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Speech Production Accuracy and Variability in Young Cochlear Implant Recipients: Comparisons with Typically Developing Age-peers

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Abstract

Purpose—The speech production accuracy and variability scores of six young cochlear implant (CI) recipients with 2 years of device experience were compared with those of typically developing (TD) age-peers.

Methods—Words from the First Words Speech Test (FWST; Ertmer, 1999) were imitated three times to assess the accuracy and variability of initial consonants, vowels, and words. The initial consonants in the four sets of the FWST followed a typical order of development.

Results—TD group produced targets with high accuracy and low variability. Their scores across FWST sets reflected the expected order of development. The CI group produced most targets less accurately and with more variability than the TD children. Relatively high accuracy for the consonants of sets 1 and 2 indicated that these phonemes were acquired early and in a typical developmental order. A trend toward greater accuracy for set 4 as compared to set 3, suggested that later-emerging consonants were not acquired in the expected order. Variability was greatest for later-emerging initial consonants and whole words.

Discussion—Although considerable speech production proficiency was evident, age-level performance was not attained after 2 years of CI experience. Factors that might influence the order of consonant acquisition are discussed.

Keywords

COCHLEAR IMPLANTS; SPEECH DEVELOPMENT; CHILDREN; VARIABILITY

The primary benefits of cochlear implantation are increased hearing sensitivity and improved speech perception ability. These auditory advances commonly facilitate secondary gains in spoken language development for deaf children (see ASHA technical report, 2004 for review). In particular, substantial gains in prelinguistic vocal development and phonological development have been observed following cochlear implantation (e.g., Ertmer, Young, & Nathani, 2007; Tobey, Geers, Brenner, Altuna, & Gabbet, 2003; Yoshinaga-Itano & Sedey, 2000). Until recently, researchers examined speech development in children who were implanted during the preschool years or later in life. The widespread adoption of newborn hearing screening and reductions in age criterion for cochlear implantation (currently 12 months) have now made it possible to study speech development in children who receive cochlear implants (CIs) as infants and toddlers.

Reductions in age-criterion were motivated by the belief that implantation at very young ages can facilitate the attainment of age-appropriate spoken language abilities. Research has

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supported this contention by documenting an advantage for speech development in children implanted by 30 months of age compared with those implanted at older ages (Connor, Craig, Raudenbush, Heavner, & Zwolan, 2006). However, little is known about the time-course for achieving accurate and consistent (i.e., stabilized) productions of consonants, vowels and word forms, or the order in which consonants are stabilized following cochlear implantation at a young age. The current investigation examined these developmental issues in children implanted by 3;0 (years;months) and employed typically developing (TD) gender- and age-matched peers as controls to assess progress toward age-appropriate speech production abilities during the first 2 years of device use.

Speech Development in Young CI Recipients

Phonological Accuracy

Several large-scale investigations have documented increases in phonological accuracy following implantation at a young age. In a study aimed primarily at determining whether children’s communication modality (Oral vs Total Communication [TC]) impacted consonant production accuracy, Conner, Heiber, Arts, & Zwolan (2000) examined the speech of 147 children who were prelingually deafened and implanted between 1 and 10 years of age. The children had between 6 months and 10 years of CI experience at the time of testing. Transcription analyses of single words revealed that both Oral and TC children significantly improved consonant production accuracy with continued CI experience. A second finding--and one of particular relevance to the current study--was that children implanted at younger ages made greater progress in consonant accuracy than those implanted at comparatively older ages.

A follow-up study by Connor and colleagues (2006), sought to further define the effects of age-at-implantation on consonant production accuracy in 100 children from four age-at-implant groups: 1 – 2.5 years, 2.6 – 3.5 years, 3.6 – 7 years, and 7.1 – 10 years. All children had congenital onset of hearing loss and were oral communicators. After comparing growth curves over 5 years of CI use, it was concluded that those who received CIs before 30 months exhibited early bursts of growth in consonant production accuracy not found in older recipients. These bursts appeared to promote greater speech gains over time. The authors concluded that a younger age at implantation provided “added value” (p. 628) for speech development in children who were oral communicators. It was unclear, however, whether these bursts would lead to normalization of phonological development.

A sense of the relative difference in phonological accuracy between children with CIs and children with normal hearing can be gained by considering the findings of Tobey, et al, (2003) and a pair of studies of typically developing children. In the Tobey et al study, phonological accuracy was examined for 108, 8 – 9 year olds who had an average age-at-implantation of 3;5 (years; months; range 1;8 – 5;4). Narrow transcription of sentences revealed that, on average, the participants produced vowels with 62% accuracy and consonants with 68% accuracy after 5.5 years of CI experience. In contrast, studies of typically developing children have shown that non-rhotic vowels are produced with 97% accuracy in words by 3 years of age (Pollack & Berni, 2003), and that most consonants are produced with at least 90% accuracy in words by 7;0 (Smit, Hand, Freilinger, Bernthal, & Bird, 1990). Although different stimuli were used in these studies (i.e., sentences or words), it is apparent that children who were implanted during the preschool years or later had not reached typical levels of phonological accuracy after more than more than 5 years of CI experience. This shortfall is especially concerning because of a plateau in progress observed after the sixth post-implantation year in studies by Blamey, Barry, and Jacq (2001) and Tomblin, Peng, Spencer, and Lu (2008).

A recent study by Warner-Czyz and Davis (2008) also examined phonological accuracy following implantation. This investigation matched four young CI recipients (all implanted by 20 months and with an average of 8.5 months of device experience) with typically developing children who were also in the first word stage of language development. Data analysis revealed that the TD children were three times more accurate in producing consonants in spontaneous words at the beginning of the study, and seven times more accurate towards the end of the study (6 months later) than the children with CIs. Vowels, however, were produced with comparable accuracy and similar error patterns by the two groups. These findings suggest that any added value of early implantation (Connor et al., 2006) leads to closer-to-typical levels of phonological accuracy for vowels, but not for consonants—at least in the short-term.

In addition to studies of consonant production accuracy, researchers are beginning to explore the order in which consonants are acquired following implantation. Knowledge in this area is important for determining whether the introduction of the CI signal stimulates a “normal” process of speech development, and for planning efficient speech training programs. To-date, the few studies that have addressed order of consonant acquisition suggest that children with CIs follow a near-typical developmental sequence (Bouchard, Normand & Cohen, 2007; Serry & Blamey, 1999). However, little is known about consonant acquisition in the increasing population of very young CI recipients. Research in this area would enable clinicians to better organize the introduction of phoneme targets for training and to emphasize the perceptual and production features of potentially difficult-to-acquire consonants.

Word Production Variability

Mature talkers are accurate and consistent in their production of words (Kent, 1992). In contrast, the speech of young, TD children often contains misarticulations and variable productions of words. Whole-word variability occurs when “multiple tokens of the same word are produced differently at the same point in time” (Vogel Sosa & Stoel-Gammon, 2006; p. 32). Three main sources and their interactions have been proposed to account for variability in children’s word productions.

Phonological factors may cause some words to be more difficult to say than other words (Leonard, Rowan, Morris, & Fey, 1982). These difficult words might have more complex syllable shapes or contain less familiar (i.e., later-emerging) segments. For example, words with CV or CVC syllable shapes might be easier to say than words with CVCC syllable shapes. Similarly, words containing only early emerging consonants (e.g., /b/, /m/, /w/) might be produced more consistently than those with later-emerging phonemes (e.g., /tʃ/, /z/).

Another viewpoint suggests that children’s neuro-motor control affects the consistency of word productions (Kent, 1992). For example, variability in lip-movements during production of phrases (e.g., “Buy Bobby a puppy”) has been shown to decrease with age (Smith & Goffman, 1998). Thus, as neuro-motor control increases with maturation, decreases in whole-word variability can be expected. Although there is debate over whether neuro-motor development is a linear process or one in which children’s neuro-motor systems reorganize and become more variable for a time to meet new challenges, improved control across childhood is evident in the greater consistency in articulatory movements with which older children produce words and sentences (Sharkey & Folkins, 1985; Walsh & Smith, 2002).

Finally, the internal stability of the linguistic rules and word representations that underlie word productions might also influence variability. That is, children who have an unstable understanding of phonological rules (e.g., phonotactic constraints) and unclear mental representations of words might produce the same intended word in different ways. Additionally, having word-level (as opposed to adult-like segmental-level) representations may increase intra-word variability (Ferguson & Farwell, 1975). In a study of four children who were typically developing, Stoel-Gammon (2004) found that high variability for spontaneously and imitatively produced words during the second year of life (60% at 21 months) was followed by much lower variability toward the end of the third year of life (19% at 33 months). This decline was accompanied by a sizable increase in word production accuracy from 7% to 59% during the same time period. It was hypothesized that advancements in consistency and accuracy corresponded with a transition from holistic (whole-word) representations to adult-like, segmental representations of words. If that is the case, as children acquire increased awareness of the segments within spoken words, they should begin to produce phonemes more accurately and consistently.

Research into the effects of CI experience on speech production variability in young children is quite limited. In a case study, Goffman, Ertmer, and Erdle (2002) assessed acoustic and kinematic variability as well as segmental accuracy before implantation and during the first year of CI use. The participant in this study (M) had normal hearing until 3;2 but experienced a bilateral, progressive, moderate -severe hearing loss following hospitalization with bacterial meningitis. His hearing sensitivity decreased to the profound range shortly before he received a CI at 7 years old. Analyses of multiple productions of the carrier sentence “I see a X again” (X = “man”, “pan”, and “fan”) yielded three main findings. First, M had maintained relatively high levels accuracy for the segments /m/, /p/, /f/, /n/, and /æ/ prior to and after receiving his CI. High accuracy was attributed to 3 years of normal hearing and M’s ability to perceive speech through his hearing aids before becoming deaf. Acoustic analyses also revealed that M’s speech timing was slower than that of two age-matched peers with normal hearing-- even though his productions were perceptually acceptable. The durations of segments and whole words shortened with CI experience, but continued to be longer than those of the controls after 12 months of CI use. Although segmental accuracy for target phonemes was not noticeably affected by progressive hearing loss, speech timing was impacted.

Kinematic measures revealed changes to a third characteristic of M’s speech. Recordings of lower lip and jaw movement showed that, prior to cochlear implantation, movement variability was slightly higher than expected for M’s age. Immediately after implant activation, his lip and jaw movements became much more variable, and increased levels of variability were sustained until 6-months post implant. After that time, lower lip/jaw variability stabilized within the expected range for age-matched, hearing children (Smith & Zelaznik, 2004). Thus, the introduction of new auditory input temporarily destabilized speech movements, but continued CI use resulted in age-appropriate movement timing and trajectories after one year of device use. Whereas the acoustic and kinematic results revealed decreased variability with continued CI use in a peri-lingually deafened child, the effects of CI use on speech variability in younger children with little or no hearing experience have not yet been adequately examined.

Research Questions

Although available research supports the efficacy of cochlear implantation in infants and toddlers for spoken language development, very little is known about two major indices of speech development: accuracy and variability. Given that phonological development extends up to 7 years in typically developing children and that the children in the current CI group had experienced only 2 years of robust hearing experience, it was anticipated that this preliminary study would reveal that phonological development was not as complete in young CI recipients as in age-peers with normal hearing. This prediction is also partially supported by Warner-Czyz and Davis (2008) who noted slower than typical gains in consonant accuracy for their young CI users but near-typical levels of vowel accuracy. In contrast, however, the “bursts” in speech development noted by Connor et al (2006) suggest that young CI recipients might acquire phonological skills more rapidly than is typical, and thereby narrow the developmental gap with their age-peers who have normal hearing. Further support for this possibility comes from investigations of prelinguistic vocal development and spoken word milestones that found young CI recipients made unexpectedly swift advancements during their first year of CI use (Ertmer & Inniger, 2009; Ertmer, Young, & Nathani, 2008). Therefore, a main purpose of the current study was to determine how closely young CI recipients approximated age-appropriate speech production accuracy and variability after 2 years of CI experience. Additionally, because the initial consonants in stimulus word sets mirrored the ages of customary usage in typically developing children (Sander, 1972), data also provided insights into the order in which consonants were stabilized.

Three specific questions were addressed in the current study: (1) How accurately do young CI recipients and their typically developing peers imitate initial consonants, vowels, and word forms? (2) How variable are the participants’ imitative productions? And (3) Do young CI recipients acquire and stabilize consonants in an order similar to that observed in children who are typically developing?

Methods

Participants

Two groups of children participated in this study. The CI group consisted of six children (two boys and four girls) who received their devices by 3;0 (see Table 1 for audiometric and background information). All of these children were full-time CI users, oral communicators, and had participated in family-centered intervention soon after their hearing losses were identified. They were enrolled in speech and language therapy at the time of the study and all except one child attended an oral education preschool. The exception, F-30 (female – implanted at 30 months) attended a regular preschool program and received private speech-language therapy before and after implantation.

The audiological background of two of the participants differed from the other CI users.. M-36 was identified later in life than all of the other children. Newborn hearing screening was not available at his birthing hospital when he was born. His parents had suspected that he had a hearing loss from an early age but formal identification was delayed until approximately 28 months. Thus it is not possible to determine whether he had a progressive hearing loss at some point before implantation. Once his profound hearing loss was detected he wore hearing aids for 7 months before implantation at 36 months. The second child, F-30, used her CI alone for approximately 4 months before being fit with a digital hearing aid for her non-implanted ear. A comparison of F-30’s speech perception ability in the HA + CI condition vs. the CI-alone condition revealed highly similar scores during live voice, auditory-only administration of the Northwestern University Children’s Perception of Speech (NU-Chips; Elliott & Katz, 1980). No other children wore hearing aids with their CIs during the course of study.

The TD group consisted of six typically developing children who were gender- and age-matched with children in the CI group. All of these children passed individual ear, pure-tone hearing screenings at 20 dB HL for the frequencies .5, 1.0, 2.0, and 4.0 Hz and were reported by their parents to have no learning or developmental difficulties. It is recognized that it would have been beneficial to include children who were matched with the CI group based on amount of hearing experience. However, pilot testing revealed that the 60 item imitative speech task used in the study (described below) was too difficult for 24 month olds.

Data Collection

Each participant imitated words from the First Words Speech Test (FWST; Ertmer, 1999; see Appendix A). The FWST is an unpublished research protocol that consists of 60 words divided into four sets based on the ages at which consonants are correctly produced by 50% of children who are typically developing (Sander, 1972). The majority of FWST words (82%) were selected from the McArthur Communicative Development Inventory (Fenson, Dale, Resnick, & Bates, 1993) so that they would be familiar to young children. All stimulus words were chosen so that they could be represented by small toys or objects, making it easier to engage young children in an elicited naming task. Set 1 contains words starting with stop, nasal, and glide consonants: /p/, /b/, /n/, /h/, /m/, and /w/. Set 2 contains words starting with stop consonants: /k/, /d/, /t/, and /g/. Set 3 contains words starting with fricatives, liquids, and glides /f/, /l/, /j/, /s/, /r/. Set 4 contains words starting with fricatives and affricates: /v/, /tʃ/, /ʃ/, /z/, and /dʒ/. Based on Sander’s data, the average ages at which at least 50% of TD children produced the initial consonants in each set were: 20, 24, 33.6, and 45.6 months for sets 1 – 4, respectively (Note: Consonants that met the 50% criteria before 24 months were assigned an age of 20 months).

The participants imitated each FWST word three times following a tester’s model for each production. Speech samples were recorded using a Sony camcorder and either a Realistic PZM microphone or a Bluetooth wireless microphone placed within 8 inches of the children’s mouth. Children in the CI group were recorded within 1 week of the 2-year anniversary of device activation. Controls were recorded when they were within one week of the same age as their match in the CI group at speech sampling.

Data Analysis and Reliability

Broad phonetic transcription was used to examine the accuracy and the variability of children’s productions. University students who had normal hearing and training in phonetic transcription served as transcribers. Segmental accuracy was measured by calculating the percentage of initial consonants and first-occurring vowels that were judged to be allophones of the target segment during three productions of each word. Whole word accuracy was measured by determining the percentage of segments within the word that were acceptable allophones. For example, a child whose imitative productions consisted of [pIg], [pIg], and [pIk] for the target word “pig” would receive an accuracy score of 100% for the initial consonant, 100% for the vowel, and 89% for word production (8/9 phonemes accurate).

Variability was measured in a similar way, but with lower scores indicating greater consistency than higher scores. Using this approach, a variability score of 1.0 was assigned when children’s productions of initial consonants and vowels did not vary across three imitative attempts (e.g., the same phoneme was perceived in all three attempts); 2.0 was assigned when two different phonemes were perceived in three attempts; and 3.0 when three different phonemes were perceived in three attempts. Using the above example of “pig” a child would receive variability scores of 1.0 for initial consonant and vowel variability (i.e., consistent productions). Whole word variability was assessed by counting the number of different forms of each word produced in three attempts. For example, the score for the preceding example would be 2.0 since two different forms of “pig” were observed in three attempts. In sum, accuracy scores ranged from 0 to 100% and variability scores ranged from

1.0 to 3.0. A combination of high accuracy and low variability scores indicated stable production of segmental targets and word forms.

Intra- and inter-transcriber reliability was assessed by re-transcribing 25 and 30%, respectively, of the children's imitative productions (total sample = 2160 words). Intra-transcriber agreement on the accuracy of segments (i.e., acceptable/not acceptable as an allophone of the target) was found to be 97% and inter-transcriber agreement was 95%.

Statistical Analyses

The main effects of Group (CI Vs Control) and FWST Set (1 – 4) were examined through mixed design ANOVAs, with Group as the between-subjects factor and Set as the within-subjects factor. Separate ANOVAs were performed for initial consonants, vowels, and whole word measures. Significant interactions were examined through post hoc testing (Tukey HSD) of scores within and between groups.

Results

Segmental and Whole-word Accuracy

Figure 1 contains the mean percent of accurate initial consonants and standard deviations for each group across each FWST set. This figure shows that children in the TD group produced initial consonants from sets 1 - 3 with near ceiling level accuracy and those from set 4 with approximately 86% accuracy. In comparison, those in the CI group had moderately lower scores on lists 1 and 2 (89 and 80% respectively) and substantially lower scores for the initial consonants found in sets 3 and 4 (30 and 47%). The observed differences were confirmed statistically by main effects of Group, $F(1, 10) = 51.76$, $p < .0001$; Set, $F(3, 30) = 24.14$, $p < .0001$; and a Group X Set interaction, $F(3,30) = 14.78$, $p < .0001$. Post hoc analysis (Tukey HSD; Pooled MS = 0.016; $df = 34.8$) revealed that initial consonant accuracy scores across the four FWST sets did not differ significantly within the TD group. A more complex picture was seen for the CI group. Their scores for sets 1 and 2 were not significantly different from each other and scores from sets 3 and 4 did not reach significance either. However, scores for sets 1 and 2 were both greater than those of set 3 ($p < .001$) and set 4 ($p < .001$). Comparisons between the groups revealed that initial consonant accuracy scores were comparable for sets 1 and 2, but that the TD group was more accurate than the CI group scores for set 3 ($p < .001$) and for set 4 ($p = .024$).

Figure 2 shows that the vowel accuracy scores for the TD group closely approximated ceiling level (range of means: 98 – 99%) whereas those of the CI group were moderately lower (range of means: 79 - 84%) across the four sets, Thus, a main effect of Group was observed $F(1,10) = 27.85$, $p = <.001$. There was no main effect for Set, $F(3,30=0.081$, $p = .97)$, nor Group X Set interaction, $F(3,30) = 0.13$, $p = .94$. The latter two outcomes were expected because vowel types were not controlled across FWST sets.

Means and standard deviations for whole-word accuracy scores can be found in Figure 3. Again, scores for the TD group approached ceiling level on all sets (range of means: 95 – 98%) whereas those of the CI group were considerably lower (range of means: 64 – 77%). ANOVA revealed significant main effects of Group, $F(1, 10) = 45.69$, $p < 0.001$, and Set, $F(3,30) = 7.55$, $p < .0001$. A significant Group X Set interaction was also observed, $F(3, 30) = 3.89$, $p < .02$. Post hoc analyses revealed that there were no differences in mean whole-word scores across the sets for the TD group. For the CI group, means from sets 1 and 2 were greater than set 3 ($p < .004$); and the mean for set 2 (but not set 1) was greater than set 4 ($p = .034$). Comparison between set 3 and set 4 did not reach significance ($p = .804$). Finally, when the two groups of children were compared, whole-word scores did not differ significantly for sets 1 and 2 but means for sets 3 and 4 were significantly lower in the CI than in the TD group ($p = .017$ and $p = .047$, respectively). These findings indicate that the TD group was more accurate in producing whole-words than the CI group and that the CI group produced whole words containing early-emerging initial consonants more accurately than those containing later-emerging ones.

Segmental and Whole-word Variability

Recall that at the segmental level, a score of 1.0 represents the production of an allophone of the same target segment in each of three imitative attempts (i.e. no perceived variability), 2.0 represents the production of two different segments in three attempts, and 3.0 represents the production of three different segments in three attempts. Similarly, whole-word variability scores represent one to three variations of a word. The following results for variability were determined.

Means and standard deviations for initial consonant variability are presented in Figure 4. ANOVA revealed a significant main effect of Group, $F(1, 10) = 98.95$, $p < .0001$, with lower variability in the TD group than in the CI group across the sets (mean ranges: 1.0 – 1.13 for TD; 1.19 – 1.52 for CI groups, respectively). A main effect of Set $F(3,10) = 6.51$, $p < .01$ revealed that variability scores for sets 1 and 2 were lower than those of set 4 ($p < .01$ and $p < .03$, respectively). Group X Set interactions did not reach significance at the .05 level.

Vowel variability scores are presented in Figure 5. Means for the TD group were low (range = 1.02 – 1.09) indicating consistent productions across three word attempts. The means for the CI group were higher (range = 1.14 – 1.22) and a main effect of Group was determined, $F(1, 10) = 36.42$, $p = <.0001$. There was no main effect of Set, $F(3, 30) =.115$, $p > .95$, or any Group X Set interaction, $F(3, 30) = .699$, $p = .56$ as vowel types were not controlled across FWST sets.

Means and standard deviations for whole-word variability can be found in Figure 6. Again, mean scores for the TD group were relatively low across the four FWST sets compared to those of the CI group $F(1,10) = 154.49$, $p < .0001$. A significant main effect of Set was also detected $F(3, 10) = 4.465$, $p = .01$. Post Hoc analyses revealed that variability scores for sets 3 and 4 were greater than those of set 2, $p = .04$ and $p =.03$, respectively. The Group X Set interaction did not reach significance $F(3,30) = 1.09$, $p = .37$. Thus, the CI group exhibited greater variability of whole word productions and both groups were more variable in producing words from sets 3 and 4 than those of sets 1 and 2. This difference was more pronounced in the CI group than the TD group.

Individual Data—Individual data were analyzed because of obvious differences in the CI users' developmental and intervention histories--especially for M-36 and F-30. The focus of this analysis was on initial consonants because these targets permitted exploration of the developmental sequence predicted by the Sander data (1972). Figure 7 reveals greater accuracy for the initial consonants of sets 1 and 2 vs those of 3 and 4 for every child in the CI group. In addition, all children had greater scores for set 4 than for set 3—although in some cases the difference was small. The latter finding suggests an atypical order of acquisition for later-emerging consonants. Figure 7 also shows that M-36 and F-30 were among the most accurate producers for each set and that their relative advantage was greatest in set 4. Overall, individual data are consistent with group findings.

For five of six children, variability was greater in set 2 than in set 1 (Figure 8). Similarly, each child showed greater variability in set 3 than in set 2. These increases suggest that children were more variable in producing progressively later-emerging consonants. However, this pattern did not hold true for set 4. As Figure 8 shows, only 2 children (F-28 and F-20) were more variable in producing set 4 consonants than those in set 3. Although M-36 was consistently among the three talkers with the lowest variability, his scores were fairly comparable with those of the other children. Similarly, F-28's variability scores were not decidedly different than those of most other children. In sum, CI users showed progressively greater variability for later- than earlier-emerging consonants although four of six children had greater variability scores for set 3 than for set 4.

Discussion

The young CI recipients in the current study appeared to be making rapid progress in speech production accuracy compared to children who received CIs at older ages. For example, the children studied by Tobey et al (2003) were implanted at a mean age of 3;5 and produced consonants with 68% accuracy and vowels with 62% accuracy in sentences after approximately 5.5 years of CI experience. Approximately half of the children in the Tobey et al study used speech with manually coded English to express themselves; the remaining children were oral communicators. Relatively higher scores might have been obtained had only oral communicators been analyzed (Osberger, Robbins, Todd, & Riley, 1994). The current participants—oral communicators who were implanted at younger ages-- produced consonants with accuracy comparable to the children in the Tobey et al study (61%), but vowels with much greater accuracy (82%) after much less CI experience. Recognizing the methodological differences with the above-cited studies, the current findings provide tentative support for the Connor et al (2006) contention that implantation before 2;6 provides added value for speech development.

Comparisons of Accuracy and Variability in Segmental Productions

Consonants—The CI group most closely approximated the high accuracy levels of the TD group for the initial consonants of sets 1 and 2. Variability scores were also closer to TD levels for the initial consonants of sets 1 and 2 as opposed to those from sets 3 and 4. The individual scores found in Figures 7 and 8 converge with the group developmental data. Thus, both group and individual data reveal an atypical order of acquisition for the later-emerging consonants of sets 3 and 4. Support for this conclusion is most apparent in the fact that every CI participant produced consonants from set 4 with greater accuracy than those of set 3.

Better accuracy and variability scores for sets 1 and 2 indicate that stop, nasal, and glide consonants were more readily acquired and stabilized than fricative, affricate and liquid consonants—as is true for typically developing children (Sander, 1972). The high visibility and simple motoric characteristics of the labial and stop consonants of sets 1 and 2 have been cited as reasons for their relatively early emergence in the speech of children with hearing loss and those who are typically developing (Kent, 1992; Stoel-Gammon, 1982).

An unexpected finding of the current investigation was that the CI group produced the initial consonants of set 4 with greater average accuracy (47%) than those of set 3 (30%). Although differences between the accuracy scores of these sets did not reach significance, these scores were surprising for two reasons. First, the TD controls achieved progressively lower scores across sets 3 and 4 (Figure 1), as predicted by the customary usage data provided by Sander (1972). The children in the CI group did not follow this pattern. Second, a relatively large time interval is expected between the ages of customary use for the consonants of set 3 (M = 33.6 months of age) and those of set 4 (M = 45.6 months of age). It was not anticipated that the initial consonants of set 4 would be produced with accuracy comparable to (or greater than) that seen for set 3, after only 2 years of CI experience. Although this outcome must be interpreted cautiously due to the small number of participants and their differing ages at identification and implantation, the data raise the possibility that later-emerging consonants might be acquired in an atypical order by young CI recipients. At least three factors could influence the order of consonant acquisition after CI activation: the perceptual characteristics of the CI signal, an atypical overlap in perceptual and production development, and the effects of intervention.

The CI signal provides artificial representation of speech features in which some consonants might be more salient than others. This possibility is supported by very low accuracy scores for /r/, /s/, and /l/ (*M* = 2%, 13%, and 15%, respectively) and relatively high accuracy for the consonants of FWST sets 1 and 2 . If the former consonants are relatively difficult to perceive with a CI, they would likely be more difficult to acquire. Conversely, the higher accuracy scores for the fricatives and affricates of set 4 support the notion that they are more salient via an implant than the liquids, glides, and low intensity, voiceless fricatives (i.e., /f/ and /s/) contained in set 3. If true, r/, /l/, and /s/, could be expected to require relatively greater amounts of auditory and speech training than /v/, /tʃ/, /ʃ/, /z/, and /dʒ/. Further research is needed to explore this possibility.

TD infants begin to develop their speech perception abilities well before they begin to produce words (see Jusczyk & Luce, 2002 for review). In contrast, children with CIs begin to develop an awareness of the acoustic features of consonants, vowels, and words at roughly the same time as they begin to say words (Ertmer & Inniger, 2009; Nikolopoulos, Archbold, & O'Donoghue, 1999). Rather than having extensive exposure to acoustic-phonetic percepts prior to attempting words, young CI recipients acquire auditory perceptual awareness of speech features as they attempt to produce meaningful speech. This unusual overlapping of speech perception and speech production development might influence the order of consonant emergence and stabilization.

Finally, unlike children with normal hearing, young CI participants receive speech training. The order in which consonants are introduced and practiced during intervention sessions might influence the accuracy and variability of their segmental productions. If set 4 consonants (/v/, / t ʃ/, /ʃ /, /z/, and /dʒ /) are emphasized to a greater extent than set 3 consonants (/f/, /l/, /j/, /s/, and /r/) then an atypical order of acquisition might result. Interactions between the three factors discussed above would also affect the order of consonant acquisition.

Vowels—Vowel accuracy scores were very high across all FWST sets for the TD children (range 98 – 99%) whereas scores for the CI group were moderately lower (range = 79 – 83%). The Controls also showed lower vowel variability (*M* = 1.04) compared to the CI group (*M* = 1.196). Thus, 2 years of CI experience had not resulted in age-level vowel stability. Although the CI recipients showed lower proficiency than their peers, their scores reflected considerable progress in developing a vowel system during their first 2 years of device use. The greater stability of vowels as compared to the consonants of sets 3 and 4 also supports the contention that vowels are among the first phonemes to be acquired after implantation (Ertmer, 2001). Pollack and Berni (2003) showed that – with 2 years of word production experience— children with normal hearing are able to produce vowels at a very high level of accuracy (97%). The children in the CI group had not fully stabilized their vowel production systems after 2 years of robust hearing experience. Further investigation is needed to determine whether young CI recipients reach the high levels of vowel accuracy and low variability seen for TD children.

Comparisons of Whole Word Production

The TD group produced whole words with very high accuracy across all sets (range 95 – 98%). The CI group had much lower accuracy scores overall (range 59 – 77%), with greater accuracy for sets 1 and 2 than for sets 3 and 4. Lower accuracy for the latter sets was expected because of the influence of later-emerging initial consonants. Comparatively greater variability across all sets indicated that the CI group had more difficulty producing word forms consistently than their age-peer controls.

Theories suggests that the CI user's word production variability might have been affected by phonological constraints (Leonard, Rowan, Morris, & Fey, 1982), a lack of knowledge of phonological rules and word representations Stoel-Gammon (2004), relatively immature neuro-motor control (Smith & Zelaznik, 2004), or a combination of these factors. Support for the first possibility can be found in the lower scores for the liquids, fricatives and affricates of sets 3 and 4.—consonants that are later-emerging and presumably more difficult to produce. Limited knowledge of linguistic rules and word representations could also help to explain low word stability scores. Children with normal hearing have been credited with switching from holistic to segment-level representations of words around 3 – 4 years of age (Vogel Sosa & Stoel-Gammon, 2006). The young CI recipients in this study may not have had enough auditory experience to make that switch and, therefore, remained at the more variable whole-word level. Finally, although it is not possible to comment on the influence of neuro-motor control directly, the introduction of CI-aided hearing resulted in timing and kinematic disruptions of speech production in a perilingually deafened child (Goffman, Ertmer, & Erdle, 2002). It seems reasonable to expect younger CI recipients with much less hearing experience would undergo a period of high variability as they become aware of the relationships between the phonemes and words they perceive and the articulatory movements needed to reproduce them. Additional studies of children who have at least 3 years of CI experience are needed to determine whether they attain adult-level word production stability, and to examine child and implant-related factors that might influence phoneme and whole-word stabilization (Geers, 2002).

Summary

The relatively high accuracy and low variability scores of the children in the TD group indicated that they were close to completing the process of phonological development. In contrast, lower accuracy and greater variability across all measures suggest that the children in the CI group were at an earlier stage of development. These differences are likely due-- to a great extent-- to the fact that the TD peers had more robust hearing experience than the CI users. Although the current findings indicate substantial phonological abilities, 2 years of CI experience did not result in age- level consonant, vowel, or word stability. Additionally, some aspects of phonological development followed a typical sequence while others did not. Further study is needed to determine whether continued CI experience leads to age-level stability and to characterize the time-course and nature of young CI recipients' progress.

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Appendix A

Stimulus words from the First Words Speech Test (Ertmer, 1999)

SET 1	SET 2	SET 3	SET 4
Pants	Cow	Fish	Van
Pig	Key	Fork	Vase
Pot	Coat	Foot	Video
Banana	Dog	Leg	Chicken
Ball	Duck	Lion	Chalk
Boy	Doll	Lid	Sheep
Nose	Girl	Yellow	Shovel
Knee	Toe	Yo-yo	Shoe
Hair	Tummy	Yogurt	Zipper
Hand	Tiger	Suitcase	Zebra
Horse	Gum	Soap	Zack
Knife	Goat	Sock	Cheek
Money		Rake	Jump
Monkey		Rock	Juice
Meat		Red	Giraffe
Wally			
Watch			
Wolf			

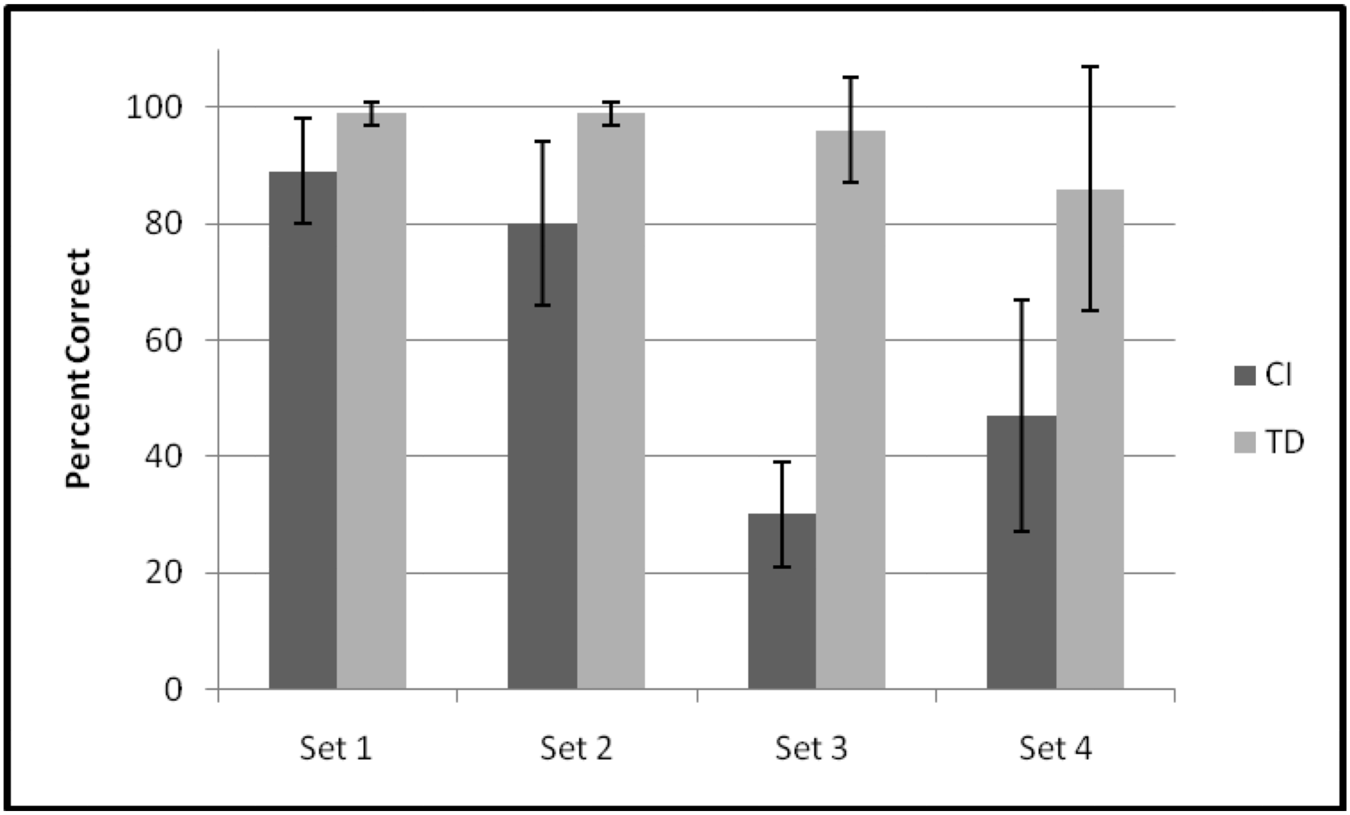

Figure 1.

Mean initial consonant accuracy scores for FWST sets 1 – 4 as produced by children with CIs and children who are typically developing (TD).

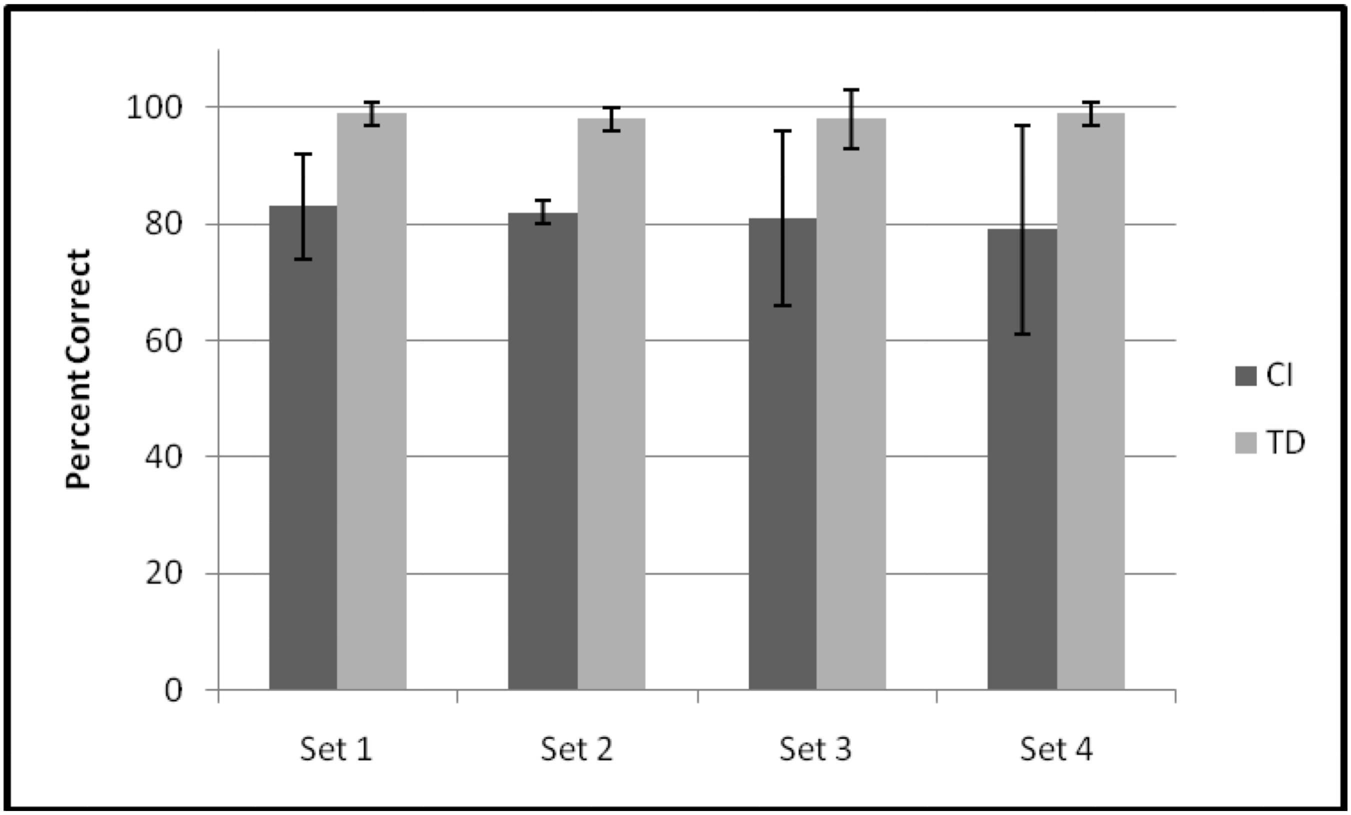

Figure 2.
Mean vowel accuracy scores for FWST sets 1 – 4 as produced by children with CIs and children who are typically developing (TD).

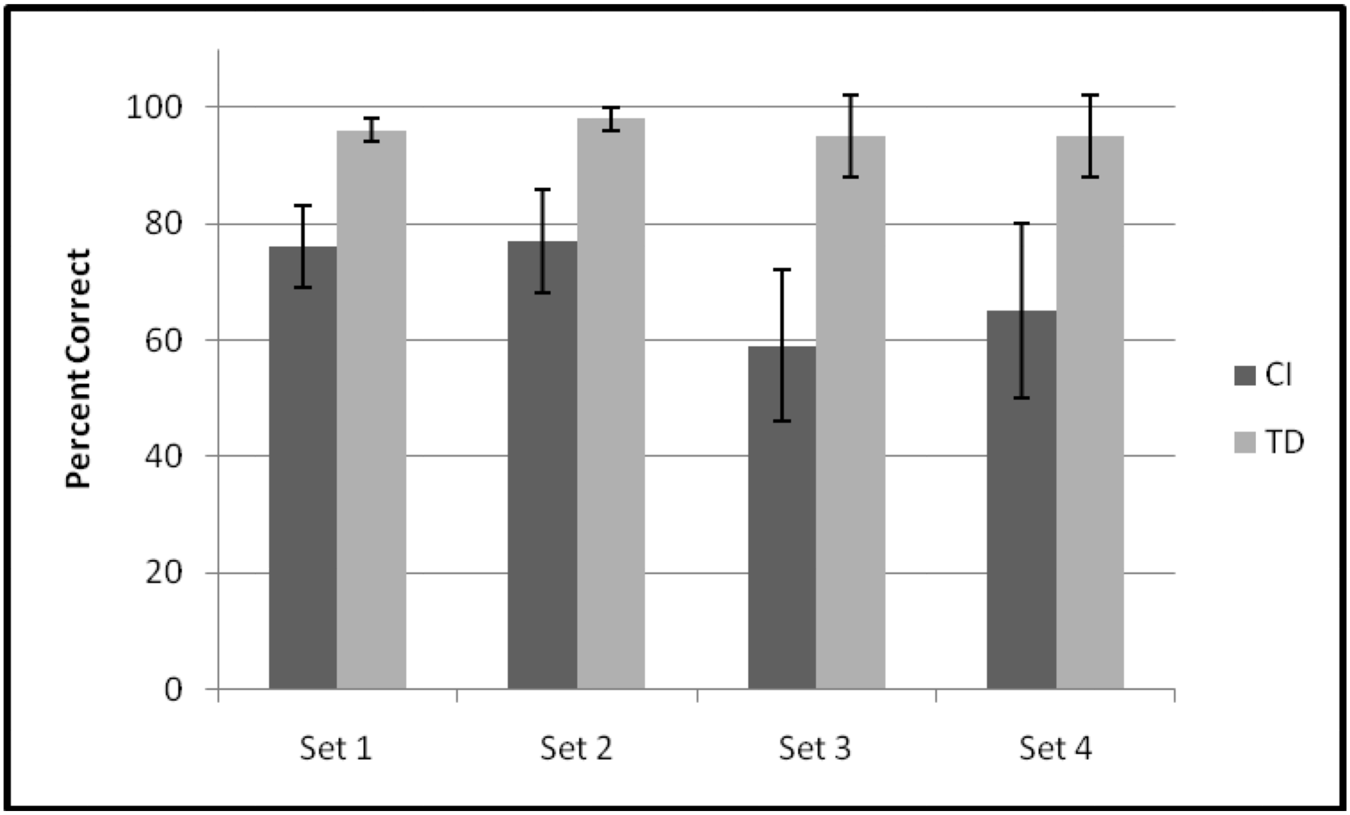

Figure 3.
Mean word accuracy scores for FWST sets 1 – 4 as produced by children with CIs and children who are typically developing (TD).

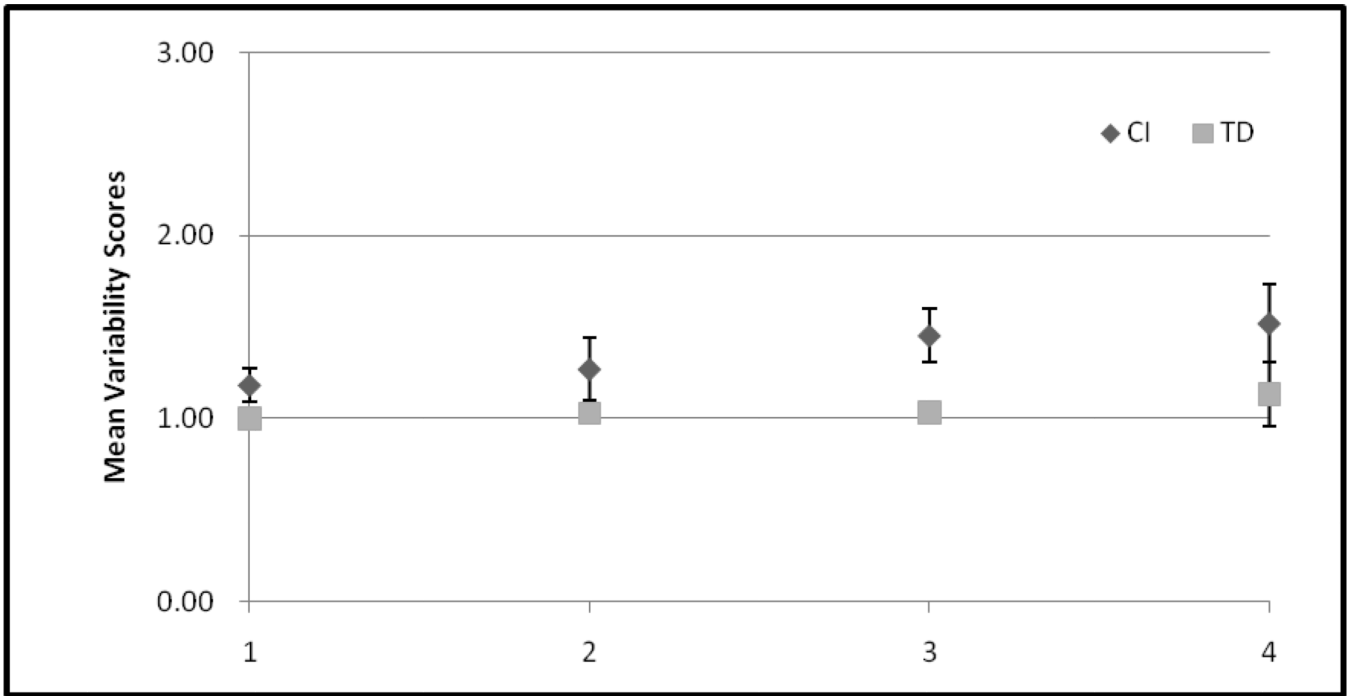

Figure 4.
Mean initial consonant variability scores for FWST sets 1 – 4 as produced by children with CIs and children who are typically developing (TD).

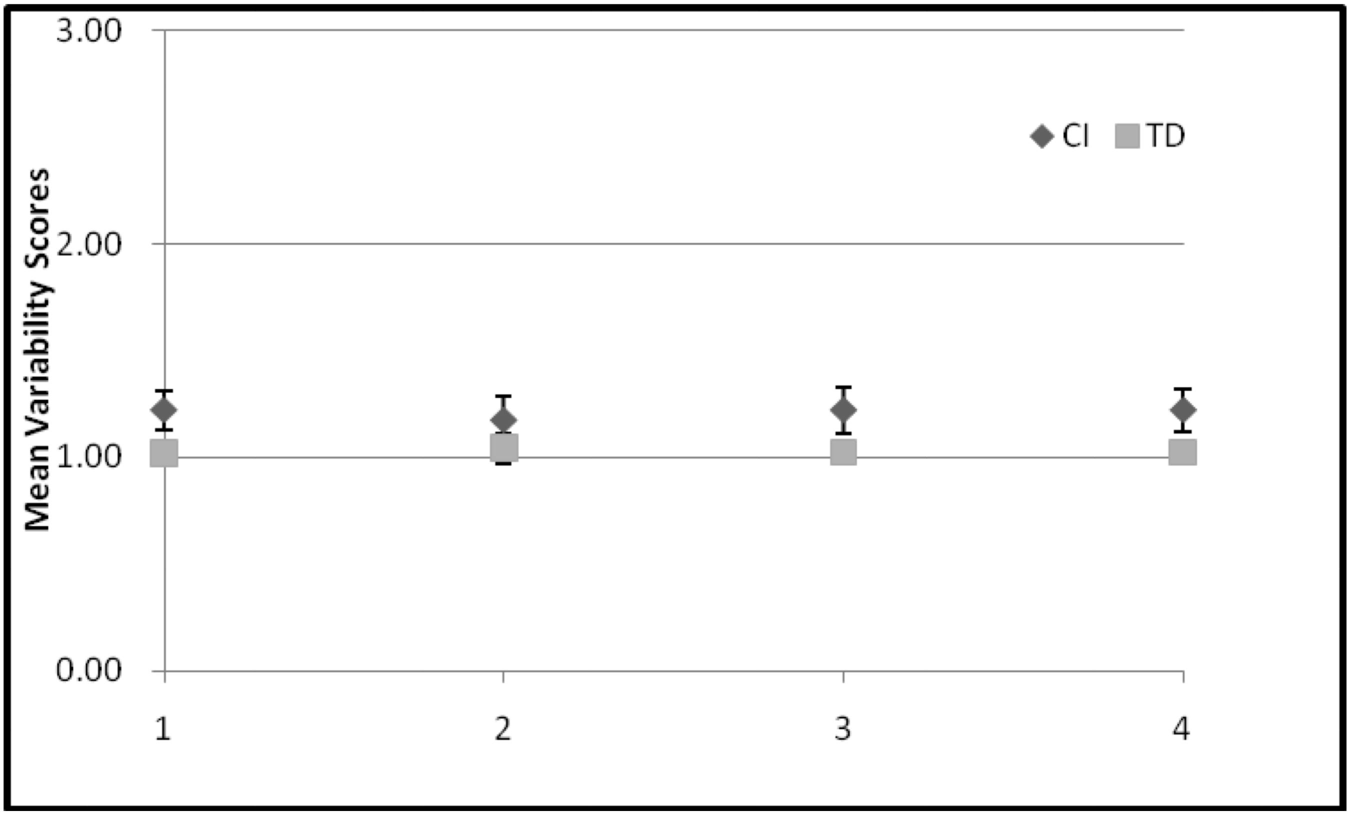

Figure 5.

Mean vowel variability scores for FWST sets 1 – 4 as produced by children with CIs and children who are typically developing (TD).

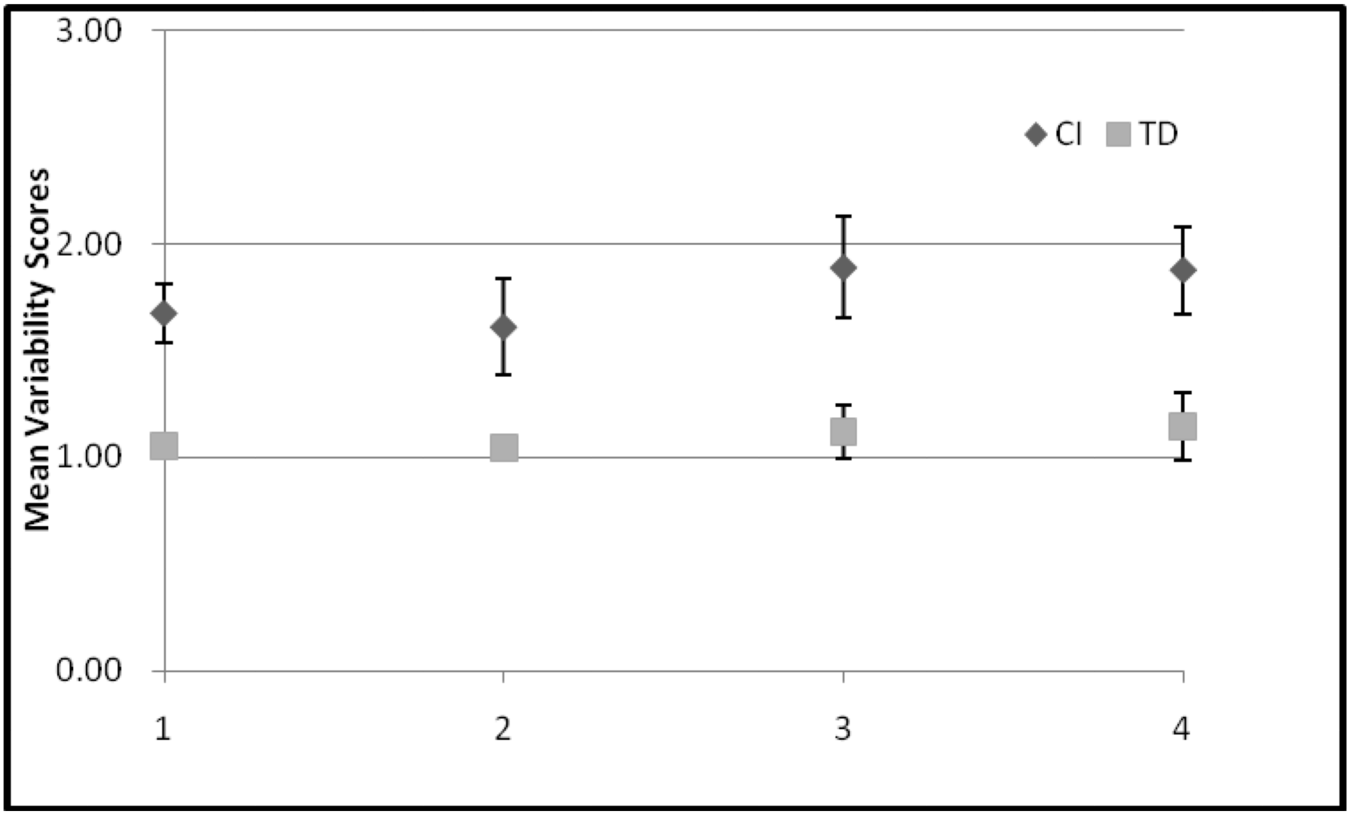

Figure 6.

Mean word variability scores for FWST sets 1 – 4 as produced by children with CIs and children who are typically developing (TD).

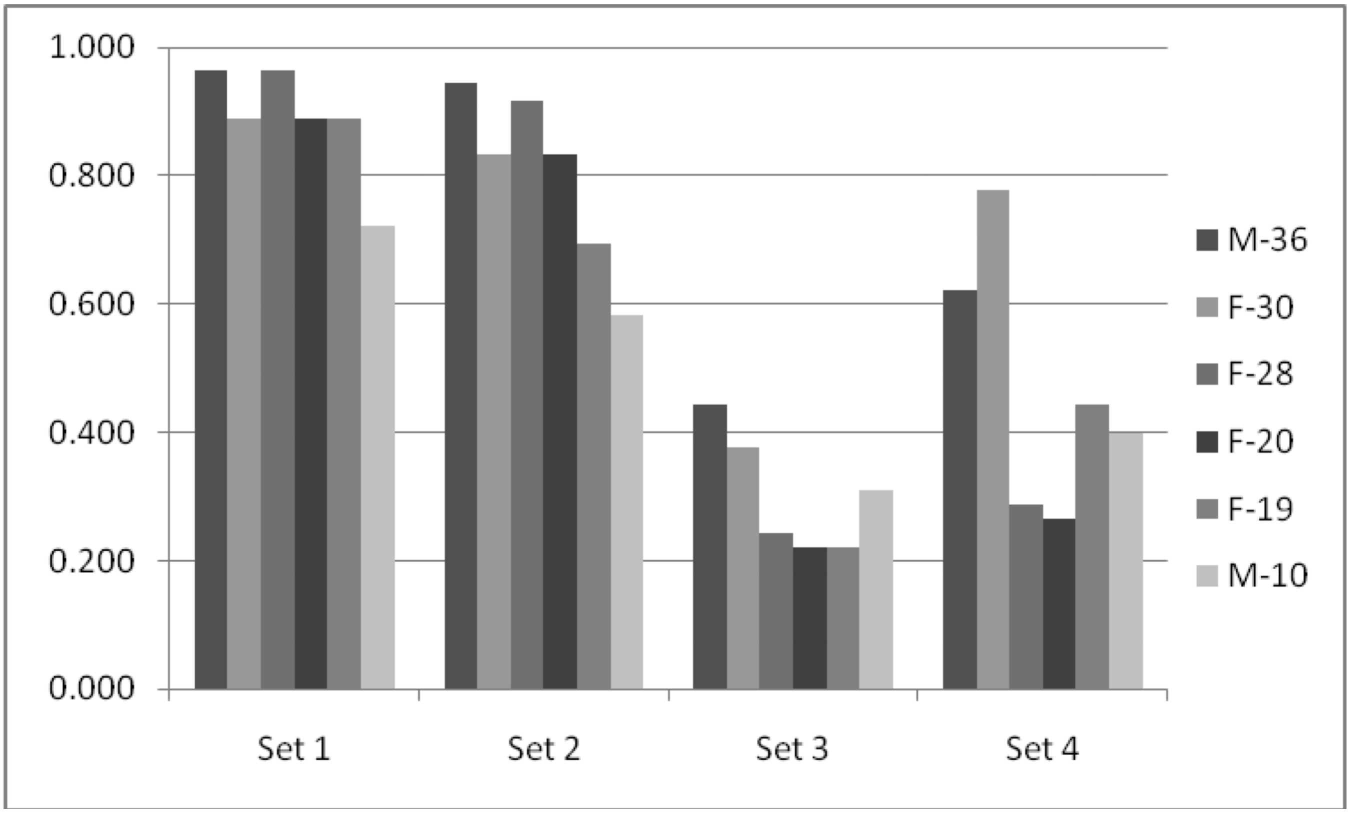

Figure 7.
Initial consonant accuracy scores for individual children with CIs.

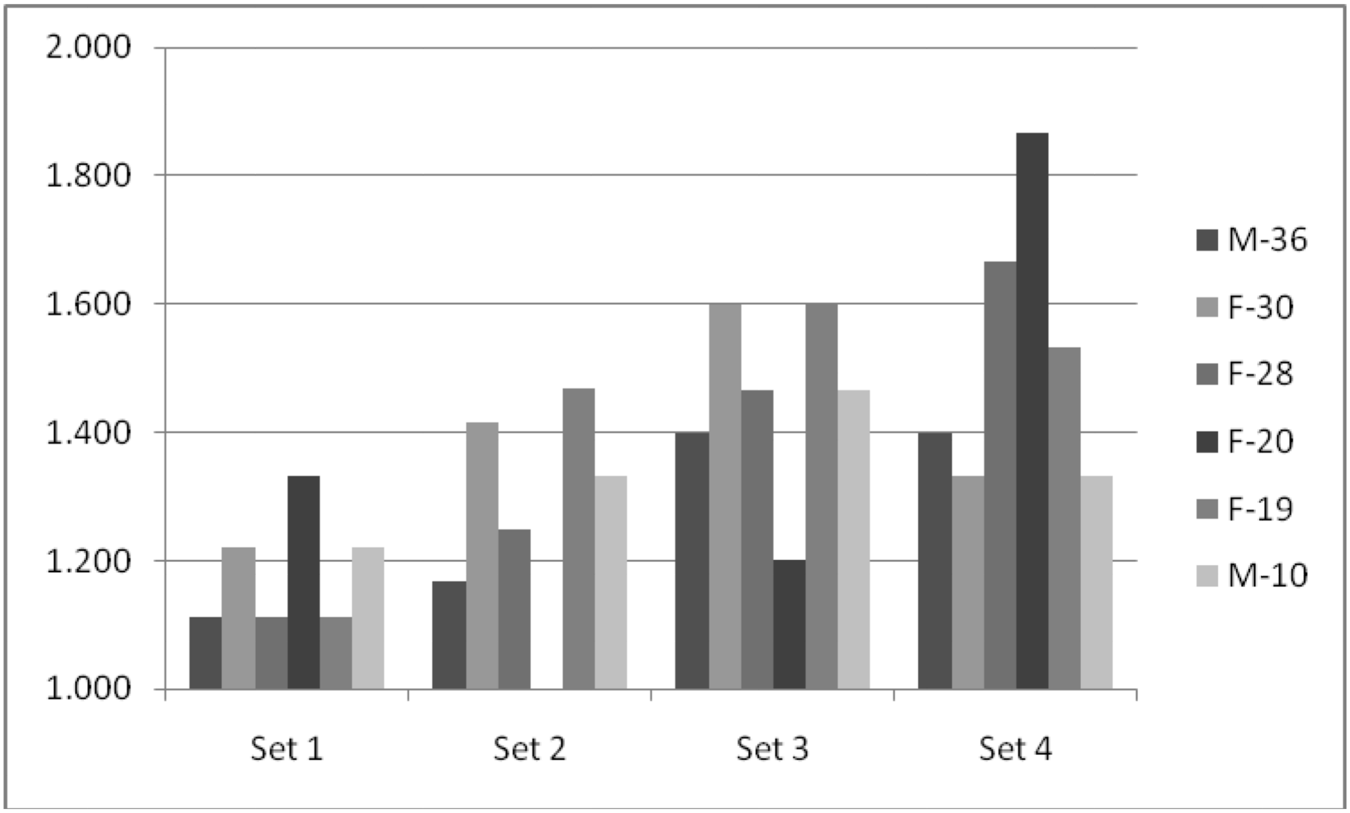

Figure 8.
Initial consonant variability scores for individual children with CIs.

Table 1

Background and audiometric information for children in the CI group. Ages in months.

Child Code (gender-age at implant)	**Etiology**	**Age Identified**	**Age at CI Activation**	**Age at Testing**	**Device (Processing Strategy)**	**Pre-CI Better-ear Unaided Thresholds (dB HL)**	**Averaged CI-aided Thresholds (dB HL, all available frequencies) at 18 – 24 months post-activation**
M-36	Unknown	32	37	61	Clarion (CIS)[2]	NR[1]	22
F-30	Connexin 26	12	31	55	Nucleus 24 (ACE)[3]	92.5	26
F-28	Unknown	23	29	53	Clarion (CIS)	NR	32
F-20	CMV[4]	10	21	45	Clarion (CIS)	NR-ABR[5]	28
F-19	Unknown	1	20	44	Clarion (CIS)	96	27.5
M-10	Unknown	2 days	11	35	Clarion (CIS)	NR	22

[1] No response to pure- or warble-tones,

[2] Continuous Interleaved Sampling,

[3] Advanced Combination Encoder,

[4] Cytomegalovirus,

[5] Auditory Brainstem Response