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Effects of early acoustic hearing on phonological processing in children with cochlear implants

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EFFECTS OF EARLY ACOUSTIC HEARING ON PHONOLOGICAL PROCESSING IN CHILDREN WITH COCHLEAR IMPLANTS

by

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Abstract: The effects of early acoustic hearing on performance on a non-word repetition test was examined for 29 children with cochlear implants (CIs). Children with normal hearing (NH) generally outperformed children with CIs in both phonetic and suprasegmental outcomes. For the children with CIs, those who had more early history of hearing aid (HA) use performed better on the non-word test than those with less HA use at an early age.
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Abbreviations

CNRep: Children’s Test of Non-word Repetition
SLI: Specific Language Impairment
CI: cochlear implant
NH: normal hearing
HA: hearing aid
CI-All: participants with at least one cochlear implant
CX26: connexin 26
EVA: enlarged vestibular aqueduct
CMV: cytomegalovirus
CI-BiMod: participants with one cochlear implant and one hearing aid
CI-BiLat: participants with two cochlear implants
CI-simBiLat: participants with two simultaneously implanted cochlear implants
CI-seqBiLat: participants with two sequentially implanted cochlear implants
C: Cochlear Americas
AB: Advanced Bionics
M: Med-El
PTA: pure-tone average
LF-PTA: low frequency pure-tone average
MLF-PTA: mid-low frequency pure-tone average
IPA: International Phonetic Alphabet
CASALA: Computer Aided Speech and Language Assessment
OLIMSPAC: Online Imitative Test of Speech Pattern Contrast Perception
VH: Vowel Height
VP: Vowel Place
CV: Consonant Voicing
CC: Consonant Continuance
CPf: pre-alveolar Consonant Place
CPr: post-alveolar Consonant Place
F0: fundamental frequency
F1: first formant frequency
F2: second formant frequency
Introduction

Children with severe-to-profound hearing loss generally have difficulty developing spoken language compared to typically developing age mates with normal hearing sensitivity. Even with appropriate intervention, delays have been documented in syntax, vocabulary, expressive and receptive language (Geers, Moog, Biedenstein, Brenner & Hayes, 2009), speech production (Connor, Craig, Raudenbush, Heavner & Zwolan, 2006), and phonological processing. Phonological processing skills enable a child to perceive and reproduce spoken language, and provide a foundation for word learning (Dillon, Cleary, Pisoni & Carter, 2004).

One way to assess phonological processing abilities in children is through the use of a non-word repetition task, such as the Children’s Test of Non-Word Repetition (CNRep) (Gathercole, Willis, Baddeley & Emslie, 1994). When imitating non-words, a child must generate responses to novel stimuli for which he/she has no previous phonological representation. The child is, hence, required to perceive and phonologically encode non-words using only auditory cues, store phonological representations in his or her working memory, and then replicate non-words with his or her articulators. Thus, a child’s performance on the non-word task reflects that child’s phonological processing, short-term memory, motor planning, and speech production skills (Dillon, Burkholder, Cleary & Pisoni, 2004). More quantitatively, the CNRep test allows assessment of a child’s ability to encode both segmental (e.g., correct consonants and vowels) and suprasegmental (e.g., correct number of syllables) features of non-words.

Previous studies have utilized non-word repetition tests to examine the phonological processing skills of typically-developing children (Gathercole, 1995) and of children with specific language impairment (SLI). Weismer et al. (2000) reported deficits in non-word
repetition ability in children with specific language impairment. Botting & Conti-Ramsden (2001) found a link between non-word repetition performance and language ability in children with SLI. For children with SLI, poor performance on non-word repetition tasks illustrates deficits in phonology, short-term memory, lexical knowledge, output processes, and serial recall (Ebbels, Dockrell & van der Lely, 2002; Archibald & Gathercole, 2006; Archibald & Gathercole, 2007).

Non-word repetition tasks have also been used to investigate the phonological processing abilities of children with cochlear implants (CIs). Previous studies compared non-word repetition performance of children with CIs to aged-matched children with normal hearing sensitivity (NH), and found NH children score higher on percentage of phonemes correct (Nittrouer, Caldwell-Tarr, Sansom, Twersky & Lowenstein, 2014; Geers, Davidson, Uchanski, & Nicholas, 2013) and percentage consonants correct (Geers et al., 2013). In other studies, the relations between CI children’s performance on the non-word repetition task and other skills were explored. Dillon, Pisoni, Cleary, & Carter (2004) examined segmental accuracy for twenty-four 8-10 year old children with CIs: they found 39% of consonants were produced correctly, and that non-word performance was positively correlated with spoken word recognition, language comprehension, working memory, and speech production. Dillon & Pisoni (2006) found 44% of vowels were produced correctly for a larger number (N=76) of 8-10 year children with CIs.

Suprasegmental analyses of non-word repetitions have also been conducted (Carter, Dillon, & Pisoni, 2002; Geers et al., 2013). Carter et al. found that while children with CIs (those same twenty-four 8-10 year olds in Dillon, Pisoni et al., 2004), on average, imitated successfully only 5% of the non-words, they produced the correct number of syllables 64% of the time and produced the correct location of primary stress 61% of the time. Carter et al. also
found non-word repetition performance was correlated with speech perception and with working memory. Geers et al. (2013) compared the accuracy of NH and CI children in producing the correct number of syllables and correct stress pattern. Their group (sixty 9-13 year olds) of CI children performed poorer in these suprasegmental measures than did NH children.

Researchers have also investigated the relations between audiological factors and non-word repetition performance. Cleary, Dillon & Pisoni (2002) found that duration of deafness prior to implantation is negatively correlated with non-word repetition performance. Dillon & Pisoni (2006) found a positive correlation between non-word repetition performance and age at onset of deafness. In this study of 14 CI children (8-10 years old), there was no mention of the amount of residual hearing (pre- or post-implant unaided or aided audiometric thresholds) or of the duration of HA use prior to cochlear implantation. In Dillon, Pisoni et al. (2004), a positive correlation was found between age of onset of deafness and non-word repetition performance. Nittrouer et al. (2014) found that early implantation and HA use on the unimplanted ear at the time of receiving the 1st CI were both positively correlated with better performance on a non-word repetition task. Additionally, non-word repetition performance generally improves with age for all children, including those with CIs. This improvement can, in part, be credited to developmental changes, as can be seen in the performance curve of percentage consonants correct, as a function of age, developed by Campbell, Dollaghan, Janosky & Adelson (2013).

It is clear that early cochlear implantation promotes speech and language development in children with severe to profound hearing loss (Svirsky, Teoh & Neuburger, 2004; Nicholas & Geers, 2006; Niparko et al., 2010). There is also growing evidence that children with better pre-implant residual hearing and who use a HA on the unimplanted ear have, on average, better spoken language than those with poorer pre-implant residual hearing (Nicholas & Geers, 2007;
Nittrouer & Chapman, 2009). In the present study, the relations between ‘early acoustic hearing’ and phonological processing abilities in children with CIs will be examined. Here, ‘early acoustic hearing’ will be described by pre- and post-implant audiograms, and durations of HA use. Phonological processing abilities will be assessed by various performance measures on the CNRep test.

**Methods**

**Participants**

Inclusion criteria for the CI group are:

- Chronological age: 4 years 11 months – 8 years 11 months
- Severe-to-Profound hearing loss, congenital or acquired before 15 months of age
- Age at first CI < 3 years
- Education in oral communication setting, in either a mainstream or oral special education classroom
- Hearing loss as primary disability with normal cognitive function
- No CI device failures lasting more than 30 days

Inclusion criteria for the NH group are:

- Chronological age: 4 years 11 months – 8 years 11 months
- NH sensitivity as defined by pure-tone thresholds of 15 dB HL or less at .25 to 4 kHz
- No significant history of middle-ear disease lasting more than a month since infancy
- Normal cognitive function

Data from 43 children participating in an ongoing nationwide study were analyzed in this project; 14 children with NH and 29 children with cochlear implants (CI). These 29 children presented with a variety of etiologies including Connexin 26 mutation (CX26), enlarged
vestibular aqueduct (EVA), exposure to cytomegalovirus (CMV), idiopathic causes, and a variety of syndromes. Of the children with CIs, seven were bimodal users (CI-BiMod) and 22 had bilateral cochlear implants (CI-BiLat). Five of the 22 bilateral implant users were implanted simultaneously (CI-simBiLat) and 17 were implanted sequentially (CI-seqBiLat), with the time between surgeries ranging from 5 to 35 months (mean: 9.6; SD: 9.6). The CI devices used by these children include all three cochlear implant manufacturers; 29 Cochlear Americas (C) devices, 20 Advanced Bionics (AB) devices, and 2 Med-El (M) devices. All of the seven bimodal users wore Phonak Naida hearing aids.

The NH participants ranged from 5 to 8.4 years (mean: 6.9; SD: 2.1) and the CI participants ranged from 4.9 to 8.9 years (mean: 7.4; SD: 1.2) at the time of testing (Figure 1). Demographic information for the NH participants is listed in Table 1. Demographics, device information, and HA use for the CI participants is shown in Table 2. Audiologic data documenting ‘early acoustic hearing’ were collected from the child’s managing audiologist, educational setting, and parental questionnaires. Pre-implant acoustic aided and unaided pure-tone averages (PTAs) are provided in Table 3. The PTAs were calculated using the thresholds at 500, 1000 and 2000 Hz. Additionally, low frequency PTAs (LF-PTA) were calculated using the thresholds at 250 and 500 Hz, and mid-low frequency PTAs (MLF-PTA) were calculated using the thresholds at 250, 500 and 1000 Hz. For the participants who had a no response at a frequency, the maximum output of the audiometer was used as the threshold.

Duration of HA use, at the time of testing, was calculated for each participant based on their device configuration. For the CI-BiMod participants, the participant’s age at which they received a first HA was subtracted from their age at test day. For the CI-seqBiLat participants, the participant’s age at which they received a first HA was subtracted from their age at which
they received the second CI. For the CI-simBiLat participants, the participant’s age at which they received their first HA was subtracted from the age at which they received the simultaneously-implanted CIs. Duration of bimodal use was also calculated. For the CI-BiMod and CI-seqBiLat participants, this value is the duration of HA use minus the age difference between 1st CI and 1st HA. For the CI-simBiLat participants, this value is zero. Three additional durations of HA use were calculated for each participant: duration of HA use at 18 months, 24 months, and 36 months of age. An algorithm (a set of rules) for calculating the Duration of HA use at a particular age (Age_{cut}) is provided in Appendix A.

A variable named “CI interval” was also calculated for each participant based on device configuration. For the CI-BiMod participants, the participant’s age at which they received their CI was subtracted from their age at test day. For the CI-seqBiLat participants, the age at which they received their second CI was subtracted from the age at which they received their first CI. For all of the CI-simBiLat participants, the CI interval was zero. These audiologic data are listed in Tables 2 and 3.

**Outcome Measures**

The shortened adapted version of the Children’s Test of Non-Word Repetition (CNRep; Gathercole et al., 1994) was used to assess phonological processing abilities of CI children. Scores based on both segmental and suprasegmental properties of 20 non-words (which range from 2 to 5 syllables in length) are reported for each child. Speech imitations were recorded at several off-site locations as a part of data collection for an ongoing study. For each of the 20 non-words in the CNRep spoken by a female talker, the child was instructed to repeat back the “funny word” (non-word) played from a loudspeaker at a level of approximately 65 dBA. All 43
children produced a response for each non-word with the exception of two children, who each omitted one response. These digitized waveform files were played using Praat software (Boersma & Weenink, 2001) and were transcribed manually. The transcriptions, using the International Phonetic Alphabet (IPA, International Phonetic Association 1999), were entered into Computer Aided Speech and Language Assessment (CASALA) software for later analyses (Serry & Blamey, 1999). An initial pass was completed by a primary transcriber, followed by a second pass with both the primary transcriber and one reader. Several rules were created for consistency in transcriptions: these are listed in Appendix B. For each non-word, the transcribers also scored using a binary value, the accuracy of three characteristics: (i) the number of syllables in the imitated non-word, (ii) the stress pattern of the imitated non-word, and (iii) the entire phonetic sequence in the imitated non-word. A correctly imitated stress pattern necessitates the correct number of syllables in the imitated non-word. If a child correctly imitates both the stress pattern and the entire phonetic sequence for a non-word, then the ‘complete word’ would be scored as correct (binary value ‘1’) automatically from the stress score (“1”) and entire phonetic sequence score (“1”). Using CASALA software and the transcriptions that were entered, three reports were generated: the percentage correct consonants, percentage correct vowels, and percentage correct consonant clusters.

For some non-words, the phonetic transcription was modified to allow several alternate targets pronunciations. The 20 non-word stimuli, including acceptable alternate pronunciations, are listed in Table 4. Also listed are the number of vowels, consonants, and clusters in each non-word, as well as the stress pattern. Examples of reports from perfect imitations are provided in Appendices C and D (Serry & Blamey, 1999).
Two additional types of outcome measures, collected previously, were used for correlational analysis with the non-word repetition scores collected in this current study. The first type of outcome was from the OLIMSPAC test, or Online Imitative Test of Speech Pattern Contrast Perception (Boothroyd, Eisenberg, & Martinez, 2006). OlimSPAC assesses segmental perception at the phoneme level. Six contrasts are evaluated: Vowel Height (VH), Vowel Place (VP), Consonant Voicing (CV), Consonant Continuance (CC), pre-alveolar Consonant Place (CPf), and post-alveolar Consonant Place (CPr). In this administration of the test, the child listened to and imitated a total of 96 vowel-consonant-vowel syllables, representing these 8 contrasts, presented in an auditory alone condition. An examiner, who is “blinded” to the test presentations, listens to the child’s imitation and chooses from a closed-set of eight syllables the syllable that best represents the child’s utterance. Scoring is recorded automatically by the OlimSPAC software.

The second type of outcome measure is the child’s performance on a stress discrimination test. This test evaluates whether a child can discriminate stress patterns of bisyllabic (CVCV) non-words. Children listen to a total of 24 trials. In each trial, two non-words are presented acoustically, and the child is asked to choose whether the two non-words (described to the children as “silly” words) were spoken with the same pattern or with different stress patterns. The bisyllabic words could have stress on the first syllable (trochaics stress), stress on the second syllable (iambic stress), or equal stress on each syllable (spondaic stress). Each child completed a training session before the actual test was administered.

**Inter-rater Reliability**

Inter-rater reliability was assessed by having a Speech-Language Pathologist (Transcriber 2) who was unfamiliar with the study transcribe imitations from 6 participants (~ 15% of this
sample). Transcriber 2 scored the three binary characteristics (number of syllables, stress pattern, and entire phonetic sequence) and transcribed the non-words from three participants in the NH group and three participants in the CI-All group. The correlation between the ‘correct number of syllable’ scores of Transcriber 1 (the primary transcriber) and those of Transcriber 2 was .95. Similarly, the correlation between the ‘correct stress pattern’ scores of Transcriber 1 and Transcriber 2 was .89. And, for the CASALA-generated reports from the transcriptions, the correlations were .91, .97 and .78, respectively, for proportion consonants correct, proportion vowels correct, and proportion clusters correct. Figures 2 and 3 display the proportion consonants and vowels correct scores for Transcribers 1 and 2 for the six participants in the reliability study.

Results

Word-level Scores

All participants were scored for accuracy for number of syllables correct, correct stress pattern, and correct entire phonetic sequence. Word-correct scores were calculated automatically (from stress and entire phonetic sequence scores). These results for each participant, separated into the NH and CI groups, are listed in Tables 5 and 6, and displayed in Figures 4 through 7.

For the NH group, the proportion of repeated non-words with the correct number of syllables ranged from .80 to 1.0 (mean: .94, SD: .06). The proportion of repeated non-words with the correct stress pattern ranged from .55 to 1.0 (mean: .84, SD: .13). The proportion of repeated non-words with the correct entire phonetic sequence ranged from .15 to .80 (mean: .42, SD: .20). The proportion of repeated total non-words correct ranged from .15 to .80 (mean: .40, SD: .20). For the CI group, the proportion of repeated non-words with the correct number of syllables ranged from .60 to 1.0 (mean: .86, SD: .13). The proportion of repeated non-words with the
correct stress pattern ranged from .40 to 1.0 (mean: .79, SD: .18). The proportion of repeated non-words with the correct phonetic sequence and that were entirely correct ranged from 0 to .40 (mean: .13, SD: .13). Accuracy scores by age can be seen for the NH listeners and the three sub-groups of CI users (CI-BiMod, CI-seqBiLat, and CI-simBiLat) in Figures 8 through 11.

**Transcription-based Scores**

Reports were generated via CASALA on percent consonants correct, percent vowels correct, and percent clusters correct. The results for all transcription-based scores for each participant are listed in Tables 5 and 6, and are displayed in Figures 12 through 14.

For the NH group, proportion consonants correct in the set of non-words ranged from .63 to .96 (mean: .82, SD: .11). Proportion vowels correct in the set of non-words ranged from .67 to .92 (mean: .81, SD: .10). Proportion clusters correct in the set of non-words ranged from .40 to .90 (mean: .64, SD: .17). For the CI group, proportion consonants correct in the set of non-words ranged from .39 to .85 (mean: .64, SD: .14). Proportion vowels correct in the set of non-words ranged from .40 to .91 (mean: .67, SD: .16). Proportion clusters correct in the set of non-words ranged from .04 to .77 (mean: .41, SD: .20). Accuracy scores by age can be seen for the NH listeners and the three sub-groups of CI users (CI-BiMod, CI-seqBiLat, and CI-simBiLat) in Figures 15 through 17.

**Correlational Analysis and Relationships**

Data analysis was performed using Pearson correlations; the results of this analysis are listed in Table 7. Correlational analysis revealed a positive correlation between OlimSPAC composite scores and all measures of non-word repetition performance. The strongest of these correlations was between OlimSPAC composite and proportion vowels correct, and these data are displayed in Figure 18. There were also significant positive correlations between a child’s
performance on the stress discrimination and non-word repetition tasks. Two of these significant correlations with stress discrimination are shown in Figures 19 and 20, namely phonetic sequence and vowels correct, respectively. A positive correlation was also found between duration of HA use at 24 months of age and proportion of repeated non-words with correct phonetic sequence; this relation is displayed in Figure 21. Also of note is the absence of a significant correlation between non-word repetition performance and two commonly-examined CI demographic variables: namely, age at first CI and the CI interval. These relations are displayed in Figures 22 and 23.

Discussion

Both groups had the same performance pattern: the best scores were achieved for proportion number of syllables correct followed by proportion correct stress pattern, proportion vowels correct, proportion consonants correct, proportion clusters correct, proportion correct phonetic sequence and proportion correct total word in the set of non-words. While their performance patterns are the same, overall the CI participants performed nearly the same, or more poorly, than the NH participants non-words. Qualitative analysis reveals most similar performance by both groups for proportion vowels correct, proportion correct stress pattern and proportion number of syllables correct. Performance on proportion consonants correct, proportion clusters correct, proportion of the repeated non-words with correct phonetic sequence and proportion of repeated correct non-words was most different.

Comparisons of these results to those reported previously are complicated for several reasons, including the fact that many of the published results do not represent independent groups of participants. All the reports by Indiana University-based researchers are based on the same set of 76 8-10 years CI users, or a sub-set of these 76 CI users (Carter et al., 202; Cleary et
The studies by Geer et al. (2013) and Nittrouer et al. (2014) report non-word performance from two other (independent) groups of CI users, 60 9-13 year old children and 55 8½ year old children, respectively. However, in the study by Nittrouer et al, the non-words are simpler than those used in all the other reports; the list used by Nittrouer et al. has a maximum of four syllables, no consonant clusters, an intentionally limited set of vowels, and the stimuli were presented as a video recording. A noteworthy difference between this study and previous reports is the age range of the participants. The participants in the current study are significantly younger, between the ages of 4-8, than those of other reports.

Average performance for number of syllables (86%) was higher than the previously reported scores of 66% correct (Cleary et al., 2002); 64% correct (Carter et al., 2002); and 55% correct (Dillon & Pisoni, 2006). Almost identical performance was found in the Geers et al. (2013) study, 85% correct. These CI participants produced the correct stress pattern 79% of the time. Previous studies analyzing stress pattern found somewhat lower performance, 61% correct (Carter et al., 2002) and 65% correct (Geers et al., 2013). These CI participants achieved a score of 64% consonants correct. Similar performance of 73% consonants correct was found in the Geers et al. study while lower scores of 33% correct and 30% correct were reported in Dillon, Pisoni et al. (2004) and Dillon & Pisoni (2006). Dillon & Pisoni also found lower performance on percent vowels correct, 44% compared to the reported 67% correct in the current study. Correct phonetic sequence performance has been reported as low as 5% correct (Carter et al., 2002; Dillon, Cleary et al., 2004), and as high as 27% correct (Geers et al., 2013). The current study found performance at a level of 13%. There are no previous reports of the proportion of consonant clusters produced correctly by children with CIs: no comparisons can be made. On all
measures, this sample performed better than the CI children in the set of articles from Indiana University researchers (all based on the same 76 CI users). Compared to the older children (9-13 yrs of age) in the Geers (2013) study, these child CI users have comparable, or better, scores for suprasegmental outcomes, but, on average, poorer scores on the segmental outcomes. Overall, there was more variability in the performance of the CI participants than amongst the NH children, a trend also found in the study by Cleary et al. (2002). It is also clear, from the Tables and box-plots of results, that some CI participants achieved scores comparable to those of the NH participants. This suggests that, at least for some children, early cochlear implantation can lead to performance equivalent to NH peers. A similar result was found by Geers et al. (2013).

The significant correlations between scores on the OlimSPAC and non-word repetition tasks for the CI group suggest that these two measures are similar; they both assess the ability to perceive and produce individual phonemes of spoken language. Possible confounding effects of a child’s lexical or vocabulary knowledge on performance in these two tests should be reduced to some degree by their designed use of phoneme-level contrasts and non-words instead of real words. By contrast, word or sentence level perceptual tests are highly influenced by a child’s existing vocabulary level (Blamey et al., 2001) and may not provide an accurate assessment of what Boothroyd calls a child’s inherent “auditory capacity” (Boothroyd & Eran, 1994).

The correlation between scores on the stress discrimination test and the non-word repetition test, specifically the phonetic sequence and vowels portions, suggest that the ability to discriminate stress patterns, and perceive and produce sequences of vowels and consonants are related. Both of these tasks are likely related to the child’s ability to resolve spectral and amplitude/timing information in the speech signal. The two-syllable stimuli in the stress discrimination test differed in fundamental frequency (F0), the relative durations of the syllables
and the amplitudes of the syllables. It has been shown that before normal hearing infants are able to encode phonemes unique to their language; they attend to the acoustic cues of intonation, stress and rhythm (suprasegmental perception) to parse the continuous speech stream into words (Jusczyk, P. W., Houston, D. M. & Newsome, M., 1999). Infants selectively attend to intonation/pitch changes at the end of clauses and within pairs of syllables that are predominantly trochaic (i.e., stress on the first syllable) to pick out words in connected speech (Seidl & Johnson, 2008; Swingley, 2009; Seidl & Cristia, 2008). Thus the correlation of these measures may indicate that both segmental and suprasegmental abilities are necessary for both word recognition and vocabulary acquisition. And, examining a child’s ability to discriminate stress may offer insight into how well a child can discriminate phoneme segments in language.

Several audiological variables were examined for their possible relation to non-word repetition abilities. Of note is the lack of correlation between ‘age at CI’ and performance on the non-word repetition test, for this group of CI recipients. While some report that ‘age at CI’ is related to both speech perception and language outcomes (e.g., Geers et al., 2013), Nittrouer and colleagues (2014) also failed to find a significant correlation between ‘age at CI’ and non-word repetition performance. Additionally, no significant correlations were found between acoustic aided or unaided thresholds, and non-word repetition for these 29 CI children. These results are in contrast to Geers et al. (2013) who found that pre-implant aided thresholds were correlated with most measures of spoken language. Similar to our results, Nittrouer and colleagues (2014) also reported no significant correlation between unaided pre-implant thresholds and measures of non-word repetition. In this study, one acoustic demographic variable was found to be correlated with a non-word repetition outcome, namely the duration of HA use at 24 months is correlated with phonetic sequence scores ($r = .451$, $p = .014$). At 24 months of age, those children who had
used a HA for a longer period of time demonstrated higher scores. This was not true for duration of use calculated at 18 months of age or 36 months of age. Whether these results (a significant correlation with HA use at 24 months of age and no significant correlations with HA use at 18 or 36 months of age) hold for a larger sample of children, remains to be seen. If these results hold, then it would appear that the optimum period for acoustic hearing was from the time the HA was fit through two years of age. It is interesting to note that while Nittrouer and colleagues found that their group of CI patients with some period of hearing use scored significantly higher on non-word repetition than those who reported no HA use at all, their correlation between duration of HA use and non-word repetition scores was not statistically significant. The authors reported that this may likely have been the result of a small sample size.

**Conclusion**

In conclusion, some children with CIs perform similar to their age mates with normal hearing on a test of non-word repetition, though most perform more poorly. CI children’s performance on the non-word repetition test was correlated with performance on a phoneme-level test of speech pattern contrasts, reflecting the idea that auditory perceptual abilities are necessary for both tasks. The ability to discriminate stress patterns (iambic vs. trochaic vs. spondaic stress) was also associated with the ability to perceive and produce phoneme sequences in spoken non-words. This may reflect the importance of suprasegmental perception for phoneme and ultimately word recognition. Future studies should consider the clinical utility of tests of suprasegmental abilities such as stress when evaluating devices.
References


*Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1536), 3617-3632.

Table 1 Demographic information for participants with normal hearing (NH).

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**EVA**

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Table 7 Correlations between non-word repetition performance, speech perception measures, and demographic information

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**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).
Figure 1: Boxplot of the ages of the participants separated into NH and CI-All groups. The upper edge of the box is the upper quartile of the distribution, the lower edge is the lower quartile of the distribution, the middle line is the median, and the whiskers represent the maximum and minimum of the distribution.
Figure 2: Correlation between percent correct consonants score for Transcriber 1 and Transcriber 2 for 6 selected participants; the dashed line represents the line of perfect match between transcribers.
Figure 3: Correlation between percent correct vowels score for Transcriber 1 and Transcriber 2 for 6 selected participants; the dashed line represents the line of perfect match between transcribers.
Figure 4: Boxplot of the proportion of repeated non-words with correct number of syllables of the participants separated into NH and CI groups. The upper edge of the box is the upper quartile of the distribution, the lower edge is the lower quartile of the distribution, the middle line is the median, and the whiskers represent the maximum and minimum of the distribution.
Figure 5: Boxplot of the proportion of repeated non-words with correct stress pattern separated into NH and CI groups. The upper edge of the box is the upper quartile of the distribution, the lower edge is the lower quartile of the distribution, the middle line is the median, and the whiskers represent the maximum and minimum of the distribution.
Figure 6: Boxplot of the proportion of repeated non-words with correct phonetic sequence separated into NH and CI groups. The upper edge of the box is the upper quartile of the distribution, the lower edge is the lower quartile of the distribution, the middle line is the median, and the whiskers represent the maximum and minimum of the distribution.
Figure 7: Boxplot of the proportion of repeated correct non-words separated into NH and CI groups. The upper edge of the box is the upper quartile of the distribution, the lower edge is the lower quartile of the distribution, the middle line is the median, and the whiskers represent the maximum and minimum of the distribution.
Figure 8: Scatterplot of the proportion of repeated non-words with correct number of syllables by age, shown separately for NH, CI-BiMod, CI-seqBiLat and CI-simBiLat participants.
Figure 9: Scatterplot of the proportion of repeated non-words with correct number of stress pattern by age, shown separately for NH, CI-BiMod, CI-seqBiLat and CI-simBiLat participants.

$r = .196$
Figure 10: Scatterplot of the proportion of repeated non-words with correct phonetic sequence by age, shown separately for NH, CI-BiMod, CI-seqBiLat and CI-simBiLat participants.

Proportion correct: phonetic sequence vs. Age

Proportion of repeated Nonwords with correct phonetic sequence vs. Age

$\textit{r} = .081$
Figure 11: Scatterplot of the proportion of repeated correct non-words by age, shown separately for NH, CI-BiMod, CI-seqBiLat and CI-simBiLat participants.
Figure 12: Boxplot of the proportion consonants correct in the set of non-words separated into NH and CI groups. The upper edge of the box is the upper quartile of the distribution, the lower edge is the lower quartile of the distribution, the middle line is the median, and the whiskers represent the maximum and minimum of the distribution.
Figure 13: Boxplot of the proportion vowels correct in the set of non-words separated into NH and CI groups. The upper edge of the box is the upper quartile of the distribution, the lower edge is the lower quartile of the distribution, the middle line is the median, and the whiskers represent the maximum and minimum of the distribution.
Figure 14: Boxplot of the proportion clusters correct in the set of non-words separated into NH and CI groups. The upper edge of the box is the upper quartile of the distribution, the lower edge is the lower quartile of the distribution, the middle line is the median, and the whiskers represent the maximum and minimum of the distribution.
Figure 15: Scatterplot of the proportion consonants correct in the set of non-words by age, shown separately for NH, CI-BiMod, CI-seqBiLat and CI-simBiLat participants.
Figure 16: Scatterplot of the proportion vowels correct in the set of non-words by age, shown separately for NH, CI-BiMod, CI-seqBiLat and CI-simBiLat participants.
Figure 17: Scatterplot of the proportion clusters correct in the set of non-words by age, shown separately for NH, CI-BiMod, CI-seqBiLat and CI-simBiLat participants.
Figure 18: Scatterplot of OlimSPAC Composite score by proportion vowels correct for CI-BiMod, CI-seqBiLat and CI-simBiLat participants.
Figure 19: Scatterplot of Stress Discrimination by proportion of repeated non-words with correct phonetic sequence for CI-BiMod, CI-seqBiLat and CI-simBiLat participants.

$r = .506^*$
Figure 20: Scatterplot of Stress Discrimination by proportion vowels correct in the set of non-words for CI-BiMod, CI-seqBiLat and CI-simBiLat participants.
Figure 21: Scatterplot of proportion of repeated non-words with correct phonetic sequence by duration of HA use at 24 months for CI-BiMod, CI-seqBiLat and CI-simBiLat participants.

Proportion of repeated Nonwords with correct phonetic sequence vs. Duration of HA Use at 24 Months

$r = .451*$

Figure 21: Scatterplot of proportion of repeated non-words with correct phonetic sequence by duration of HA use at 24 months for CI-BiMod, CI-seqBiLat and CI-simBiLat participants.
Figure 22: CI interval by Proportion of repeated non-words with correct phonetic sequence for CI-BiMod, CI-seqBiLat and CI-simBiLat participants. 

$r = -.024$
Figure 23: Age at 1st CI by Proportion of repeated non-words with correct phonetic sequence for CI-BiMod, CI-seqBiLat and CI-simBiLat participants.

$r = -.177$
Appendix A

Algorithm for computing
Durations of Hearing Aid use at a particular Age

Variables:
\( \text{Age}_{\text{cut}} \) = the ‘cutoff’ age, or particular age, for which to calculate Duration of HA use
\( \text{HA}_1 \) = the age at which the child received his/her 1st hearing aid
\( \text{CI}_1 \) = the age at which the child received his/her 1st cochlear implant \([\text{CI}_1 > 0]\)
\( \text{CI}_2 \) = the age at which the child received his/her 2nd cochlear implant, if applicable

To Calculate the variable HA\(_{\text{use}}\)@\(\text{Age}_{\text{cut}}\)

\[
\begin{align*}
\text{If CI}_2 &= 0 \ [\text{this is the case for Bimodal users}] \\
\text{If } \text{Age}_{\text{cut}} &> \text{HA}_1 \\
\text{HA}_{\text{use}}@\text{Age}_{\text{cut}} &= \text{Age}_{\text{cut}} - \text{HA}_1 \\
\text{Else} \\
\text{HA}_{\text{use}}@\text{Age}_{\text{cut}} &= 0 \\
\text{Elseif (CI}_2 > \text{CI}_1 \) & [Bilateral Sequential CI users] \\
\text{If } \text{Age}_{\text{cut}} &< \text{CI}_2 \\
\text{If } \text{Age}_{\text{cut}} &> \text{HA}_1 \\
\text{HA}_{\text{use}}@\text{Age}_{\text{cut}} &= \text{Age}_{\text{cut}} - \text{HA}_1 \\
\text{Else} \\
\text{HA}_{\text{use}}@\text{Age}_{\text{cut}} &= 0 \\
\text{Else (i.e., } \text{Age}_{\text{cut}} &\geq \text{CI}_2) \\
\text{If } \text{CI}_2 &> \text{HA}_1 \\
\text{HA}_{\text{use}}@\text{Age}_{\text{cut}} &= \text{CI}_2 - \text{HA}_1 \\
\text{Else} \\
\text{HA}_{\text{use}}@\text{Age}_{\text{cut}} &= 0 \\
\text{Elseif (CI}_2 = \text{CI}_1 \) & [Bilateral Simultaneous CI users] \\
\text{If } \text{Age}_{\text{cut}} &< \text{CI}_1 \ (\text{which is also } \text{CI}_2) \\
\text{If } \text{Age}_{\text{cut}} &> \text{HA}_1 \\
\text{HA}_{\text{use}}@\text{Age}_{\text{cut}} &= \text{Age}_{\text{cut}} - \text{HA}_1 \\
\text{Else} \\
\text{HA}_{\text{use}}@\text{Age}_{\text{cut}} &= 0 \\
\text{Else (i.e., } \text{Age}_{\text{cut}} &\geq \text{CI}_1) \\
\text{If } \text{CI}_1 &> \text{HA}_1 \\
\text{HA}_{\text{use}}@\text{Age}_{\text{cut}} &= \text{CI}_1 - \text{HA}_1 \\
\text{Else} \\
\text{HA}_{\text{use}}@\text{Age}_{\text{cut}} &= 0 \\
\end{align*}
\]

endif
Appendix B

Rules for Transcription

• If the number of syllables in an utterance is wrong, the stress is automatically wrong

• If there is more than one utterance recorded for a nonword target, the first one should be used unless further utterances are much clearer. The utterance transcribed is noted in the “repeat number” column with a 1 or 2.

• If a subject false starts, ignore the false start and transcribe the first whole utterance

• There are two ways to account for missing data in the transcript. If the recording includes the target but the child does not or cannot make an attempt to imitate for whatever reason, the child will receive 0s. If the target is not on the recording or it is not viable, the target will not be included in the transcript. It will be omitted and the child will not be penalized

• Some subjects put emphasis on certain syllables but it does not effect the primary stress location

• Stress patterns that are question-like: make a judgment call on counting stress correct or incorrect

• When a subject is uncertain, they can be very soft and whisper-like, it can be hard to hear correct stress

• Compare subject’s stress pattern to recorded model and use best judgment on stress if there are any questions
Appendix C

Perfect Percentage Consonants Correct report from CASALA

### Percentage Consonants Correct - Broad

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**PCC**

All figures include consonants in clusters as well as singleton consonants.

Total no of words = 20
No of words correct = 20
Percentage of words correct = 100.0 %
Appendix D

Perfect Phonetic Inventory report from CASALA

## Phonetic Inventory - Broad

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| Monophthongs | 2 | 60 | 4 | 66 | 2 | 60 | 4 | 66 | 100% | 100% | 100% | 2 | 60 | 4 | 66 |
| Diphthongs   | 0 | 4  | 0 | 4  | 0 | 4  | 0 | 4  | 100% | 100% | 100% | 0 | 4  | 0 | 4  |
| Vowels       | 2 | 64 | 4 | 70 | 2 | 64 | 4 | 70 | 100% | 100% | 100% | 2 | 64 | 4 | 70 |
| Consonants   | 13 | 35 | 11 | 59 | 13 | 35 | 11 | 59 | 100% | 100% | 100% | 13 | 35 | 11 | 59 |
| Phonemes     | 15 | 99 | 15 | 129| 15 | 99 | 15 | 129| 100% | 100% | 100% | 15 | 99 | 15 | 129|
| Clusters     | 5  | 12 | 5  | 22 | 5  | 12 | 5  | 22 | 100% | 100% | 100% | 5  | 12 | 5  | 22 |

Total no of words = 20
No of words correct = 20
Percentage of words correct = 100.0%

Phonemes acquired according to the TARGET criteria (correct occurrences >= 2, percent correct >= 50%)

Monophthongs:
\[ \text{e, a, i, a, u, o} \]

Diphthongs:
\[ \text{et} \]

Consonants:
\[ \text{t, d, f, k, l, n, p, r, s, t, v, z} \]

Phonemes acquired according to the TARGETLESS criterion (occurrences >= 2)

Monophthongs:
\[ \text{e, a, i, a, u, o} \]

Diphthongs:
\[ \text{et} \]

Consonants:
\[ \text{t, d, f, k, l, n, p, r, s, t, v, z} \]