NONWORD REPETITION ACCURACY OF CHILDREN WITH BILATERAL COCHLEAR IMPLANTS: EFFECTS OF AGE AND VOCABULARY SIZE

by

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Abstract

Within the population of children with profound hearing loss, children who use cochlear implants (CIs) have much better speech and language development than children who use hearing aids. However, CI users still perform more poorly than children with normal hearing (NH). Few studies have examined nonword repetition accuracy in children with CIs, although this measure is important because of its relationship to vocabulary development. This study analyzes initial consonant accuracy in real words and nonwords for 18 children with bilateral CIs between age 4;0 and 9;2 and for two comparison groups of children with NH. The accuracy of word-initial singletons /t/, /d/, /k/, /g/ and word-initial clusters /tw/, /kw/, and /kj/ in real words and nonwords were examined. Results indicate that consonant production in children with CIs is comparable to their hearing age peers with NH in many respects. However, consonant accuracy in real words and nonwords was not correlated with vocabulary size in children with CIs, although this correlation was observed for children with NH. These results will be discussed with respect to word learning in children with CIs.

Introduction

Typically developing children acquire speech and language skills at a rapid pace. By the time that children are 0;7 (years; months), they are producing canonical babbling (babbling with speech-like consonant and vowel sequences) (Oller, Eilers, Bull, & Carney, 1985). Speech sounds continue to develop quickly. Robb and Bleile (1994) reported that, on average, children who are 1;0 have a repertoire of five consonants in the syllable-initial position, while at 2;1, fifteen syllable-initial consonants is average. Typically developing children have systematic error patterns, often termed "phonological processes," such as "stopping" and "velar fronting" that simplify their speech output, but by age 5;0, these systematic error patterns are no longer observed (Ingram, 1976). By age 4;0, speech is 93 percent intelligible in conversational speech with unfamiliar listeners (Gordon-Brannan, 1994).

Vocabulary also grows swiftly in typically developing children. At 1;0, mean receptive vocabulary size exceeds 80 words. Expressive vocabulary takes off rapidly from an average of less than 10 words at 1;0 to 40 words at 1;4, and 573 words at age 2;6 (Fenson et al., 1994). The expressive vocabularies of kindergarten-age children range between 3000 and 5000 words (Paul, 2007). Syntax is another area of rapid language development. While typically developing children use two-word utterances at age 2;0, the use of auxiliary verbs and other aspects of inflectional morphology such as past tense and regular third person is mastered by age 5;0 (Brown, 1973).

However, the speech and language development of children with hearing impairment has a much slower trajectory. Delays in each of the areas mentioned above have been observed. Children with hearing impairment do not produce canonical babbling at the same age as typically developing children. (Clement & Koopmans-van Beinum, 1995; Oller et al., 1985). Phonological development is also more generally delayed. Since the typical intensity level of spoken language falls between 40 and 60 dB, children with hearing losses in excess of 60 dB have difficulty developing the phonological and phonetic skills required for intelligible speech (Fletcher & Miller, 2005). Vowels are often distorted and centralized (Dagenais & Critz-Crosby, 1992). Children with hearing impairment also use phonological processes later into childhood than typically developing children. Abraham, (1989) found that the speech of children with hearing impairment between ages 5;11 and 15;11 continued to contain the following systematic error patterns: cluster reduction, liquid simplification, deaffrication, and final consonant deletion. Prosody can also be affected with poor phrasing, unusual stress patterns and atypical resonance being common characteristics of the speech of children with hearing impairment (Paul, 2007).

Language development is also affected by hearing loss. Gilbertson and Kamhi (1995) studied receptive vocabulary measures for 20 school-aged children with mild-moderate hearing impairment. They found that the top ten highest performers scored in the low average range on the *Peabody Picture Vocabulary Test-R.* The lowest 10 performers among this group scored significantly below average. Syntactic deficits are also common among children with hearing impairment. Elfenbein, Hardin-Jones, and Davis (1994) analyzed language samples and found that children between ages 5;0 and 18;0 with mild to severe hearing loss produced many more syntactic errors than their typically developing peers, with errors on bound morphemes and complex sentences being the most common.

The use of cochlear implants promises to dramatically improve speech and language development in children with hearing impairment, although this is a relatively new phenomenon. It was only in 1990 that the Food and Drug Administration approved the use of cochlear implants in children (Balkany, Hodges, Miyamoto, Gibbin, & Odabasi, 2001) and it was not until 2000 that the FDA approved implantation at age 1;0. Early studies on the efficacy of cochlear implants compared the speech and language development of children with cochlear implants (CI users) to that of their peers with hearing impairment who use hearing aids (HA users). In all respects, the performance of CI users was superior to that of HA users. In a study comparing the language development of children with CIs to expected development rates for children with HAs, Svirsky, Robbins, Kirk, Pisoni, and Miyamoto (2000) found that children with CIs outpace their HA peers in language development after implantation and their mean rate of language development after implantation is close to what is expected of children with normal hearing. Speech production has been found to be superior in CI users when compared to HA users. For example, Tobey, Geers, and Brenner (1994) found that children who use CIs imitate vowels and consonants better than HA users with similar levels of hearing loss. Syntactic development is also better in children with CIs relative to children with HAs. Tomblin and colleagues (Tomblin, Spencer, Flock, Tyler, & Gantz, 1999) observed that children with cochlear implants scored more than one standard deviation higher than their peers who use hearing aids on the Index of Productive Syntax. Children with CIs also have better morphological development than children with HAs. In a study by Spencer, Tye-Murray, and Tomblin, (1998) children with hearing impairment were split into two groups; one group consisted of experienced

CI users and the other consisted of HA users. Both groups used sign language and spoken English simultaneously. Results indicate that CI users produce significantly more inflectional morphemes in spoken English than HA users do. Children with CIs also have better receptive language than children with HAs. Geers and Moog (1994) found that children with three years of CI experience performed better on the receptive language measure, *Rhode Island Test of Language Structure*, than HA users.

While children with CIs consistently out-perform their peers with hearing aids, their speech and language skills are not at the level of their normally hearing peers (NH children). In a study of children ages 8;0 to 9;0 who received CIs by the age of 5;0, Geers, Nicholas, and Sedey (2003) found that only slightly more than 50 percent of CI users with average intelligence exhibited English language skills such as verbal reasoning, narrative ability, utterance length, and lexical diversity that were comparable to children with NH of the same age. Houston, Carter, Pisoni, Kirk, and Ying (2002), compared children ages 2;0 to 5;0 with CIs to age-matched children with NH on a measure of word-learning using familiar and unfamiliar proper nouns. They found that children with CIs performed significantly worse than their NH age-matched peers. In particular, children with CIs, but not their age peers with NH, performed more poorly on tasks requiring the children to use lexically unfamiliar words (per parent questionnaire).

Age of implant is an important factor that influences the benefits that a child receives from cochlear implantation. Studies by Tomblin, Barker, Spencer, and Zhang, (2005) and Fryauf-Bertschy, Tyler, Kelsay, Gantz, and Woodworth (1997) have shown that speech perception, speech production, and language outcomes are better when children are implanted earlier in life. In a long-term study of 34 prelingually deafened CI users, Fryauf-Bertschy et al. (1997) found that children implanted before the age of 5;0 performed significantly better on open-set word recognition tasks at 36 and 48 months post implantation. Tye-Murray and Spencer (1995) found that children implanted under the age of 5;0 demonstrated faster phoneme and word acquisition than children implanted after 5;0. In a study of 29 children who received CI's between ages 0;10 and 3;4, Tomblin et al. (2005) found that language growth curves were more rapid in children who received their implants as infants than those who were implanted as toddlers. Tomblin and colleagues suggested that early implantation is most effective because of the greater neuroplasticity of the very young brain, both with respect to sensory and to language development.

While most of the research on phonological acquisition of children with CIs has focused on what sounds these children can produce, there are a few studies of higher-level phonological knowledge, which have also examined phonological awareness and nonword repetition abilities in this group of children. Children with NH first develop awareness of syllables, then intersyllabic units such as onset and rime, and then awareness of phonemic units (James et al., 2005). Children with CIs appear to follow this same sequence after implantation. In a study of CI users between ages 5;0 and 10;0, James et al. (2005) found that the use of CIs offers benefits in phonological awareness, most significantly at the syllable level. This was consistent with findings by Carter, Dillon, and Pisoni (2002) and Dillon, Cleary, Pisoni, and Carter (2004) in which it was found that use of CIs resulted in more benefits at the suprasegmental level rather than segmental. A longitudinal portion of the James et al. (2005) study found that the children made significant improvements in rhyme awareness over time, suggesting that CI users, like children with NH, develop awareness of phonemic units after developing syllabic awareness. Although little research has investigated phonemic awareness in CI users, James et al. (2005) suggest that language and literacy support the development of segmental phonological representations in NH children. In Geers et al. (2003), the role of orthographic knowledge in rhyme awareness of CI users between ages 8;0 and 9;0 was examined. In a task requiring the subjects to identify rhymes in either graphemically similar or phonemically similar sets of cards, CI users committed most errors in sets that were both phonemically similar and graphemically dissimilar, such as “word” and “bird”. Geers et al. (2003) suggest that CI users must rely on both phonemic and orthographic cues when identifying rhymes and developing further phonological awareness skills.

Nonword repetition tasks are often used as a measure of phonological working memory in typically developing children and children with specific language impairment. In nonword repetition tasks, children are asked to repeat a nonsense word stimulus that is presented auditorally. This measure is thought to employ a number of processes, including speech perception, phonological encoding, and articulation. A number of studies have shown that nonword repetition accuracy is related to vocabulary size. For example, Gathercole and Baddeley (1989) found that nonword repetition scores (number of nonwords repeated correctly) of children between age 4;0 and 5;0 accounted for a significant amount of the variance in vocabulary scores on the *British Picture Vocabulary Scale*. In another study, Gathercole and Baddeley (1990b) found that children with poor nonword repetition abilities were less able to learn new words than children with good nonword repetition abilities. They studied children between age 4;0 and 6;0 and divided them into two groups: a “high repetition” (performance at least one standard deviation above the mean) and a “low repetition” (performance at least one standard deviation below the mean) group. The groups were matched on non-verbal skills. In a name-learning task (learning “names” of toys), the high repetition group was faster than the low repetition group at learning nonwords as names, but the groups were equal in speed of learning real names. Another study has found that typically developing children are not the only population that demonstrates a relationship between nonword repetition tasks and vocabulary. Gathercole and Baddeley (1990a) found a relationship between nonword repetition accuracy and vocabulary size in children with specific language impairment (SLI). SLI is a language disorder characterized by significantly delayed language development in spite of normal cognitive ability, normal hearing, normal socio-emotional development, and normal motor development (Leonard, 2000). When children with SLI were compared to younger children matched on vocabulary and reading skills, it was found that the children with SLI have poorer nonword repetition scores. This finding of a relationship between nonword repetition accuracy and receptive vocabulary has been shown in a number of studies since this early work of Gathercole and Baddeley (1989, 1990a, 1990b). For example, a recent study of children between age 3;0 and 8;0 by Edwards, Beckman, and Munson (2004) found that vocabulary size was a better predictor than age of nonword repetition accuracy.

Nonword repetition tasks should be particularly difficult for children with CIs because these tasks require participants to rely only on auditory cues to encode a novel sequence of phonemes, without the assistance of semantic support. Cleary, Dillon, and Pisoni (2002) studied nonword repetition in CI users between age 8;0 and 10;0. Initial consonants of words that were two to five syllables in length were found to be correct

39% of the time. Further analysis showed that stops were more accurate than fricatives. In a study by Carter et al. (2002) of experienced CI users between age 8;0 and 10;0, it was found that only 5% of all nonwords were produced without error and only 64% of the nonwords contained the correct number of syllables. Carter et al. suggested that this greater accuracy rate for syllables as compared to individual sounds indicates that children with CIs were encoding the overall prosodic shape, but were not retaining the more fine phonetic detail of the nonwords.

Most of the existing research on cochlear implant users has focused on children with unilateral implants or bimodal children with one hearing aid and one cochlear implant. Bilateral cochlear implant users are a rapidly emerging population; however, they have been studied little thus far. Further research investigating hearing, speech, and language outcomes is needed in order to justify the added expense and surgical risk associated with a second implant. Existing studies on bilateral CI users have indicated that binaural hearing provides improved sound localization and speech perception in noise. In a study by Grieco-Calub and Litovsky (2009), 11 out of 19 bilateral CI users localized sounds better when their second CI was activated as compared to when they relied on their first implant alone. Individual bilateral CI users' results, however, were variable and their localization skills were found to be poorer than typically developing children's. In another study of ten children with bilateral implants and ten children who had a CI in one ear and a hearing aid in the other, Litovsky, Johnstone, and Godar (2006) investigated the speech recognition thresholds, ability to understand speech in noise, when only one CI was activated in comparison to when the additional CI or HA was activated. The bilateral CI users experienced significantly higher improvement in speech recognition thresholds when the second CI was added relative to the bimodal children when their HAs were activated.

The focus of this paper is to examine the nonword repetition abilities of children with bilateral cochlear implants relative to two comparison groups: one, children with NH matched for hearing age (relative to age at the first CI implantation) and receptive vocabulary size; and two, children with NH matched for chronological age and receptive vocabulary size. The design of the study is to compare real word repetition to nonword repetition for word-initial consonants and consonant clusters. Edwards and Beckman (2008) found that children with NH produce the same sounds more accurately in real words than in nonwords. The accuracy of word-initial /t/, /d/, /k/, and /g/ will be examined because these are early acquired sounds (e.g., Smit, Hand, Freilinger, Bernthal, & Bird, 1990) and, unlike fricatives, relatively easy for CI users to perceive and produce (Tye-Murray & Spencer, 1995). The accuracy of clusters /tw/, /kw/, and /kj/ are also included as these sequences are later acquired and more difficult to produce, at least for children with NH (e.g., Barton, Miller, & Macken, 1973).

Three questions will be addressed. First, what are the relative differences in accuracy for initial consonants in nonwords relative to real words for children with CIs, as compared to the two comparison groups of children with NH and do these differences vary for singleton stops as compared to consonant clusters? Second, what is the relationship between initial consonant accuracy in nonwords and real words relative to age in children with CIs and children with NH? Finally, what is the relationship between initial consonant accuracy in nonwords and real words relative to receptive vocabulary size in children with CIs and children with NH?

Methods

Participants:

The participants were 18 children with bilateral CIs between the ages of 4;1 and 9;2 and 25 typically developing children between the ages of 2;6 and 5;9. The children with CIs were part of a larger study on binaural hearing and speech/language development in children with bilateral CIs. All of the children were monolingual speakers of English except for one CI subject who uses American Sign Language at home. The children with NH were from Columbus, OH and the CI users were from across the US and traveled for testing in Madison, WI. All of the children with CIs used in this study were implanted by 2;6 except for one subject that was implanted at age 5;0. The time between the first and second implant ranged from 0;8 to 5;0. Beyond hearing loss, the children with CIs did not have any other known disorders.

The children from the NH chronological and hearing age match groups were chosen from a database of subjects from a larger cross-linguistic study on phonological acquisition in children with normal hearing (Edwards and Beckman, 2008). All of the children in the NH comparison groups had normal hearing (based on a hearing screening) and age-appropriate articulation and receptive vocabulary, defined as standard scores of at least 80 on the Goldman-Fristoe Test of Articulation: 2 (Goldman & Fristoe, 2000) and the *Peabody Picture Vocabulary Test-4 (PPVT-4)* (Dunn & Dunn, 2007). The children with CIs were individually matched to children in both comparison groups based on either chronological or hearing age (within 9 months), PPVT-4 standard score (within 17 points), sex, and ethnicity. Hearing age was defined as the time period since the activation of the first implant (e.g., if a CI user was 4;0 and the first implant had been activated at age 2;0, then the hearing age of the CI user was 2;0). Because the oldest children in the NH data base were 5;11, only 11 of the 18 children with CIs could be matched for chronological age. Thus, the hearing age comparison group includes 18 children, while the chronological age comparison group includes only 11 children. The sex, mean ages, and standard scores for the different groups are presented in Tables 1 and 2.

Insert Tables 1 and 2 here

Stimuli:

The stimuli were familiar real words and nonwords with word-initial /t/, /d/, /k/, or /ɡ/ followed by vowels in /i/, /a/, /u/, and /o/ categories, such as the real word *tepee* or the nonword /tivætʃ/. For three of these vowel categories, several vowels with similar coarticulary effects were combined into a single category. The /i/ category included /i/ and /ɪ/, the /a/ category included /a/, /ɔ/, and /ʌ/, and the /u/ category included /u/ and /ʊ/. The stimuli also included word-initial /tw/, /kw/, and /kj/ clusters in high phonotactic-probability consonant-consonant-vowel contexts and in low or zero phonotactic-probability contexts. (High phonotactic probability sequences occur in many words such as /kwɪ/ in *quick*, *quiz*, *quilt*, while low or zero phonotactic probability sequences occur in few or no words such as /kjo/ which is unattested in English.) All words had a syllable initial stress pattern. Real words were one to two syllables and the nonwords were two to three syllables in length. Nonwords did not include common English morphological endings. See Appendices A and B for a list of all stimuli. The singletons in this study were chosen because they are early acquired sounds (Smit et al., 1990) and are relatively easy for CI users to produce (Tye-Murray et al., 1995). The clusters were chosen because the sequences are later acquired and more difficult to produce, at least for children with NH (Barton et al., 1973). All stimuli were recorded by a female speaker of the Columbus, Ohio dialect.

Procedures:

All testing for CI users was administered in an Acoustic Systems x2 wall sound booth. For NH children, testing took place in a quiet room at a day care or preschool. The children's productions of real words and nonwords were elicited in two separate auditory word repetition tasks. In both tasks, children were presented with both auditory and visual prompts: a picture of a familiar (or unfamiliar) object and a digitized recording of a real word (or nonword). Visual stimuli were presented on an IBM ThinkPad portable computer. So that the child could follow his or her own progress through the experiment, an image of an animal (frog, koala, or duck) climbing a ladder appeared next to the stimuli images. Auditory stimuli were presented at a comfortable listening level over computer speakers for children with NH and over Audix powered speakers for children with CIs. The children's productions were recorded through an AKG microphone on a Marantz Professional Solid State Recorder for subsequent transcription.

Testing was completed in two thirty-minute blocks. On the first day, the children were administered a practice real word repetition task in order to familiarize them with the task. They were then presented with the list of 63 target stimuli. The *PPVT-4* was also administered on the first day of testing to measure receptive vocabulary. On day two, a practice nonword measure was administered, followed by the 63 nonword target stimuli. For children with NH, all real words and nonwords were played once and the child repeated the stimuli into a microphone. For CI users, real words were also played once and followed by the child's repetition. For nonwords, the stimuli were played twice for CI users and the children were instructed to repeat after each presentation of the stimuli. The second day of testing was always completed within two days of the first for CI users and within one week for the children with NH. Three different versions of the real word and nonword lists were used. The assignment of the wordlists was balanced. In each list, the stimuli were randomized. When the children completed the real word and nonword repetition tasks, the animal climbing the ladder made a sound and the child was presented with a small prize.

Analysis:

The children's repetitions of nonwords and real words were segmented using Praat computer phonetics software (Boersma & Weenink, 2009) and the initial consonant or consonant cluster in each real word and nonword was transcribed by a native English speaker, who was also a trained phonetician (the author). A fairly narrow transcription was done, using the auditory signal, the waveform, and the spectrogram. Target sounds were coded as correct or incorrect and substitution errors were transcribed. Inter-rater reliability of phonemic accuracy ratings was calculated separately for NH children and CI users. For NH children, productions of a broad range of initial consonants and consonant clusters in real words and nonwords for ten participants (two children were 2;0 to 3;0, three children were 3;0 to 4;0, three children were 4;0 to 5;0, and two children were 5;0 to 6;0) were transcribed independently by a second trained phonetician (the author). Phoneme-by-phoneme inter-rater reliability for initial consonant and consonant cluster accuracy for the productions of the children with NH was 89%. For CI users, the real word and nonword productions of the same set of stop consonants and consonant clusters for three children (chronological ages were 4;1, 6;2, and 7;1 and hearing ages were 2;9, 5;1, and 5;5) were transcribed independently by a second trained phonetician. Phoneme-by-phoneme inter-rater reliability for initial consonant and consonant cluster accuracy for the children with CIs was 87%.

Results

The first question of interest was what are the relative differences in accuracy for initial consonants in nonwords relative to real words for children with CIs, as compared to the two comparison groups of children with NH and do these differences vary for singleton stops as compared to consonant clusters? To address this question, two three-way ANOVAs were performed, one for the comparison of children with CIs to their hearing age peers and one for the comparison of children with CIs to their chronological age peers. For both ANOVAs, the dependent variable was percent correct; syllable structure (singleton vs. cluster) and word-type (real word vs. nonword) were within-subject variables and group (NH vs. CI) was a between-subjects variable.

Figure 1 shows mean accuracy rates for each group, plotted separately by word-type and syllable structure for the comparison of children with CIs to their hearing age peers. There was a significant main effect of wordtype ($F[1, 34] = 103.25, p < .001$) and, as can be observed in Fig. 1, the same consonants and consonant clusters are consistently produced more accurately in real words as compared to nonwords. There was also a significant main effect of syllable structure ($F[1, 34] = 56.5, p < .001$), with a tendency for singletons to be more accurate than clusters. As can be observed in Fig. 1, there was no significant main effect of group – the children with CIs produced initial stop consonants and consonant clusters as accurately as their NH peers, matched for hearing age. The interaction between word type and group approached significance ($F[1, 34] = 4.07, p = .052$). It can be observed in Fig. 1 that there is a tendency for there to be a larger difference between real word and nonword accuracy for the children with NH as compared to the children with CIs. A marginally significant three-way interaction among word type, syllable structure, and group (*F*[1, 34] = 4.14, *p* =.05) was also observed. This interaction seems to be due to the existence of a somewhat a larger difference between real word and nonword accuracy in singletons for children with CIs, while the children with NH have a larger difference between real word and nonword accuracy in clusters.

Insert Figure 1 here

The three-way ANOVA for the comparison of children with CIs to their chronological age peers had a smaller N (N= 11, as compared to the N = 18 for the hearing age comparison). Mean accuracy rates for the two groups, plotted separately by word-type and syllable structure are shown in Figure 2. Again, a significant main effect of word-type was found (*F*[1, 20] = 62.57, *p* < .001) with more accurate production of consonants and consonant clusters in real words relative to nonwords. A significant main effect of syllable structure (*F*[1, 20] = 17.18, *p* = .001) was also observed again, with singleton consonants produced more accurately than consonant clusters. There was also a significant main effect of group (*F*[1, 20] = 5.11, *p* = .035). As Fig. 2 shows, the productions of the children with CIs were less accurate than those of their chronological age peers with NH. A significant three-way interaction (group x word-type x syllable structure) was again found for the CI users and their NH chronological age matches (*F*[1, 20] = 12.89, *p* =.002). As in the earlier analysis, there was a tendency for children with CIs to have a larger difference between real word and nonword accuracy for singletons and for children with NH to have a larger difference between real word and nonword accuracy for clusters.

Insert Figure 2 here

The second question of interest concerned the relationship between initial consonant accuracy in nonwords and real words relative to age in children with CIs and children with NH. To address this question, separate correlations for the children with CIs and the children with NH were performed. For all of these correlations, accuracy for singleton consonants and consonant clusters were combined, as there were no significant word-type x syllable structure interactions. For the children with CIs, accuracy in real words and nonwords with both hearing age and chronological age was correlated. For the children with NH, accuracy was correlated in real words and nonwords with chronological age. Only the children from the hearing age comparison group were included in the NH analysis, so that the N's would be equal for the two sets of correlations.

Figures 3 and 4 show accuracy for consonants in real words and nonwords plotted against hearing and chronological age for children with CIs. For the children with CIs, hearing age was found to be correlated with real word accuracy ($r^2 = .56$, $p < .001$) and marginally correlated with nonword accuracy ($r^2 = .22$, $p = .05$). Chronological age was correlated with real word accuracy ($r^2 = .40$, $p = .004$), but it was not correlated with nonword accuracy.

Insert Figures 3 and 4 here

Figure 5 shows accuracy for consonants in real words and nonwords plotted against chronological age for children with NH. For this group, age was found to be highly correlated with both real word accuracy ($r^2 = .49$, $p = .001$) and nonword accuracy ($r^2 = .66$, $p < .001$).

Insert Figure 5 here

The final question of interest concerned the relationship between initial consonant accuracy in nonwords and real words relative to receptive vocabulary size in children with CIs and children with NH. As in the previous analysis, correlations were performed separately for the children with CIs and the hearing age comparison group of children with NH. *PPVT-4* raw score was used as a measure of vocabulary size, as has been done in many previous studies (e.g., Edwards et al., 2004). Figure 6 plots real word and nonword accuracy against *PPVT-4* raw score for children with CIs. As can be observed in Fig. 6, *PPVT-4* raw score is not significantly correlated with real word or nonword accuracy for this group of children.

Figure 7 plots real word and nonword accuracy against *PPVT-4* raw score for children with NH. For this group of children, there was a significant correlation between *PPVT-4* raw score and between *PPVT-4* raw score and real word accuracy ($r^2 = .52$, $p = .001$) and nonword accuracy ($r^2 = .61$, $p < .001$).

Insert Figures 6 and 7 here

The finding that there was no correlation between *PPVT-4* raw score and real word and nonword production accuracy for the children with CIs was somewhat surprising. To investigate this finding further, the relationship between vocabulary size and age for both groups of children was examined. Vocabulary size should be highly correlated with age – the older a child is, the more words that he or she knows. Again, correlations were performed separately for the children with CIs and the children with NH. For the children with NH, *PPVT-4* raw score was correlated with chronological age ($r^2 = .52$, $p = .001$). For children with CIs, PPVT-4 raw score was correlated with chronological age ($r^2 = .42$, $p = .004$), but not with hearing age. Figures 8 and 9 show *PPVT-4* raw score plotted against hearing age and chronological age for children with CIs and against chronological age for children with NH.

Insert Figures 8 and 9 here

Discussion

This study addressed three questions. The first question concerned whether word type (that is, whether the stimuli were real words or nonwords) and syllable structure (whether the initial consonants were in singletons or clusters) would differentially impact on accuracy for children with CIs relative to their normal hearing peers. While children with CIs produced consonants significantly less accurately than NH children matched on chronological age, their accuracy scores are equal to those of their hearing age peers with NH. Furthermore, while both word type and syllable structure affected accuracy as predicted, the impact of these factors was similar for children with CIs and their NH peers. These results suggest that children with CIs perform very similarly to children with NH who have had the same amount of exposure to sound as they have for consonants that are relatively easy for them to perceive.

The second question concerned the issue of whether there was a similar relationship between consonant accuracy in real words and nonwords relative to age in the two groups of children. As in previous research (e.g., Edwards et al., 2004), a significant correlation was observed between age and consonant accuracy in both real words and nonwords for the NH children. For the children with CIs, hearing age appeared to be a better predictor of accuracy overall than chronological age. For these children, hearing age was correlated with consonant accuracy in real words and the correlation between hearing age and consonant accuracy in nonwords approached significance. However, chronological age was correlated only with consonant accuracy in real words and the amount of variance explained was less for the correlation with chronological age (.40), as compared to the correlation with hearing age (.56). This finding is consistent with the above finding that articulatory development in children with CIs is similar to that of their peers who have been exposed to sound for the same amount of time as they have.

The third question of interest concerned the relationship between consonant accuracy in nonwords and real words in relation to receptive vocabulary size. Consistent with findings by Gathercole et al. (1989) and others, NH children showed a significant correlation between receptive vocabulary size and both real word and nonword accuracy. However, the children with CIs do not show a significant correlation between *PPVT-4* raw score and either accuracy in real words or nonwords.

In an attempt to understand this lack of a relationship between receptive vocabulary size and repetition accuracy, the relationship between receptive vocabulary size relative to age was investigated in both groups of children. *PPVT-4* raw scores were correlated with chronological age in both children with NH and children with CIs. Interestingly, no correlation was found between *PPVT-4* raw score and hearing age for the children with CIs. This result is probably due to the fact that children with CIs have a discontinuity in word learning that is not observed for children with NH. Children with CIs are learning about concepts (the semantic content of words) from the time they are born, but are learning about sound sequences (the phonological content of words) only after they receive a cochlear implant. This discontinuity in word learning also may be related to the lack of a correlation between receptive vocabulary and accuracy in real words and nonwords for the children with CIs.

There were several limitations to this study. First, it is unclear what role perceptual difficulties played for the children in the nonword repetition task. Ongoing analysis of the subject data in this study includes *Goldman Fristoe Test of Articulation: 2* (*GFTA-2*) results (Goldman & Fristoe, 2000). Results of the *GFTA-2* may provide more information regarding perceptual difficulties in these children because it is a picture naming task rather than an auditory repetition task. Another limitation to this study is the lack of a unilateral cochlear implant user control group. Future research comparing unilateral and bilateral cochlear implant users is warranted as it is important to consider the functional speech and language differences between these populations in order to provide evidence for or against the necessity of the increased financial cost and surgical risk to patients receiving second implants. Future research could also focus on more difficult sounds such as /s/ and /ʃ/. With more difficult sounds, there may be more dramatic differences between CI users and their hearing and chronological age NH matches.

Based on these results, there is evidence to support that children with CIs develop speech production and vocabulary skills on a different trajectory than children with NH and the relationship between vocabulary and speech production skills differs for both populations. Amount of experience with a CI is an important factor to consider in the development of speech production skills. Correlations between CI users' hearing age and accuracy suggest that phonological skills begin developing when the first implant is activated rather than birth. Language, however, appears to be more correlated with chronological age suggesting that, like children with NH, CI users begin forming the semantic concepts necessary for vocabulary acquisition at birth. Also, children with NH have a correlation between receptive vocabulary scores and accuracy, showing a trend for children with higher vocabulary scores to have better initial consonant accuracy. This is not the case for CI users which may mean that they do not have a strong relationship between vocabulary and speech production skills. These findings have clinical implications regarding vocabulary instruction for children with bilateral CIs. This population can be expected to have vocabulary skills more commensurate with chronological age than hearing age, even though phonological skills may be lagging. Rather than teaching vocabulary appropriate for a CI user's hearing age, a teacher or speech-language pathologist can focus on words more appropriate for the child's chronological age. It should also be noted that a CI user with poor phonological skills should not be assumed to have poor vocabulary skills as there is no correlation between measures of vocabulary and initial consonant accuracy for CI users as there is for NH children.

Clearly, further research is needed in order to better understand the speech production and language skills in this population. However, the results of this study suggest that CI users are a unique population that should be expected to follow a different course of developmental linguistic and phonological milestones than NH children.

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Table 1. Demographic information for the children with CIs and the hearing age comparison group:

	Number of females	Number of males	Mean hearing age in years; months (age range in parentheses)	Mean PPVT-4 standard score (SD in parentheses) and range
Children with CIs	12	6	4;1 (2;8-5;11)	98.56 (13.84), 82-122
Children with NH	12	6	4;1 (2;6-5;9)	99.16 (10.83), 83-117

Table 2. Demographic information for the children with CIs and the chronological age comparison group

	Number of females	Number of males	Mean chronological age in years; months (age range in parentheses)	Mean PPVT-4 standard score (SD in parentheses) and range
Children with CIs	10	1	4;10 (4;1-5;11)	102.64 (13.49), 82-122
Children with NH	10	1	4;9 (4;3-5;9)	103.82 (12.61), 85-122

Figure Captions

Figure 1. Mean accuracy of initial consonant and initial consonant clusters plotted separately by group (CI users vs. NH hearing age matches), word-type (real word vs. nonword) and syllable structure (singleton consonant vs. consonant cluster).

Figure 2. Mean accuracy of initial consonant and initial consonant clusters plotted separately by group (CI users vs. NH chronological age matches), word-type (real word vs. nonword) and syllable structure (singleton consonant vs. consonant cluster).

Figure 3. Percent correct plotted against hearing age for children with CIs. Regression lines were added for a significant correlation for real words and a marginally significant correlation for nonwords.

Figure 4. Percent correct plotted against chronological age for children with CIs. Regression lines added for significant correlations only.

Figure 5. Percent correct plotted against age for children with NH. Regression lines added for significant correlations only.

Figure 6. Percent correct plotted against PPVT-4 raw score for children with CIs.

Figure 7. Percent correct plotted against PPVT-4 raw score for children with NH. Regression lines added for significant correlations only.

Figure 8. PPVT-4 raw score plotted against hearing age for children with CIs and children with NH. Regression lines added for significant correlations only.

Figure 9. PPVT-4 raw score plotted against chronological age for children with CIs and children with NH. Regression lines added for significant correlations only.

Figure 1.

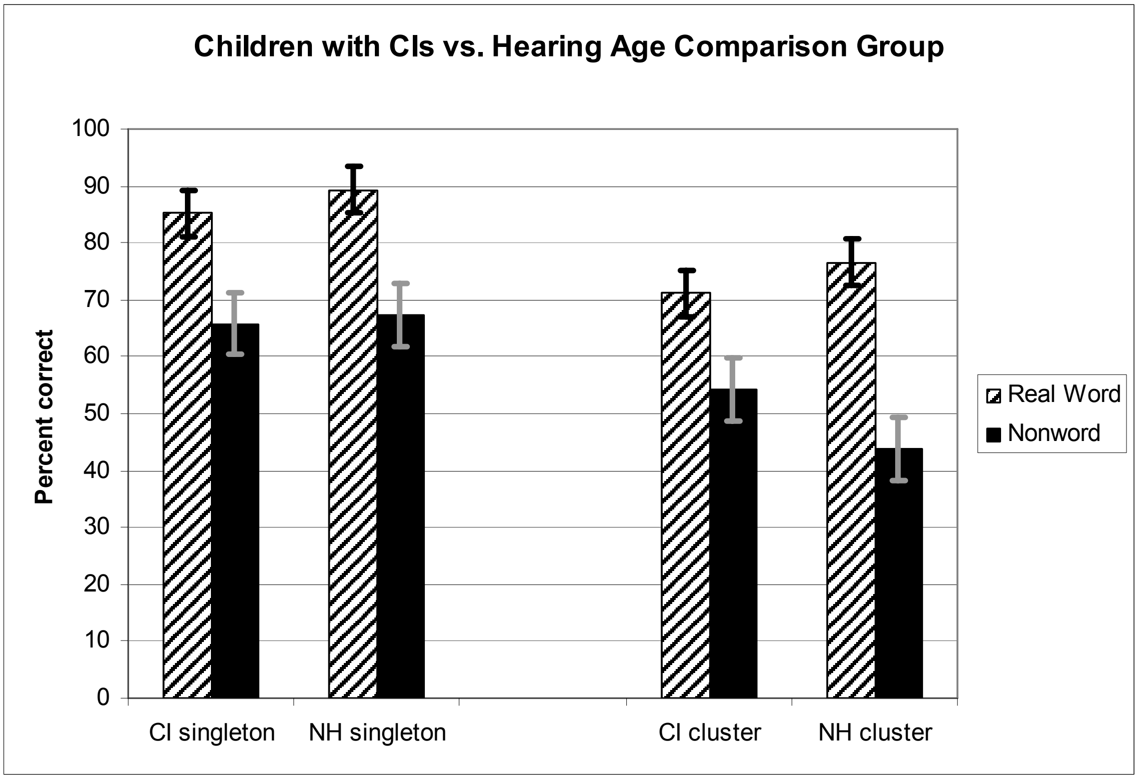


Figure 2.

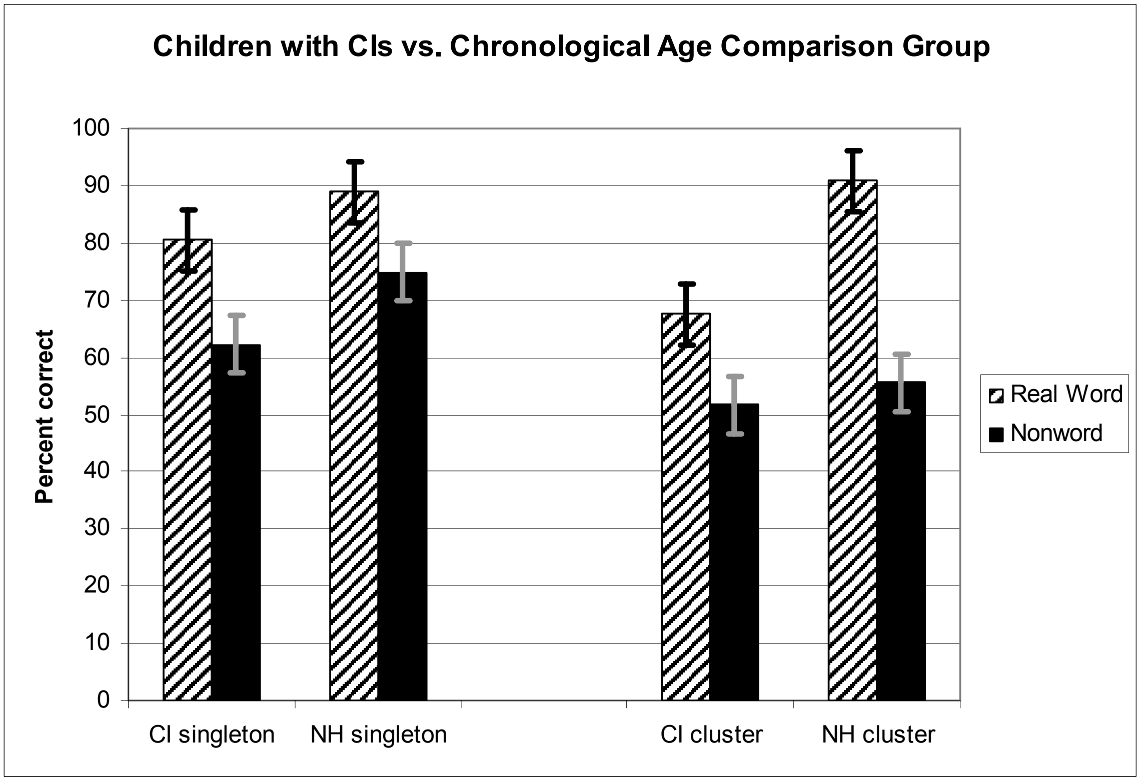


Figure 3.

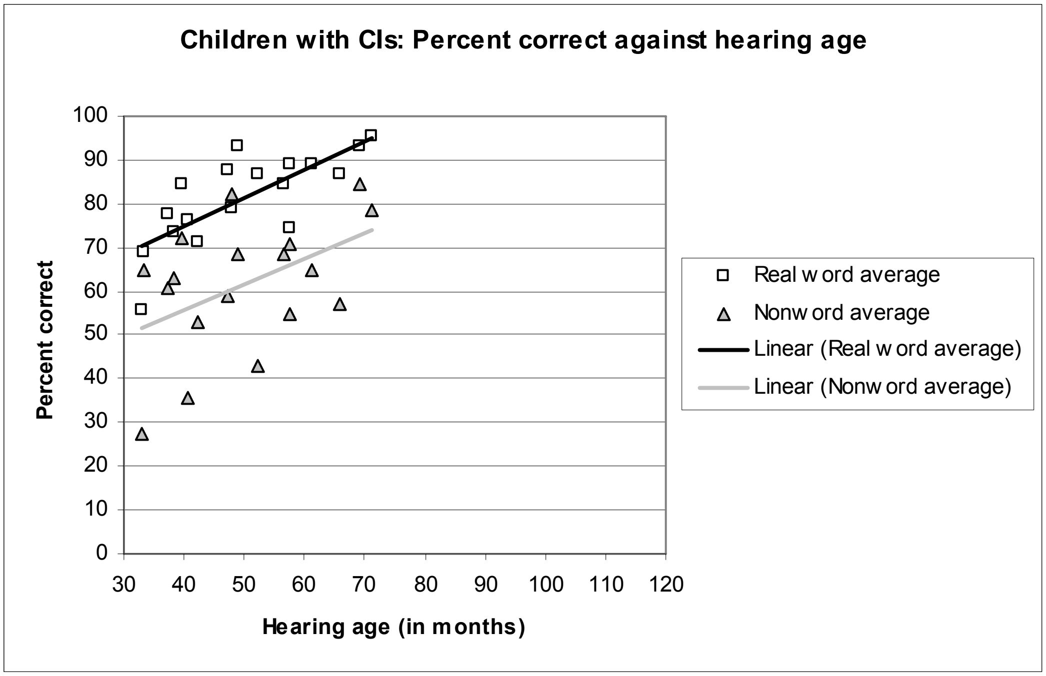


Figure 4.

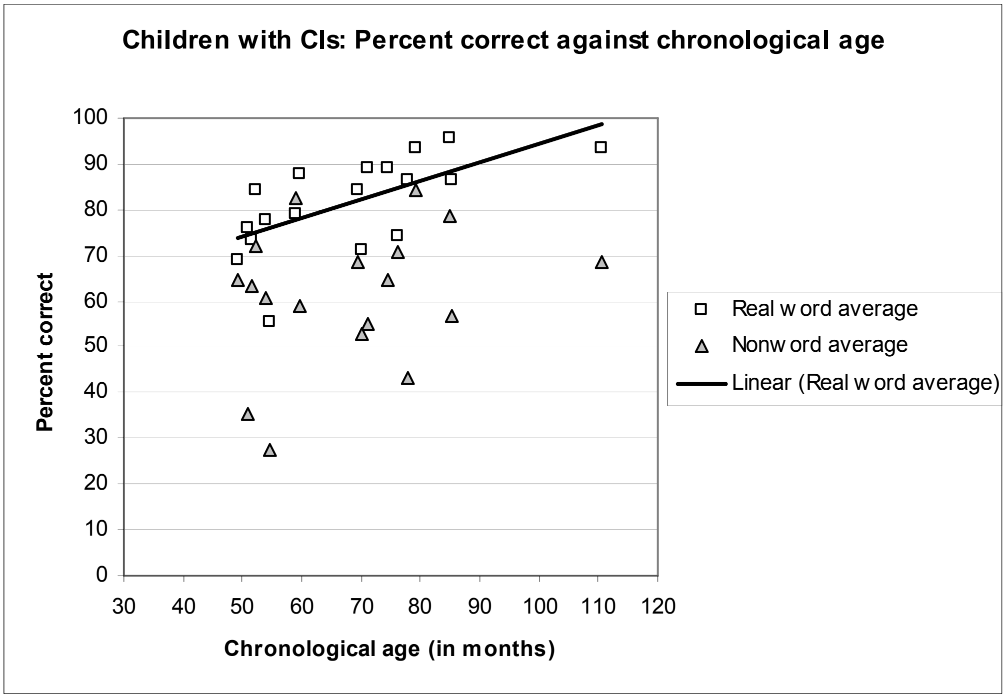


Figure 5.

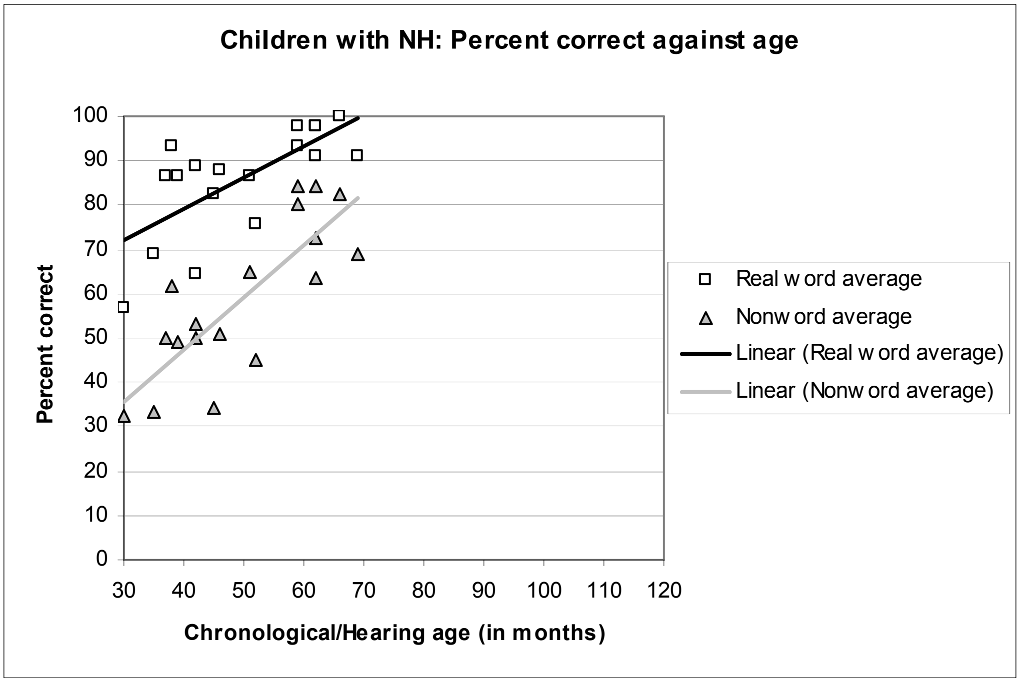


Figure 6.

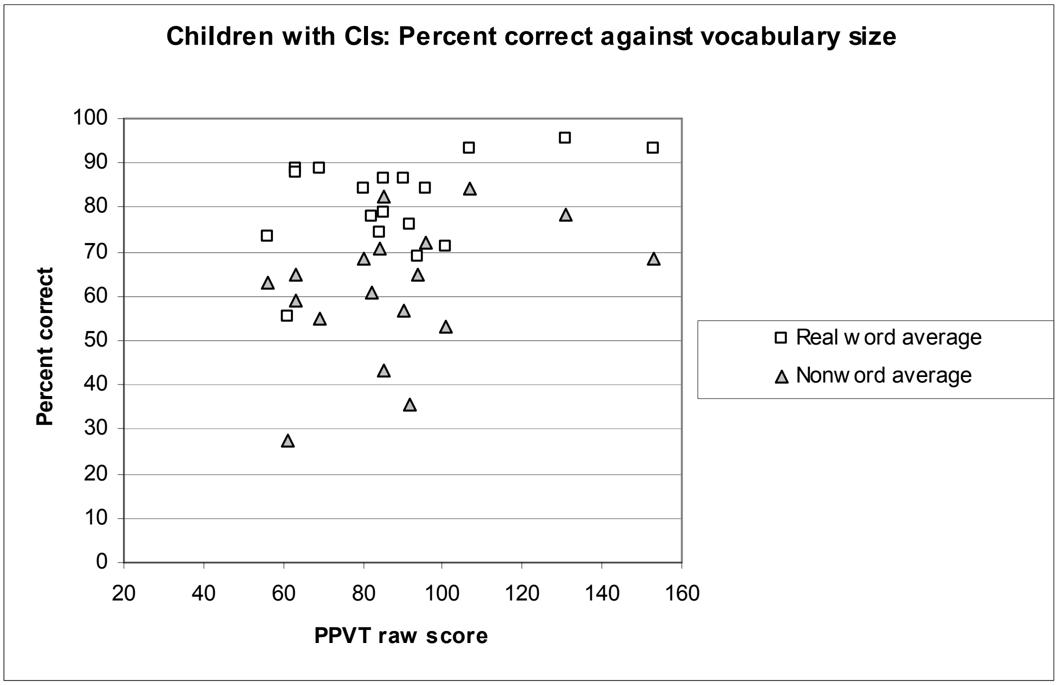


Figure 7.

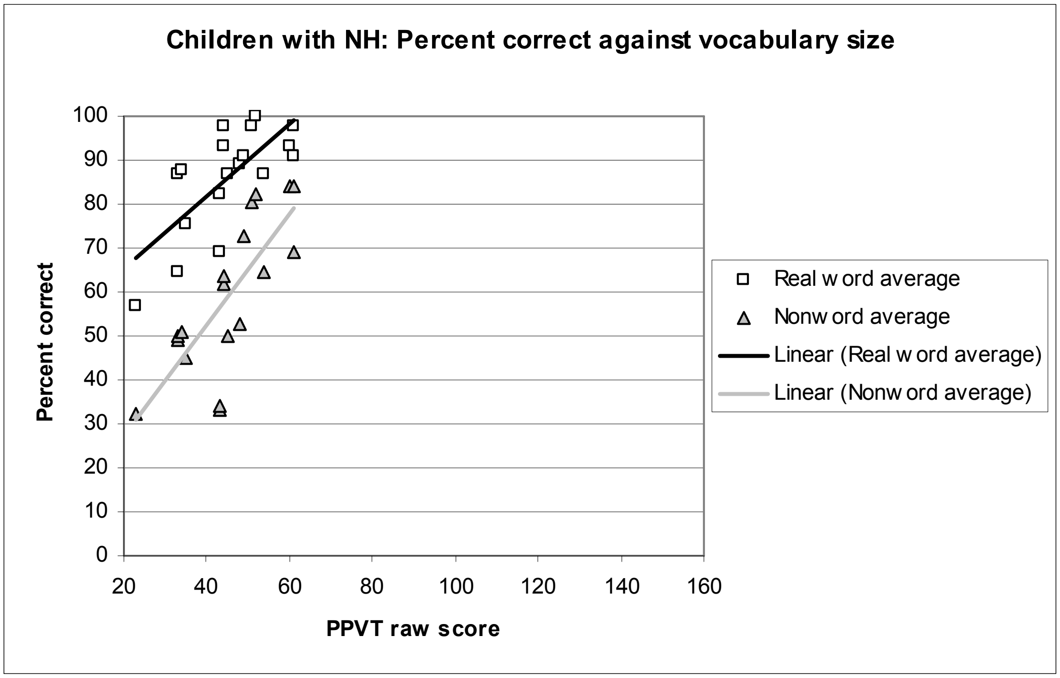


Figure 8.

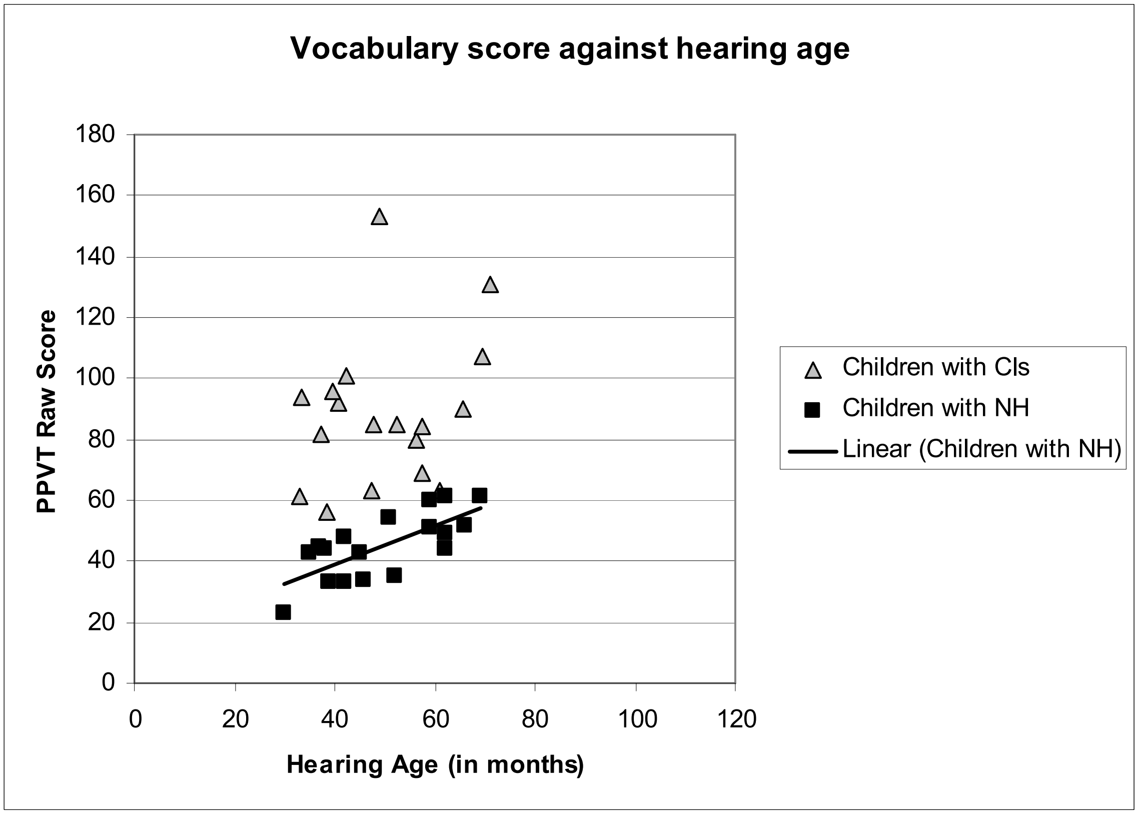
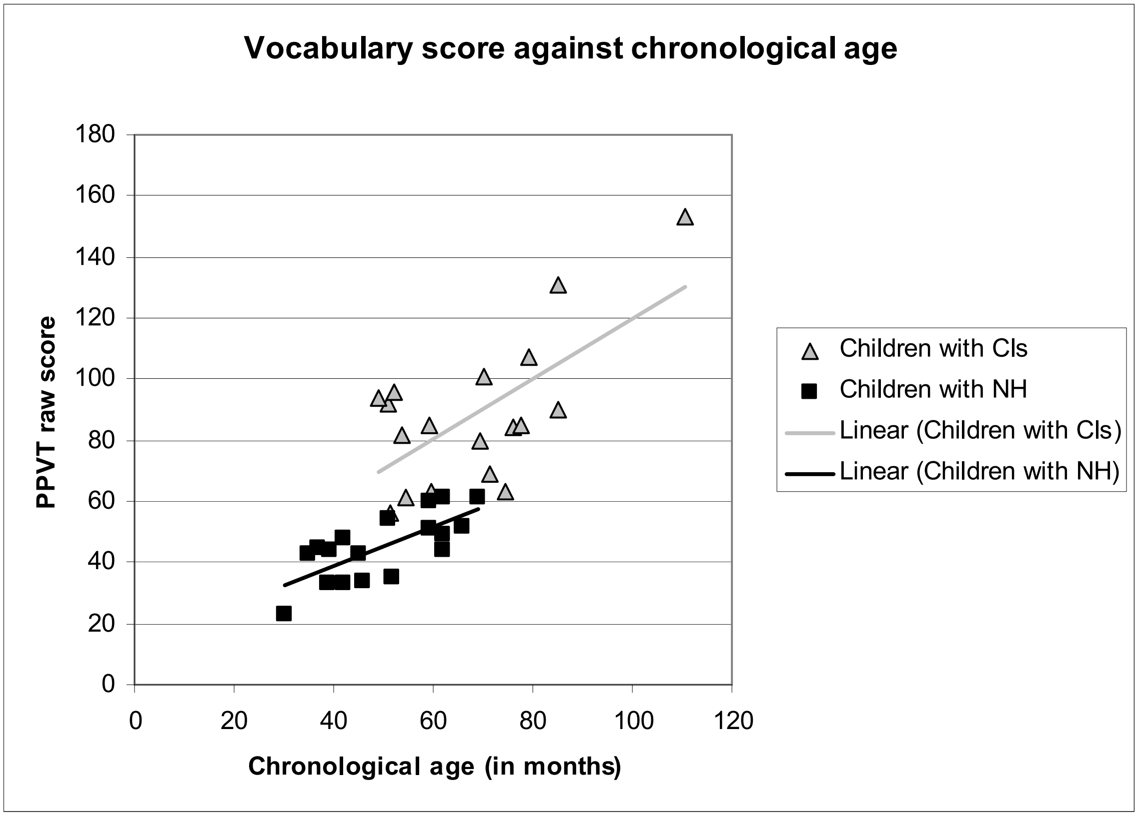


Figure 9.


Vocabulary score against chronological age
PPVT raw score
180
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
Chronological age (in months)
△ Children with CIs
■ Children with NH
Linear (Children with CIs)
Linear (Children with NH)

Appendix A. Real words

Initial Consonant	Vowel	Real Words	
		Gloss	Transcription
/t/	/i/	tickle	tʰɪkl
		teacher	tʰitʃer
		teepee	tʰipi
	/a/	taco	tʰako
		tall	tʰal
		tongue	tʰʌŋ
	/u/	tube	tʰub
		tooth	tʰuθ
		tuna	tʰunə
		tube	tʰub
/d/	/i/	deer	diər
		ditch	ditʃ
		digging	dɪgɪŋ
	/a/	donkey	dɔnki
		dolphin	dɔlfin
		dove	dʌv
	/u/	duke	duk
		dude	dud
		duel	duəl
/k/	/i/	kicking	kʰɪkɪŋ
	/a/	cutting	kʰʌtɪŋ
		car	kʰar
	/u/	cooking	kʰʊkɪŋ
		cookie	kʰʊki
		cougar	kʰugər
/g/	/i/	giving	gɪvɪŋ
		gift	gɪft
	/a/	gumdrops	gʌmdrɑps
/tw/	/i/	tweezers	twizerz
		twisted	twɪstɪd
		twin	twɪn

/kw/	/i/	quick	kwʰɪk
		quill	kwʰɪl
		quilt	kwʰɪlt
		question	kwʰɛstʃən
		quail	kwʰel
/kj/	/u/	cute	kjʰut
		cube	kjʰub
		cupid	kjʰupɪd

Appendix B. Nonwords

“Word Frequency” is the number of words in the Hoosier Mental Lexicon (Pisoni, Nusbaum, Luce, & Slowiacek, 1985) that begin with this CV or CCV sequence.

Initial Consonant	Vowel	Nonwords Transcription	Word Frequency
/t/	/i/	tʰivɑtʃ tʰigədraɪk tʰikəmæb tʰigəklot tʰidɑp tʰigɪnok tʰipɔid tʰikəfrɑl tʰivɪfaɪp	81
	/a/	tʰɑzɪkrætʃ tʰɑvɪdrot tʰɑfədrɑm tʰʌvɪt tʰʌzənæk tʰʌzem tʰʌθɪmaɪd tʰʌvɪnut tʰʌpɪdʒ	94
	/u/	tʰugɪnok tʰukəfrɑl tʰupɔid tʰuvɑtʃ tʰugədraɪk tʰukəmæb tʰugəklot tʰuvɪfaɪp tʰudɑp	46
/d/	/i/	disɛm ditʃɪplɑf difəraɪk didʒɛp difɪmon dibɪkrus	376

		diʃəlɑp dibaʊn dizəgrɔɪd	
	/a/	dazəgrɔɪd datʃiplɑf dabɪkrus dʌbaʊn dʌʃəlɑp dʌsɛm dʌfəraɪk dʌdʒɛp dʌfɪmon	107
	/u/	dufɪmon dudʒɛp dubɪkrus dubaʊn duzəgrɔɪd duʃəlɑp dusɛm dutʃɪplɑf dufəraɪk	40
/k/	/i/	k^{h}inədrok k^{h}igɪtus k^{h}idɪtʃ k^{h}imæg k^{h}ibəglot k^{h}imɪkɑʃ k^{h}imɪgraɪf k^{h}izɑm k^{h}iʃəbɪp	51
	/a/	k^{h}aʃəfrɑm k^{h}anəblɑm k^{h}azɪplok k^{h}ʌdɪbɪf k^{h}ʌluf k^{h}ʌzəfæs k^{h}ʌtuʃ k^{h}ʌdʒɪmok	455

		kʰʌbɪθ	
	/u/	kʰugəklot kʰudɑp kʰuvɪfaɪp kʰukəfrɑl kʰupɔid kʰugɪnok kʰugədraɪk kʰukəmæb kʰuvɑtʃ	21
/g/	/i/	gislɑʃ gipot gibɪklod giðəbaɪn gizem gifəgluk giθɪdroz gidʒɪmæb gifɪtʃ	23
	/a/	gɑθɪdroz gɑbɪklod gɑfəgluk gʌdʒɪmæb gʌfɪtʃ gʌs̄lɑʃ gʌpot gʌzem gʌðəbaɪn	84
/tw/	/i/	twʰivɪnut twʰizɪkrætʃ twʰipɪdʒ twʰivɪt twʰizənæk twʰifədrɑm twʰizem twʰivɪdrot twʰiθɪmaɪd	14

	/a/	tw^{h}ɑvɪdrot tw^{h}ɑzɪkrætʃ tw^{h}ɑfədrɑm tw^{h}ʌzem tw^{h}ʌθɪmaɪd tw^{h}ʌvɪnut w^{h}ʌpɪdʒ tw^{h}ʌvɪt tw^{h}ʌzənæk	2
/kw/	/i/	kw^{h}ivəglor kw^{h}izun kw^{h}ifɪzɑm kw^{h}imɪpek kw^{h}idɪblɔɪd kw^{h}ivor kw^{h}izəpræθ kw^{h}ifɪgɑs kw^{h}idɪdʒ kw^{h}efɪzɑm kw^{h}evor kw^{h}emɪpek kw^{h}edɪdʒ kw^{h}efɪgɑs kw^{h}ezun kw^{h}evəglor kw^{h}ɛdɪblɔɪd kw^{h}ɛzəpræθ	26
/kj/	/u/	kj^{h}umæg kj^{h}umɪkɑʃ kj^{h}ubɪglot kj^{h}umɪgraɪf kj^{h}uzɑm kj^{h}uʃəbɪp kj^{h}unədrok kj^{h}ugɪtus kj^{h}uðɪdʒ	24

	/o/	kj^{h}oʃəbɪp kj^{h}ozɑm kj^{h}omɪgraɪf kj^{h}onədrok kj^{h}ogɪtus kj^{h}oðɪdʒ kj^{h}obɪglot kj^{h}omɪkɑʃ kj^{h}omæg	0