*
	BKB	+0.48*	+0.48*
	WIPI	+0.46*	+0.36
Comprehension	TACL	+0.68**	+0.30*
Speech intelligibility	McGarr sentences	+0.50*	+0.60*
Sentence duration (inverse of speaking rate)	McGarr 7-syllable sentences	−0.55*	−0.52**
Short-term memory	WISC (Forward Digit Span)	+0.47*	+0.57**
Executive function	WISC (Backward Digit Span)	+0.14	+0.18
Perceived accuracy (goodness)	Perceptual ratings	+0.67**	+0.69**

* $p<0.05$,

** $p<0.01$.