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Durations of repeated non-words for children with cochlear implants

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DURATIONS OF REPEATED NON-WORDS FOR CHILDREN WITH COCHLEAR IMPLANTS

by

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Abstract: Durations of syllables for repeated non-words were calculated for 76 children with cochlear implants (CIs) and 16 children with normal hearing (NH). Average syllable durations did not differ significantly between the groups, however a final syllable lengthening ratio in CI children was significantly shorter than for their NH peers. Measures of hearing related demographics were not correlated with CI syllable measures.

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Abbreviations

CNRep: Children's Test of Non-word Repetition

CI: cochlear implant

NH: normal hearing

HA: hearing aid

BM: participants with one cochlear implant and one hearing aid (Bimodal)

CI-BiLat: participants with two (Bilateral) cochlear implants

simCI: participants with two cochlear implants, implanted simultaneously

seqCI: participants with two cochlear implants, implanted sequentially

PTA: pure-tone average

LF-PTA: low frequency pure-tone average

Introduction

Good speech perception is often considered the gold standard of performance for users of hearing aids (HAs) and/or cochlear implants (CIs). While good speech perception is foremost, good speech *production* should also be considered. Children with severe-to-profound hearing loss have difficulty developing spoken language, even with appropriate intervention as compared to their normal hearing aged mates (Connor, Craig, Raudenbush, Heavner, & Zwolan, 2006; Monsen, 1974; Robb & Pang-Ching, 1992; Uchanski & Geers, 2003). Speech perception and speech production are closely related, however the acoustic cues needed for accurate production are much more finite and specific than those needed for perception (Peng, Tomblin, & Turner, 2008; Tye-Murray, Spencer, & Gilbert-Bedia, 1995). Good speech production generally: i) facilitates spoken communication, ii) reflects good hearing abilities, and iii) might not develop fully in child CI users as their auditory feedback is degraded at early ages due to hearing loss. Children with CIs have poorer speech production skills compared to their age mates with normal hearing sensitivity. Specifically, children with CIs exhibit poorer overall speech intelligibility as well as poorer vocal quality (i.e. pitch control, speaking rate etc.) (Burkholder & Pisoni, 2003; Carter, Dillon, & Pisoni, 2002; Cleary, Dillon, & Pisoni, 2002; Dillon, Cleary, Pisoni, & Carter, 2004; Guerrero Lopez, Mondain, Breteque, Serrafero, Trottier &Barkat-Defradas, 2013; Nicholas & Geers, 2006; Niparko et al., 2010; Peng et al., 2008; Poissant, Peters, & Robb, 2006; Tobey, Geers, Brenner, Altuna, & Gabbert, 2003; Tobey, Geers, Sundarrajan, & Shin, 2011).

Pisoni and colleagues have focused research efforts on using an information processing model to examine the substantial variability seen in spoken language outcomes in pediatric cochlear implant recipients (Dillon, Burkholder, Cleary, & Pisoni, 2004). Under this model the ability to perceive and produce an auditory stimulus involves a hierarchical sequence of processes including sensation, perception, attention, learning and memory. This type of model

views the human nervous system as an information processing system that encodes, stores and manipulates various types of symbolic representations (Haber, 1969; Lachman, Lachman, & Butterfield, 1979). Working memory, and in particular verbal short-term memory, has been reported to be associated with normal-hearing children's ability to recognize and comprehend spoken words (Gathercole, Hitch, Service, & Martin, 1997; Gupta & McWhinney, 1997). Working memory has been described as a temporary storage mechanism for holding, in conscious awareness, information obtained from perception or retrieved from long-term memory (Baddeley, 1992; Baddeley & Hitch, 1975; Pisoni, 2000). The strategy to maintain information in short term memory, until it is recalled, is referred to as rehearsal. In the case of repeating items out loud or silently, this strategy is called verbal rehearsal (Atkinson & Shiffrin, 1968). Moreover, studies in adults and children suggest that measures of speech production speed are related to verbal rehearsal speed (Landauer, 1962; McGilly & Siegler, 1989; Standing & Curtis, 1989).

Two early studies by Pisoni and colleagues examine the relation between verbal working memory and speech production. They examined the relation between the timing of speech produced by pediatric CI users (average sentence duration) and verbal working memory (performance on a digit span task) (Burkholder & Pisoni, 2003; Pisoni & Cleary, 2003). Burkholder and Pisoni (2003) found that children with CIs displayed longer sentence durations and shorter digit spans compared to their normal hearing age mates. They suggested that the longer sentence durations and poorer working memories (shorter digit spans) resulted from an early period of auditory deprivation and its consequent impact on brain plasticity. Pisoni and Geers (2000) found that the intelligibility of the speech produced by these same pediatric CI users was related to the speed at which sentences were articulated; CI users who produced

sentences with longer durations tended to have both shorter digit spans and less intelligible speech.

Performance on Non-word repetition tasks can be viewed as processing-dependent measures that reflect a wide range of spoken language abilities (Cleary et al., 2002; Nittrouer, Caldwell-Tarr, Sansom, Twersky, & Lowenstein, 2014). As such, these tasks have been used as a measure of phonological processing for typically developing children as well as clinical populations, e.g., those with language impairments and CIs. The Children's Test of Non-word Repetition (CNRep) is used frequently to assess phonological processing (Gathercole, Willis, Baddeley, & Emslie, 1994). When imitating non-words, a child generates a response to novel stimuli for which she has no previous phonological representation. This forces the child to encode the non-words using only the auditory cues, store that information in her working memory and then replicate those non-words with her articulators. Children's performance on the CNRep reflects their phonological processing, short term memory, motor planning and speech production (Dillon, et al., 2004). Thus, the CNRep test allows assessment of children's working memory and speech production skills on a single-word level rather than a sentence level, all without the confounds of vocabulary knowledge

Similar to other measures of spoken language, children with CIs show poorer performance on non-word repetition tasks when compared to aged-matched peers with normal hearing sensitivity (NH). Children with CIs produce fewer non-words correctly including individual consonants and vowels (Geers, Davidson, Uchanski, & Nicholas, 2013; Nittrouer et al., 2014). Geers et al. (2013) compared the accuracy of NH and CI children in producing the correct number of syllables and correct stress pattern on the CNRep test. Again, children with

CIs did worse than their age mates with NH sensitivity; they produced the target number of syllables and target stress patterns less accurately.

Non-word repetition generally improves with age for all children, including those with CIs. This improvement is primarily due to developmental changes, which can been seen in the performance curve of percentage consonants correct as a function of age (Campbell, Dollaghan, Janosky, & Adelson, 2007). Developmental changes also influence timing characteristics of speech. Polyanskaya and Ordin found that the mean durations of syllables varied greatly across age groups of NH children. The largest variability was seen between the ages of 8 and 11 years, reaching adult-like values by 11 to 12 years, indicating the greatest development of these rhythmic patterns occur during this time (Polyanskaya & Ordin, 2015).

The abilities of a CI user to identify voice pitch information are poor compared to their normal hearing peers (Straatman, Rietveld, Beijen, Mylanus, & Mens, 2010). The perception of voice pitch (i.e., fundamental frequency) requires accurate encoding of low-frequency and or temporal information in the speech signal (Grant, 1987; Grant & Walden, 1996). Thus, CI recipients' poor performance in tasks requiring accurate encoding of voice pitch is in part the result of the poor spectral resolution of current CI systems (Carroll & Zeng, 2007). Several studies have shown that speech perception scores of CI recipients' improve when they use a HA at the non-implanted ear (CI + HA), compared to listening with their CI alone (Ching, Wanrooy, & Dillon, 2007; Kong, Stickney, & Zeng, 2005). Most research suggests that the low frequency acoustic cues from the HA allow for better transmission of fundamental frequency and result in improved overall speech perception (Carroll & Zeng, 2007; Chang, Bai, & Zeng, 2006). Improved phoneme perception, including consonant voicing and manner, and transmission of low frequency phonemes such as nasals, diphthongs and glides have been documented when

electrical and acoustic hearing are combined through what is frequently termed bimodal device use (Ching et al., 2005). Furthermore changes in vocal pitch, syllable duration and stress are thought to be the primary cues that enable listeners to parse the continuous, connected speech stream into meaningful units (Spitzer, Liss, Spahr, Dorman, & Lansford, 2009).

Acoustic hearing (via HAs) could enhance the perception of fundamental frequency for young CI users, although the degree of residual hearing necessary for good fundamental-frequency perception remains unclear (Dorman, Gifford, Spahr, & McKarns, 2008; Gifford, Dorman, McKarns, & Spahr, 2007; Golub, Won, Drennan, Worman, & Rubinstein, 2012; Kong et al., 2005; Zhang, Spahr, & Dorman, 2010). Few studies have compared the ability of CI users and HA users to perceive voice pitch stress and syllable duration (Carney, Kienle, & Miyamoto, 1990). However, a recent study found that pediatric HA users with severe to profound hearing loss outperformed CI users on tasks requiring the perception of word pattern, syllable stress, sentence intonation, and word emphasis (Most & Peled, 2007). More recently, Hegarty and Faulkner (2013) found that the children who used a hearing aid with an implant relied upon duration cues to interpret stress and intonation when pitch and amplitude cues are not available (Hegarty & Faulkner, 2013).

Researchers have also looked at the relationship between audiological factors, such as degree of hearing loss (pure-tone average at .5, 1 and 2 kHz), age of implantation and length of acoustic hearing, and non-word repetition performance of pediatric CI users. Cleary, Dillon and Pisoni (2002) found that the duration of deafness prior to implantation was negatively correlated with non-word repetition performance (Cleary et al., 2002). Similarly, a positive correlation between non-word repetition performance and age at onset of deafness has been reported (Dillon et al., 2004). Dillon and Pisoni (2006) also found that age at onset of deafness and non-word

repetition performance were positively correlated. However, in both of these studies, using the same group of participants, there was no mention of residual hearing (pre- and post-implant thresholds) or of duration of acoustic hearing through a HA prior to implantation (Dillon et al., 2004; Dillon & Pisoni, 2006). Nittrouer et al. (2014) found that early implantation and HA use on the unimplanted side at the time of the first implant were positively correlated with better performance on a non-word repetition task (Nittrouer et al., 2014). Nittrouer and Chapman (2009) found that receptive language scores were not impacted by device configuration used at the time of testing (one CI, bilateral CIs or bimodal). However, they did find that any experience with bimodal listening resulted in better speech production abilities (Nittrouer & Chapman, 2009). The research is clear that early cochlear implantation promotes speech and language development in children with severe to profound hearing loss (Nicholas & Geers, 2006; Niparko et al., 2010; Tomblin, Brittan A., Linda J., Xuyang, & Bruce J., 2005; Yoshinaga-Itano, Baca, & Sedey, 2010) There is also growing evidence that children with better pre-implant residual hearing and who use a HA on the unimplanted ear have better spoken language than those with poorer pre-implant residual hearing (Nicholas & Geers, 2006; Nittrouer & Chapman, 2009).

In the present study, the relationship between ‘early acoustic hearing’, working memory, durations and number of syllables of repeated non-words in children with CIs will be examined. For this study, ‘early acoustic hearing’ will be described by pre- and post-implant audiograms, and duration of HA use.

Methods

Participants

Inclusion criteria for the CI group were:

1. Chronological age: 4 years 11 months – 8 years 11 months
2. Severe-to-profound hearing loss, congenital or acquired before 15 months of age
3. Age at first CI < 4.5 years
4. Education in an oral communication setting, in either a mainstream or oral special education classroom
5. Hearing loss as primary disability with normal cognitive function
6. No CI device failures lasting more than 30 days

Inclusion criteria for the NH group were:

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

Data from 92 children participating in a nationwide study were analyzed for this project: 16 children with NH and 76 children with CIs. Participants were a subset of a larger longitudinal study (N=159; CI = 117 and NH = 42) being conducted across the US. The children in the CI group presented with a variety of etiologies including Connexin 26 mutation (CX26) enlarged vestibular aqueduct (EVA), exposure to cytomegalovirus (CMV), idiopathic causes, and various syndromes. Of the CI participants, 25 were bimodal users (BM) and 54 were bilateral CI users (CI-BiLat). Twenty-one of the bilateral users were implanted simultaneously (simCI) and 33 were implanted sequentially (seqCI) with the time between surgeries ranging from 2 to 35

months (Mean: 11.1, SD: 8.0. All three manufacturers were represented in this sample: 56 Cochlear Americas (C), 16 Advanced Bionics (AB) and 4 Med-El (M). There were 23 bimodal users with Phonak hearing aids, 1 with Widex and 1 with Oticon.

At the time of testing the NH participants ranged from 5.0 to 8.4 years (Mean: 6.6, SD 1.1) and the CI participants ranged from 4.9 to 9.4 years (Mean: 7.0, SD: 1.2). Demographic information for the NH group is listed in Table 1. Demographics, device information and HA use for the CI group are listed in Table 2. Data to document 'early acoustic hearing' were collected from the child's audiological records, and parental questionnaires. Pure tone averages (PTAs) are listed for pre-implant acoustic aided and unaided conditions in Table 3. The first four columns represent the "acoustic experience ear"; so for BM participants it represents the HA ear, for seqCI participants, it represents the second CI ear and for the simCI participants it represents the better ear. The last two columns represent the aided and unaided thresholds for the 1st CI/only CI for BM and seqCI participants, and represents the better ear PTA for simCI participants. The PTAs were calculated using the thresholds at .5, 1 and 2 kHz. Additionally, low frequency PTAs (LF-PTA) were calculated using thresholds at .25 and .5 kHz. The maximum output of the audiometer was used in the case of no response at a frequency.

'Early acoustic hearing' is defined here as 'Duration of Acoustic Experience'. And, this term is nearly the same as 'Duration of HA use', at the time of testing. However, there are exceptions, which will be described subsequently. The calculation of 'Duration of HA use' (at the time of testing) is different for each of the three device configurations and is based solely on dates in medical records for initial HA fittings and CI implant surgeries. For the BM (bimodal) participants, 'Duration of HA use' equals their age on testing day minus their age when they received their first HA. For the seqCI participants, 'Duration of HA use' equals their age when

they received their second CI minus their age when they received their first HA. And, for the simCI participants, 'Duration of HA use' equals their age when they were simultaneously-implanted minus their age when they received their first HA.

Further examination of parental questionnaires and medical records indicated that, for some participants, acoustic hearing was not exactly coincident with HA use. Hence a new variable was created, 'Duration of Acoustic Experience', which reflects such adjustments. In this subset of 76 CI users, 2 participants (CI 204 & CI 2002) have values for Duration of Acoustic Experience that differ from their calculated 'Duration of HA use' values. For example, some responses in the parent questionnaires indicated that HA use was infrequent or discontinued before the first or second CI. Alternatively, some subjects with progressive losses (N=1) or meningitis (N=1) had a short period of time where unaided thresholds were within or near normal hearing. Compared to this child's calculated Duration of HA use, his/her Duration of Acoustic Experience would be smaller or larger to reflect appropriately the discontinued use of a HA or previous near normal hearing.

A variable named 'CI interval' was also calculated, but only for those participants with two CIs. 'CI interval' is zero for bilateral CI users who were implanted simultaneously. And, for those implanted sequentially, 'CI interval' equals their age when they received their second CI minus is their age when they received their first CI. There is no value for children using bimodal devices. All three of these variables, 'Duration of HA use', 'Acoustic Experience' and 'CI Interval' are listed in Table 4 for each participant.

Test Materials and Procedures

The shortened adapted version of the Children's Test of Non-Word Repetition (CNRep; (Gathercole et al., 1994) was recorded for each participant to assess phonological processing abilities of CI children. Speech imitations were recorded at several off-site locations throughout the United States for this ongoing study. Twenty non-words, four each ranging from 2 to 5 syllables, were spoken by a female talker. The child was instructed to repeat back the "funny word" (non-word) played from a loud speaker at a level of approximately 65 dBA. All 92 children produced a response for each non-word presented with the exception of 1 NH child, who omitted 3 responses, 7 CI children who omitted 1 response, and 3 CI children who omitted 2 responses. Using Praat Software (Boersma & Weenink, 2015), the recordings of the children's imitations were played and viewed (time waveforms and spectrograms) such that the boundaries of each word and each syllable could be labeled using the Praat textgrid tool (Styler, 2016). Several rules were created for consistency of duration measurements: these are listed in Appendix A. From these labeled boundaries, word and syllable durations could be computed easily (see the script provided in Appendix B). Additionally, implicit in the syllable duration measurements is a count of the number of syllables produced by the child for each imitated non-word. Using Lartz's (2015) previous analyses (phonetic-transcriptions and scoring of stress-patterns) of these same recordings, it was possible to verify these judgments of whether the child produced the correct number of syllables.

Two additional outcome measures, ones that assess working memory, were used for correlational analysis with the durations of the non-words in this current study. Collected previously, these are Visual Digit Span and CELF Number Repetition scores. For the Visual Digit Span task, participants viewed a series of 2 to 7 digits presented on a computer screen. Each digit of a given series was presented individually and participants were instructed to

verbally repeat each digit when it appeared on the screen. Digits were on the screen for 2000 ms with an inter-stimulus interval of 500 ms. A green box was illuminated at the completion of each digit series to signal the participant to verbally repeat the digits in the order they appeared. Four trials were presented for each digit series; correct serial recall of 3 out of the 4 trials was required to proceed to the next higher digit series (e.g., from 2 to 3 digits). A practice trial of 2-digit series was given before the test was initiated. Memory span was calculated by taking the longest digit span at which the participant correctly recalled 3 out of 4 trials. The CELF Number Repetition score is a subtest from the *Clinical Evaluation of Language Fundamentals* *4th Edition — (CELF-4)* (Semel, Wiig, & Secord, 2004). Results from the Visual Digit Span and CELF Number Repetition tests are listed in Table 5 for these 76 participants.

Results

Syllable Produced and Syllable Durations

The total number of syllables produced by each individual in the NH and CI group is shown in Table 6. There are 20 non-words, 5 words each with 2-, 3-, 4-, and 5-syllable lengths, for a total of 70 syllables. The NH participants had 7 individuals, or 44%, of the group producing the correct number of syllables for the entire set of 20 non-words. The CI participants had 16 individuals, or 21%, producing the correct number of syllables. The boxplot in Figure 1 displays these data.

The number of syllables produced for each of the different-length non-words were tallied and are shown in Tables 7 and 8, for the NH and CI participant groups respectively. Since there are 5 non-words for each word-length, the maximum count for the NH group was 80 (16 participants x 5 words at each syllable length). For the NH group, all 16 participants produced a 2-syllable word in their imitations of the five 2-syllable non-words. However, for the 5-syllable

non-words, only 68 (of the possible 80) imitations were 5-syllables in length, while 6 imitations had 4 syllables, 1 imitation had 3 syllables, 2 imitations had 6 syllables, and 3 times no imitation was made. For the CI group the maximum count was 380 (76 participants x 5). Notice that even for 2-syllable non-words for the CI group, there are 6 instances of no imitation, 13 imitations with 3 syllables and 1 imitation with 4 syllables. Again, as the number of syllables in the non-word increased, fewer imitations were produced with the target number of syllables, though this effect seems stronger in the CI group. Most often, too-few syllables are produced. However, there are several instances of children producing more syllables than in the target non-word. E.g., for CI participants, there are 16 instances of 6 syllables produced in imitation of a 5-syllable non-word. The data in Tables 7 and 8 are depicted in Figures 2 and 3, respectively.

Shown in the four panels of Figure 4, for the CI participants only, are the same data as in Figure 3, except they are now separated by target word length and by each non-word. There is one panel each for the 2-syllable, 3-syllable, 4-syllable and 5-syllable non-words. As the number of syllables in the target non-word increased, fewer CI participants produced the target number of syllables, i.e., there are more errors in the number of syllables produced. The errors are skewed toward too-few rather than too-many syllables produced. Also, it is noteworthy that there is little variation across words of the same syllable length.

Syllable durations, for each syllable position and each of the syllable-lengths, are listed in Table 9 and 10 for the NH and CI participants, respectively. Shown are mean and median syllable duration values as well as minima, maxima and standard deviations. There is a general trend, seen for both the NH and CI groups, for the final syllable to be lengthened.

To examine this lengthening effect, a final-syllable-lengthening ratio was calculated for each participant. This ratio is the average of 4 separate ratios, one calculated for each of the

syllable-lengths. E.g., for the 5-syllable words, the ratio is the average duration of the last syllables divided by the average of all the previous syllable durations (i.e., the average of the 1st, 2nd, 3rd and 4th syllables produced in these 5-syllable non-words). Similar calculations were done for the 2-, 3- and 4-syllable non-words, and the average of the four ratios is then reported for each participant. These data are show in Tables 11 and 12 and are displayed in a box plot in Figure 5. The final-syllable-lengthening ratios for the NH group ranged from 1.437 to 2.262 (mean: 1.926, SD: .187) and ranged from 1.298 to 2.305 (mean: 1.727, SD: .207) for the CI group. Figure 4 shows that there is a significant difference, using an ANOVA test, between CI and NH groups for the final-syllable-lengthening ratio ($F(1, 90) = 12.6$, $p=.001$), with NH participants lengthening final syllables more than the CI participants.

Syllable durations for individual NH participants are shown in Table 13. For each talker, the median syllable duration, duration summed across all syllables, the number of syllables produced across all non-words, average syllable duration, and speaking rate (in syllable/sec; calculated as 1/[average syllable duration]) are listed. The median syllable duration for the NH group ranged from .227 to .344 sec (mean: .274, SD: .031), the summed duration ranged from 14.000 to 28.686 sec (mean: 21.082, SD: 3.417), the average syllable duration ranged from .251 to .416 msec (mean: .307, SD: .042), the total number of syllables produced ranged from 55 to 71 (mean: 68.4, SD: 3.8) and the speaking rate ranged from 2.405 to 3.989 syllables/sec (mean: 3.309, SD: .428). Analogous data for the CI participants are shown in Table 14. The median syllable duration for the CI group ranged from .212 to .366 sec (mean: .283, SD: .037), the summed duration ranged from 16.500 to 28.925 sec (mean: 21.313, SD: 3.024), the average syllable duration ranged from .246 to .434 sec (mean: .316, SD: .044), the total number of syllables produced ranged from 49 to 76 (mean: 67.6, SD: 4.2) and the speaking rate ranged from

2.304 to 4.06 syllable/sec (mean: 3.225, SD: .434). The median syllable durations are shown in a boxplot in Figure 6 with no significant difference between the NH and CI groups (p=.405).

Correlational Analyses and Relationships

Data analysis was performed using Pearson correlations; the results of this analysis are listed in Tables 15 and 16. First, the relations, if any, between syllable and work-memory measures are presented (Table 15). Correlational analysis revealed that CELF Num Rep scores are significantly correlated with number of syllables produced (r = .380, p=.001) and with age (r = -.228, p=.048). This relationship, between CELF Num Rep score and number of syllables produced, is displayed in Figure 7. Also, visual digit span was found to be significantly correlated with number of syllables produced (r = 0.263, p=.022), median syllable duration (r = -.252, p=.028), average final-syllable-lengthening ratio (r = -0.233, p=.043), and age (r = .441, p=.000). The strongest of these correlations, between visual digit span and any of the duration measures, was with median syllable duration; this relation is shown in Figure 8.

Second, relations, if any, between syllable measures and participant's age are noted (Table 15). Participant's age is significantly negatively correlated with median syllable duration (r = -.271, p=.018), average syllable duration (r = -.236, p=.041), and final-syllable-lengthening ratio (r = -.295, p=.010). Two of these relations, those with median syllable duration and average syllable duration ratio, are displayed in Figures 9 and 10 respectively. Third, correlations between syllable measures and hearing-related demographics were explored (Table 16). The absence of significant correlations, between syllable measures and any of these demographic variables, is also noteworthy. For example, age at 1st CI is not significantly correlated with any of the syllable measures, nor is Unaided LF PTA. These relations are shown in Figures 11 and 12.

Discussion

Overall, compared to NH talkers, CI users were significantly different in the number of syllables produced in imitation of a non-word. Compared to NH talkers, CI users more often produced non-words with a different number of syllables (most often, too few) than in the target non-word (see Figure 1). Both groups showed similar trends in number of syllables produced as non-word syllable-length increased. That is, as the number of syllables in the target non-word increased, talkers in each group generally produced fewer syllables. The variability for the CI group, however, was much greater. This was expected based on CI users' Number-syllables-correct scores described previously by Lartz (2015). While the number of syllables in the target non-word has an effect on the number of syllables produced, there does not seem to be any dependence on the identity of the non-word (refer to the four panels of Figure 4). That is, within each syllable-length non-word, the trend seems independent of the non-word produced: there are roughly the same number of syllables produced in imitation of 'emplifervent' as produced in imitation of 'penneriful'. This presumably indicates that the set of non-words were well-designed by Gathercole et al. (1994) in their phonotactic structure such that no non-word was particularly easier or harder to imitate than any other non-word of the same syllable-length.

The final-syllable-lengthening ratio may reflect a talker's incorporation of spoken English prosodic, syllabic-rhythm timing rules. Previous research shows that syllable lengthening is standard for American English, and occurs before syntactic boundaries, such as phrase and sentence endings. Syllable lengthening, primarily through vowel-duration lengthening, is largest for utterance-final words/syllables (Oller, 1973; Umeda, 1975). Since these participants spoke the non-words in isolation, each non-word can be considered an utterance-final word, and hence would be expected to exhibit final-syllable lengthening. Overall,

the NH group has significantly larger ratios (greater final-syllable lengthening) than those of the CI users (refer to Figure 5). Also, as a group, the NH talkers showed less variability in this ratio than did the CI group. Oller (1973) found that for utterance final words, the vowel in the final syllable was about 240 msec while vowel durations in the previous syllables ranged from 140 to 160 msec, equivalent to final-syllable-lengthening ratios of 1.9 to 1.5. These values from Oller are comparable to the ratios found for the 16 NH participants in this study, where the median ratio for the NH group is 1.9. Many of the CI participants had ratios in this same range (1.5 – 1.9). However, many were well outside of that range, especially at the low end reflecting not-enough final-syllable-lengthening. Hence, there may be some factor, perhaps hearing-related, that affects these CI users' ability to develop this 'rule' of spoken language. Curiously, there is a modest, though significant, negative correlation between age and final-syllable-lengthening ratio. That is, the older children exhibited shorter (less 'good'; less 'typical') final-syllable-lengthening ratios.

The median syllable durations show no significant differences between the NH and CI participants. To examine this further and to compare our results to previous studies, the average speaking rate was calculated (the reciprocal of the average syllable duration). The CI participants' speaking rates ranged from 2.3 to 4.1 syllables/sec, while those for the NH participants ranged from 2.4 to 4.0 syllables/sec. As the two groups did not differ significantly in median duration measures, we cannot expect speaking rates to be different either. Our participants' speaking rates are similar to those reported in previous studies with NH and CI children (Pindzola, Jenkins, & Lokken, 1989; Pisoni & Cleary, 2003). In their study of the relation between sentence duration and working memory, Pisoni & Cleary (2003) measured the duration of 7-syllable-length McGarr sentences produced by child CI users. Converting their

participants' sentence durations to speaking rates yields values that range from 1 to 3.5 syllables/sec. The lower end of this range is much slower than the speaking rates of the 76 CI participants in this study, but the upper end is fairly comparable. However, since these converted speaking rates were calculated from spoken sentences instead of isolated non-words, a direct comparison may not be valid. For children with NH, Pindzola and colleagues report an average speaking rate for young children (ages 3.0-5.9 years) of 2.5 syllables/sec (Pindzola et al., 1989). Again, this value is comparable to the speaking rates of both the NH and CI groups in this study.

For these CI participants, a significant, negative correlation was found between age and median syllable duration, and between age and final-syllable-lengthening ratio. While the relation between age and median syllable duration is in the expected direction (older children produce shorter syllables), the relation between age and lengthening ratio is not. This is unexpected and is not understood. The older children have shorter lengthening ratios, i.e., ratios closer to 1.0, which would seemingly be less likely developmentally. The effects of age on non-word repetition performance and on syllable duration have been reported by others (Campbell et al., 2007; Polyanskaya & Ordin, 2015). Polyanskaya and Ordin (2015) found that durations of consonants and vowels in sentence production vary significantly between the ages of 5 to 8 years for NH children, however they did not see consistent variation in syllable duration with age. They conclude that rhythmic changes during development happen at a sub-syllabic level. However, developmental trends seen, or not seen, in children with NH may not necessarily extend to those with impaired hearing using CIs.

Based on previous studies by Pisoni and colleagues, there was an expected relation between working memory and duration measures. And, indeed, for these 76 CI participants, a modest, significant negative correlation was found between Visual Digit Span and Median

Syllable Duration. However, significant correlations were not found between Visual Digit Span and Average Syllable Duration, nor between the other measure of working memory, CELF Num Rep score and either of the two Duration measures. Yet, the significant correlation result is somewhat similar to that of Pisoni and Cleary (2003), who reported a stronger, significant negative correlation (r = -0.55) between 7-syllable sentence durations and performance on a forward digit span task. Differences in results across studies could be due to several factors. Perhaps the most important is the age of the Pisoni study (almost 20 years old), and the consequent cochlear-implant technology available at the time and differences in implant criteria. The participants in Pisoni's study, due to the implant guidelines at that time, were implanted at older ages and had poorer pre-implant acoustic hearing than participants in this study.

Though not a duration measurement, the total number of syllables produced was found to be significantly positively correlated with both working memory assessments (Visual Digit Span and CELF Num rep score). Though the correlations are modest, the trends are in the expected direction. CI participants with higher CELF Num Rep scores tend to have greater number of syllables produced (for the set of 20 non-words). Thus, a poorer ability to recall a series of numbers seems to be related to a talker's ability to remember the syllables in the non-word he/she needs to imitate in a non-word repetition task.

Several audiologic variables were examined for possible relations with syllable measures in repeated non-words. For these 76 CI participants, no correlations were significant between any of the six audiologic variables examined here and any of the syllable measures. While no other research has reported explicitly the relation, or lack thereof, between duration measures of speech and audiologic variables, much research has shown an impact of audiologic variables on other aspects of speech and language production. Nittrouer and Chapman (2009) found that

experience with bimodal listening, similar to our acoustic experience measure, resulted in significantly longer mean length utterances. Nicholas and Geers (2006) found that better acoustic hearing and bimodal use resulted in better language scores, including mean length utterance and sentence length. This is not to say that they found longer sentence durations, but rather a greater number of language units. Based on these reports and research that shows that audiologic factors influence performance on a non-word repetition task (Dillon et al., 2004; Nittrouer et al., 2014), we had anticipated audiologic factors would also influence duration measures. The apparent lack of consistency across studies and lack of previous research looking at syllable duration measures lead us to believe that more research needs to be done in this area. Whether audiologic variables influence various duration measures remains to be seen.

Conclusion

In conclusion, while audiologic factors might not influence syllable measures, these data do show some potentially important differences between CI children and their NH aged mates. Children with CIs produce the last syllable in an utterance-final word with significantly greater variability and less final-syllable-lengthening. This suggests that something about CI children's language development for this particular aspect of spoken English is different from their NH age mates. Future studies should consider how syllable measures are related to overall speech production and measures of acoustic hearing, especially during the critical years of spoken language development.

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Table 1 Demographic information for NH participants

Participant ID	Gender	Age at test (years)
NH.101	M	5.40
NH.102	M	5.22
NH.103	F	5.40
NH.501	F	6.28
NH.502	F	4.98
NH.503	F	6.55
NH.504	F	7.27
NH.505	F	7.90
NH.506	M	5.64
NH.507	M	6.17
NH.701	M	6.31
NH.901	M	8.19
NH.902	M	8.19
NH.1101	M	7.06
NH.1102	F	8.41
NH.1401	F	6.38

Average		6.59
SD		1.14
min		4.98
max		8.41

Table 2 Demographics, device information and hearing aid use for CI participants.

SubID	Cond	Age at test (Yrs)	Gender	Age 1st HA (Mos)	Age 1st CI (Yr)	CI device	Age 2ndCI (Yrs)
CI.101	seqCI	8.91	M	20	1.96	C	3.54
CI.103	BM	6.46	F	24	2.79	C	
CI.201	seqCI	8.56	M	2	1.05	C	2.27
CI.202	BM	8.84	M	3	1.55	AB	
CI.203	BM	8.79	M	24	2.89	AB	
CI.204	seqCI	7.88	F	15	2.71	AB	2.87
CI.205	simCI	7.75	M	6	0.9	AB	0.9
CI.301	seqCI	7.49	M	13	2.06	AB	2.6
CI.302	seqCI	5.04	M	1	0.85	C	4.44
CI.303	seqCI	8.64	M	11	1.39	C Freedom	2.08
CI.304	seqCI	8.16	M	21	2.3	C	2.8
CI.305	simCI	7.1	F	2	1.07	C	1.07
CI.401	simCI	4.93	M	2	1.12	C	1.12
CI.404	seqCI	7.79	M	15	1.85	M Opus 2	2.02
CI.405	simCI	6.34	F	22	2.23	C	2.23
CI.406	seqCI	8.62	F	2	1.25	C	3.84
CI.501	seqCI	8.63	F	18	2.09	AB	2.49
CI.502	seqCI	6.05	F	24	2.4	C	3.73
CI.602	seqCI	8.93	M	1	1.02	C	1.9
CI.603	simCI	6.81	F	12	1.48	C	1.48
CI.604	seqCI	5.74	M	15	1.48	C Nuc 5	2.46
CI.605	seqCI	7.39	F	6	0.89	AB	1.28
CI.606	seqCI	5.79	M	1	0.88	C	1.13
CI.607	seqCI	7.14	M	16	3.33	C	5.17
CI.608	simCI	7.52	M	15	1.91	C	1.91
CI.701	seqCI	7.6	F	16	2.98	AB	5.98
CI.702	simCI	6.78	M	3	0.7	C	0.7
CI.704	simCI	6.34	M	17	1.64	AB Harmony	1.64
CI.801	BM	5.62	M	4	2.52	C	
CI.807	BM	5.85	F	10	1.74	C	
CI.808	BM	5.71	F	2	4.48	C	
CI.901	seqCI	7.22	F	14	1.57	AB	2.09
CI.902	BM	5.81	M	3	2.17	C	
CI.903	seqCI	5.68	F	18	2.03	M Opus	3.03
CI.904	BM	6.63	M	11	4.13	C Freedom	
CI.905	simCI	8.6	M	7	1.35	C	1.35
CI.906	BM	7.02	F	24	4.5	C Freedom	
CI.908	simCI	6.38	F	4	0.82	C Freedom	0.82

CI.1001	simCI	5.48	M	2	1.1	C	1.1
CI.1002	seqCI	5.02	F	3	1.43	C	2.03
CI.1003	seqCI	4.94	F	17	2.84	C	3.54
CI.1004	simCI	5.68	M	8	1.41	C	1.41
CI.1101	simCI	6.13	M	28	2.76	M	2.76
CI.1102	simCI	7.12	F	2	1.09	C	1.09
CI.1103	simCI	7.54	M	2	0.94	C	0.94
CI.1104	BM	8.35	M	26	2.81	M	
CI.1105	BM	8.87	M	6	3.44	C	
CI.1106	seqCI	6.37	M	12	1.14	C	2.07
CI.1201	BM	5.49	M	5	1.3	AB Naida	
CI.1202	BM	7.83	F	4	3.62	AB	
CI.1203	BM	5.05	M	28	2.64	C	
CI.1205	BM	7.66	M	8	4.41	C	
CI.1206	BM	7.86	M	5	3.9	C	
CI.1301	BM	7.1	F	25	3.06	C	
CI.1401	seqCI	8.24	M	23	1.95	AB	2.11
CI.1402	BM	7.96	M	3	1.57	C Freedom	
CI.1404	seqCI	8.21	F	6	1.05	AB	3.13
CI.1405	simCI	8.46	M	7	0.88	C	0.88
CI.1502	seqCI	5.58	F	15	2.41	C	3.35
CI.1504	BM	6.03	F	6	1.03	C	
CI.1505	seqCI	7.55	M	14	4.27	C	4.98
CI.1506	simCI	6.89	F	8	1.01	C	1.01
CI.1602	BM	6.4	M	6	3.71	C	
CI.1606	BM	7.09	M	13	2.91	C N5	
CI.1608	seqCI	5.83	F	2	1.09	C N5	1.81
CI.1609	seqCI	8.57	F	6	1.13	C N5	2.05
CI.1703	simCI	8.06	F	22	2.08	C Freedom	2.08
CI.1802	BM	9.38	M	4	1.58	C	
CI.1803	BM	7.05	F	1	2.95	C CP810	
CI.1804	seqCI	8.64	F	1	0.7	AB HiRes 90K	1.27
CI.1902	seqCI	6.2	F	3	1.07	AB	1.58
CI.1906	seqCI	5.39	F	4	1.07	C	1.47
CI.2002	simCI	5.68	M		1.82	C	1.82
CI.2004	seqCI	7.26	F	11	1.35	C	2.71
CI.2103	BM	5.15	F	27	4.54	C	
CI.2105	BM	8.59	M	29	3.9	C	
Avg		**7.04**		**10.87**	**2.05**		**2.24**
Std		**1.23**		**8.49**	**1.09**		**1.19**
Min		**4.93**		**1**	**0.70**		**.70**
Max		**9.38**		**29**	**4.54**		**5.98**

Table 3 Pure Tone Averages in dB HL; PTA (.5, 1, 2 kHz), LF PTA (.25, .5 kHz) for CI participants

SubID	Acoustic Ear Unaided PTA	Acoustic Ear Aided PTA	Acoustic Ear Unaided LF PTA	Acoustic Ear Aided LF PTA	Pre-CI Aided PTA	Pre-CI Unaided PTA
CI.101	86.7	53.3	107.5	45.0	53.3	86.7
CI.103	60.0	31.7	65.0	27.5	31.7	96.7
CI.201	98.3	85.0	95.0	85.0	85.0	105.0
CI.202	83.3	36.7	75	32.5	40	100
CI.203	78.3	33.3	80	42.5	38.3	96.7
CI.204	44.5	26.5	29.4	20.8	70	125
CI.205	121.7	71.7	102.5	52.5	71.7	121.7
CI.301	93.3	71.7	90	70	51.7	93.3
CI.302	86.7	43.3	90	40	53.3	91.7
CI.303	103.3	50	97.5	45	50	96.7
CI.304	75.5	63.6	70.5	56.7	81.7	121.7
CI.305	125	70	117.5	65	70	125
CI.401	120	61.7	112.5	45	61.7	120
CI.404	115	41.7	115	47.5	38.3	110
CI.405	101.7	68.3	95	62.5	68.3	101.7
CI.406	113.3	55	87.5	60	55	113.3
CI.501	70	50	70	45	50	65
CI.502	108.3	63.3	95	42.5	110	121.7
CI.602	111.7	78.3	107.5	70	78.3	112.5
CI.603	93.3	61.7	80	62.5	61.7	93.3
CI.604	85	41.7	90	37.5	48.3	91.7
CI.605	90	43.3	90	40	43.3	90
CI.606	88.3	35	87.5	30	35	81.7
CI.607	51.7	20	45	25	45	88.3
CI.608	71.7	25	65	25	25	71.7
CI.701	88.3	36.7	60	30	56.7	100
CI.702	103.3	90	95	72.5	90	103.3
CI.704	111.7	50	95	42.5	50	111.7
CI.801	76.7	56.7	90	45	51.7	78.3
CI.807	69.6	25.5	46.6	16.5	31.7	73.3
CI.808	93.3	26.7	92.5	22.5	33.3	96.7
CI.901	80	44.5	72.5	45.9	56.7	90
CI.902	91.7	60	85	42.5	60	95
CI.903	115	96.7	107.5	75	96.7	118.3
CI.904	56.7	27	42.5	27.9	49	72.2
CI.905	88.3	83.3	70	65	83.3	88.3
CI.906	81.7	61.7	57.5	57.5	61.7	100

CI.908	100	58.3	95	50	58.3	100
CI.1001	105	56.7	105	50	56.7	105
CI.1002	86.7	32.3	80	36	32.3	86.7
CI.1003	73.6	31.3	68.1	34.1	50	100
CI.1004	105	88.3	105	85	88.3	105
CI.1101	91.7	63.3	95	62.5	63.3	91.7
CI.1102	103.3	68.3	97.5	65	68.3	103.3
CI.1103	100	58.3	95	50	58.3	100
CI.1104	90	43.3	77.5	30	45	88.3
CI.1105	76.7	38.3	70	40	68.3	95
CI.1106	106.7	61.7	97.5	55	61.7	103.3
CI.1201	93.3	40	87.5	27.5	40	88.3
CI.1202	55	26.7	55	20	55	115
CI.1203	66.7	26.7	40	20	26.7	65
CI.1205	81.7	38.3	75	22.5	28.3	86.7
CI.1206	78.3	31.7	60	25	55	111.7
CI.1301	86.7	26.7	72.5	27.5	43.3	91.7
CI.1401	110	71.7	107.5	70	71.7	108.3
CI.1402	96.7	48.3	90	52.5	85	125
CI.1404	115	50	105	37.5	50	118.3
CI.1405	120	76.7	112.5	60	76.7	120
CI.1502	86.7	61.8	67.5	43	45	81.7
CI.1504	78.3	36.7	60	35	43.3	86.7
CI.1505	50	45	42.5	30	45	50
CI.1506	113.3	71.7	102.5	65	71.7	113.3
CI.1602	86.7	41.7	72.5	40	45	88.3
CI.1606	73.3	33.3	85	30	48.3	73.3
CI.1608	85	45	60	32.5	51.7	98.3
CI.1609	106.7	53.3	97.5	50	53.3	103.3
CI.1703	108.3	56.7	97.5	50	56.7	108.3
CI.1802	100	85	97.5	85	56.7	108.3
CI.1803	71.7	30	60	30	53.3	88.3
CI.1804	100	65	95	57.5	65	95
CI.1902	120	95	112.5	90	95	120
CI.1906	100	81.7	75	65	88.3	116.7
CI.2002	118.3	15	105	15	15	118.3
CI.2004	111.7	78.3	90	75	85	111.7
CI.2103	41.7	23.3	30	22.5	60	113.3
CI.2105	75	35	77.5	32.5	35	103.3
Avg	90.81	51.72	82.82	45.87	57.01	99.14
Std	19.447	20.045	20.941	18.330	18.645	15.826
Min	41.67	15	29.4	15	15	50
Max	125	96.67	117.5	90	110	125

Table 4 Audiologic variables for CI participants: duration of HA use, acoustic experience and interval between C (blank indicates no second CI)

SubID	Duration HA Use (Yrs)	Acoustic Experience (Yrs)	CI-Interval (Mos)
CI.101	1.87	1.87	19
CI.103	4.46	4.46	
CI.201	2.11	2.11	14
CI.202	8.63	8.63	
CI.203	6.79	6.79	
CI.204	1.62	2.62	2
CI.205	0.4	0.4	0
CI.301	1.51	1.51	6
CI.302	4.36	4.36	17
CI.303	1.17	1.17	8
CI.304	1.05	1.05	6
CI.305	0.9	0.9	0
CI.401	0.95	0.95	0
CI.404	0.77	0.77	2
CI.405	0.4	0.4	0
CI.406	3.67	3.67	31
CI.501	0.99	0.99	5
CI.502	1.73	1.73	15
CI.602	1.82	1.82	9
CI.603	0.48	0.48	0
CI.604	1.21	1.21	11
CI.605	0.78	0.78	5
CI.606	1.04	1.04	3
CI.607	3.84	3.84	22
CI.608	0.66	0.66	0
CI.701	1.67	1.67	35
CI.702	0.45	0.45	0
CI.704	0.22	0.22	0
CI.801	5.29	5.29	
CI.807	5.02	5.02	
CI.808	5.55	5.55	
CI.901	0.93	0.93	6
CI.902	5.56	5.56	
CI.903	1.53	1.53	12
CI.904	5.72	5.72	
CI.905	0.76	0.76	0
CI.906	5.02	5.02	

CI.908	0.48	0.48	0
CI.1001	0.93	0.93	0
CI.1002	1.17	1.17	8
CI.1003	2.12	2.12	6
CI.1004	0.58	0.58	0
CI.1101	0.43	0.43	0
CI.1102	0.92	0.92	0
CI.1103	0.77	0.77	0
CI.1104	6.18	6.18	
CI.1105	8.37	8.37	
CI.1106	1.07	1.07	11
CI.1201	5.08	5.08	
CI.1202	7.5	7.5	
CI.1203	2.72	2.72	
CI.1205	6.99	6.99	
CI.1206	7.44	7.44	
CI.1301	5.02	5.02	
CI.1401	0.19	0.19	2
CI.1402	7.71	7.71	
CI.1404	2.63	2.63	25
CI.1405	0.3	0.3	0
CI.1502	2.1	2.1	12
CI.1504	5.53	5.53	
CI.1505	3.82	3.82	9
CI.1506	0.34	0.34	0
CI.1602	5.9	5.9	
CI.1606	6	6	
CI.1608	1.69	1.69	9
CI.1609	0.75	0.75	11
CI.1703	0.24	0.24	0
CI.1802	9.05	9.05	
CI.1803	6.97	6.97	
CI.1804	1.19	1.19	5
CI.1902	1.33	1.33	7
CI.1906	0.03	0.03	6
CI.2002	0	1.75	0
CI.2004	1.79	1.79	17
CI.2103	2.9	2.9	
CI.2105	6.17	6.17	
Avg	**2.83**	**2.87**	**6.98**
Std	**2.58**	**2.55**	**8.39**
Min	**0**	**.03**	**0**
Max	**9.04**	**9.05**	**35**

Table 5 Measures of Working Memory for CI participants

Subject ID	Visual Digit Span	CELF Num Rep
CI.101	2	6
CI.103	3	10
CI.201	4	7
CI.202	4	11
CI.203	3	5
CI.204	3	10
CI.205	4	14
CI.301	3	6
CI.302	3	12
CI.303	2	8
CI.304	3	5
CI.305	3	11
CI.401	3	12
CI.404	2	5
CI.405	3	11
CI.406	5	10
CI.501	3	5
CI.502	2	11
CI.602	4	15
CI.603	3	7
CI.604	2	8
CI.605	2	7
CI.606	3	7
CI.607	3	11
CI.608	3	13
CI.701	3	7
CI.702	4	11
CI.704	3	12
CI.801	3	14
CI.807	3	12
CI.808	3	10
CI.901	3	10
CI.902	2	9
CI.903	3	12
CI.904	4	13
CI.905	4	7
CI.906	3	10
CI.908	2	13
CI.1001	1	3

CI.1002	2	12
CI.1003	2	10
CI.1004	3	6
CI.1101	1	3
CI.1102	3	10
CI.1103	3	7
CI.1104	5	11
CI.1105	3	5
CI.1106	3	10
CI.1201	3	9
CI.1202	7	13
CI.1203	1	8
CI.1205	4	14
CI.1206	2	6
CI.1301	3	10
CI.1401	3	5
CI.1402	6	10
CI.1404	3	3
CI.1405	6	11
CI.1502	2	12
CI.1504	3	8
CI.1505	5	11
CI.1506	3	12
CI.1602	3	10
CI.1606	4	8
CI.1608	3	9
CI.1609	4	10
CI.1703	3	10
CI.1802	2	10
CI.1803	3	10
CI.1804	3	7
CI.1902	3	13
CI.1906	2	11
CI.2002	2	8
CI.2004	4	13
CI.2103	2	11
CI.2105	4	7
Average	**3.08**	**9.38**
Min	**1**	**3.00**
Max	**7**	**15.00**
Std	**1.068**	**2.85**

Table 6 Distributions of the Number of Syllables Produced by CI and NH participants. There are 70 syllables in the 20 non-words.

Number of Syllables Produced	Number of CI Participants	Number of NH Participants
49	1	0
50	0	0
51	0	0
52	0	0
53	0	0
54	0	0
55	0	1
56	1	0
57	1	0
58	0	0
59	0	0
60	1	0
61	0	0
62	2	0
63	5	0
64	3	0
65	2	1
66	7	0
67	6	0
68	6	0
69	13	6
70	16	7
71	6	1
72	3	0
73	1	0
74	0	0
75	1	0
76	1	0

Table 7 For NH participants (N=16), the number of instances that No. Syllables were produced for the five-each 2-syll, 3-syll, 4-syll and 5-syll non-words.

No. Syll Produced	2-SYLL WORDS	3-SYLL WORDS	4- SYLL WORDS	5-SYLL WORDS
0	0	0	0	3
1	0	0	0	0
2	80	3	0	0
3	0	77	2	1
4	0	0	77	6
5	0	0	1	68
6	0	0	0	2
7	0	0	0	0
8	0	0	0	0
Total	80	80	80	80

Table 8 For CI participants (N=76), the number of instances that No. Syllables were produced for the five-each 2-syll, 3-syll, 4-syll and 5-syll non-words.

No. Syll Produced	2-SYLL WORD	3-SYLL WORDS	4- SYLL WORDS	5-SYLL WORDS
0	6	0	3	4
1	0	0	1	0
2	360	32	4	0
3	13	333	50	17
4	1	14	312	75
5	0	1	10	265
6	0	0	0	16
7	0	0	0	2
8	0	0	0	1
Total	380	380	380	380

Table 9 Syllable Duration Summary for NH participants (sec)

	All 2-syll words		All 3-syll words			All 4-syll words				All 5-syll words				
	Dur s1	Dur s2	Dur s1	Dur s2	Dur s3	Dur s1	Dur s2	Dur s3	Dur s4	Dur s1	Dur s2	Dur s3	Dur s4	Dur s5
Mean	0.296	0.422	0.242	0.213	0.485	0.216	0.256	0.221	0.511	0.228	0.310	0.271	0.269	0.387
Median	0.277	0.388	0.213	0.181	0.455	0.198	0.237	0.214	0.476	0.201	0.275	0.248	0.251	0.365
Min	0.136	0.178	0.077	0.095	0.289	0.077	0.107	0.046	0.257	0.083	0.123	0.074	0.099	0.141
Max	0.690	1.032	0.582	0.654	0.933	1.070	0.881	0.938	2.049	0.699	1.146	0.951	0.866	0.688
Std	0.114	0.157	0.097	0.107	0.134	0.125	0.104	0.107	0.233	0.102	0.164	0.174	0.127	0.133

Table 10 Syllable Duration Summary for CI participants (sec)

	All 2-syll words		All 3-syll words			All 4-syll words				All 5-syll words				
	Dur s1	Dur s2	Dur s1	Dur s2	Dur s3	Dur s1	Dur s2	Dur s3	Dur s4	Dur s1	Dur s2	Dur s3	Dur s4	Dur s5
Mean	0.296	0.394	0.272	0.240	0.433	0.219	0.312	0.275	0.464	0.235	0.311	0.294	0.325	0.376
Median	0.273	0.376	0.234	0.206	0.413	0.195	0.267	0.247	0.440	0.209	0.284	0.272	0.278	0.345
Min	0.099	0.100	0.089	0.067	0.101	0.061	0.113	0.076	0.151	0.083	0.106	0.065	0.105	0.111
Max	0.722	0.977	1.695	1.068	1.132	1.077	1.936	0.976	1.178	0.926	1.361	0.982	1.554	1.155
Std	0.110	0.156	0.140	0.145	0.139	0.114	0.182	0.135	0.161	0.104	0.130	0.152	0.183	0.149

Table 11 Final-Syllable-Lengthening Ratio for NH Participants

Subject ID	Average Ratio
NH.101	1.765
NH.102	1.983
NH.103	2.156
NH.501	1.832
NH.502	2.262
NH.503	1.437
NH.504	1.839
NH.505	2.105
NH.506	1.990
NH.507	1.857
NH.701	1.819
NH.901	2.017
NH.902	1.902
NH.1101	1.895
NH.1102	1.926
NH.1401	2.026
Average	**1.926**
Min	**1.437**
Max	**2.262**
Std	**0.187**

Table 12 Final-Syllable-Lengthening Ratio for CI participants

Subject ID	Average Ratio
CI.101	1.554
CI.103	1.727
CI.201	1.678
CI.202	1.560
CI.203	1.789
CI.204	1.557
CI.205	1.560
CI.301	1.690
CI.302	1.983
CI.303	1.762
CI.304	1.298
CI.305	1.898
CI.401	1.555
CI.404	1.631
CI.405	1.752
CI.406	1.851
CI.501	1.807
CI.502	1.765
CI.602	1.695
CI.603	1.819
CI.604	1.796
CI.605	1.930
CI.606	1.301
CI.607	2.025
CI.608	1.692
CI.701	1.706
CI.702	1.634
CI.704	1.886
CI.801	1.702
CI.807	2.031
CI.808	1.604
CI.901	1.374
CI.902	1.781
CI.903	1.560
CI.904	1.900
CI.905	1.627
CI.906	2.070
CI.908	1.808

CI.1001	1.517
CI.1002	1.994
CI.1003	1.882
CI.1004	1.309
CI.1101	1.637
CI.1102	2.058
CI.1103	1.984
CI.1104	1.523
CI.1105	1.554
CI.1106	1.678
CI.1201	2.082
CI.1202	1.438
CI.1203	1.756
CI.1205	1.642
CI.1206	1.579
CI.1301	1.848
CI.1401	1.625
CI.1402	1.878
CI.1404	1.985
CI.1405	1.517
CI.1502	1.941
CI.1504	1.816
CI.1505	1.662
CI.1506	1.551
CI.1602	1.873
CI.1606	1.658
CI.1608	1.772
CI.1609	1.362
CI.1703	1.303
CI.1802	1.791
CI.1803	1.579
CI.1804	1.862
CI.1902	1.685
CI.1906	2.305
CI.2002	1.852
CI.2004	1.885
CI.2103	2.009
CI.2105	1.482
Average	**1.727**
Min	**1.298**
Max	**2.305**
Std	**0.207**

Table 13 Syllable Measures for Individual NH- Total syllables produced is for all 20 non-words (target=70), and speaking rate is the reciprocal of average syllable duration for each participant

Subject ID	Median Syll Duration (sec)	Summed Duration (sec)	Total Syll Produced	Average Syll Duration (sec)	Speaking Rate (Syllables/Sec)
NH.101	0.294	21.837	70	0.312	3.206
NH.102	0.257	14.000	55	0.255	3.929
NH.103	0.268	22.565	69	0.327	3.058
NH.501	0.296	21.578	69	0.313	3.198
NH.502	0.303	24.599	71	0.346	2.886
NH.503	0.344	28.686	69	0.416	2.405
NH.504	0.280	21.851	70	0.312	3.204
NH.505	0.281	22.262	69	0.323	3.099
NH.506	0.233	19.205	69	0.278	3.593
NH.507	0.299	22.902	70	0.327	3.057
NH.701	0.263	18.762	69	0.272	3.678
NH.901	0.261	18.832	70	0.269	3.717
NH.902	0.290	22.432	70	0.320	3.121
NH.1101	0.227	17.268	65	0.266	3.764
NH.1102	0.265	22.986	70	0.328	3.045
NH.1401	0.227	17.549	70	0.251	3.989
Average	**0.274**	**21.082**	**68.438**	**0.307**	**3.309**
Min	**0.227**	**14.000**	**55.000**	**0.251**	**2.405**
Max	**0.344**	**28.686**	**71.000**	**0.416**	**3.989**
Std	**0.031**	**3.417**	**3.812**	**0.042**	**0.428**
Median	**0.274**	**21.844**	**69.500**	**0.312**	**3.201**

Table 14 Syllable Measures for Individual CI- Total syllables produced is for all 20 non-words (target=70), and speaking rate is the reciprocal of average syllable duration for each participant

Subject ID	Median Syll Duration (sec)	Summed Duration (sec)	Total Syll produced	Average Syll Duration (sec)	Speaking Rate (Syll/Sec)
CI.101	0.265	17.859	64	0.279	3.584
CI.103	0.271	20.713	69	0.300	3.331
CI.201	0.315	26.196	72	0.364	2.749
CI.202	0.265	20.101	69	0.291	3.433
CI.203	0.248	17.513	66	0.265	3.769
CI.204	0.269	19.553	70	0.279	3.580
CI.205	0.256	18.838	70	0.269	3.716
CI.301	0.261	21.048	70	0.301	3.326
CI.302	0.342	24.387	66	0.370	2.706
CI.303	0.240	17.248	69	0.250	4.000
CI.304	0.346	28.191	69	0.409	2.448
CI.305	0.232	18.401	70	0.263	3.804
CI.401	0.260	20.680	73	0.283	3.530
CI.404	0.245	16.906	66	0.256	3.904
CI.405	0.300	21.798	70	0.311	3.211
CI.406	0.244	19.874	68	0.292	3.422
CI.501	0.332	26.120	76	0.344	2.910
CI.502	0.269	20.032	69	0.290	3.444
CI.602	0.250	19.323	70	0.276	3.623
CI.603	0.245	20.049	66	0.304	3.292
CI.604	0.271	20.697	66	0.314	3.189
CI.605	0.241	19.563	69	0.284	3.527
CI.606	0.318	22.206	62	0.358	2.792
CI.607	0.232	16.500	64	0.258	3.879
CI.608	0.262	19.515	68	0.287	3.484
CI.701	0.270	23.980	62	0.387	2.585
CI.702	0.299	25.988	71	0.366	2.732
CI.704	0.297	22.211	69	0.322	3.107
CI.801	0.271	18.896	63	0.300	3.334
CI.807	0.310	24.005	68	0.353	2.833
CI.808	0.366	27.344	63	0.434	2.304
CI.901	0.257	19.295	70	0.276	3.628
CI.902	0.312	22.120	66	0.335	2.984
CI.903	0.331	23.538	67	0.351	2.846
CI.904	0.225	18.255	69	0.265	3.780
CI.905	0.219	17.790	70	0.254	3.935
CI.906	0.290	19.891	60	0.332	3.016
CI.908	0.263	19.839	71	0.279	3.579

CI.1001	0.310	19.435	57	0.341	2.933
CI.1002	0.307	22.301	63	0.354	2.825
CI.1003	0.256	20.650	69	0.299	3.341
CI.1004	0.306	18.473	56	0.330	3.031
CI.1101	0.347	19.603	49	0.400	2.500
CI.1102	0.294	23.771	70	0.340	2.945
CI.1103	0.298	23.587	67	0.352	2.841
CI.1104	0.252	20.573	70	0.294	3.403
CI.1105	0.251	19.106	63	0.303	3.297
CI.1106	0.339	22.832	65	0.351	2.847
CI.1201	0.284	22.137	68	0.326	3.072
CI.1202	0.253	19.707	69	0.286	3.501
CI.1203	0.250	20.146	72	0.280	3.574
CI.1205	0.304	22.258	67	0.332	3.010
CI.1206	0.219	16.994	69	0.246	4.060
CI.1301	0.290	24.458	72	0.340	2.944
CI.1401	0.280	18.161	63	0.288	3.469
CI.1402	0.212	17.776	70	0.254	3.938
CI.1404	0.237	17.811	66	0.270	3.706
CI.1405	0.265	20.037	70	0.286	3.494
CI.1502	0.342	27.232	70	0.389	2.571
CI.1504	0.262	19.698	67	0.294	3.401
CI.1505	0.253	17.821	69	0.258	3.872
CI.1506	0.306	21.755	67	0.325	3.080
CI.1602	0.259	19.467	70	0.278	3.596
CI.1606	0.266	20.547	69	0.298	3.358
CI.1608	0.325	25.450	71	0.358	2.790
CI.1609	0.361	26.966	68	0.397	2.522
CI.1703	0.270	20.952	65	0.322	3.102
CI.1802	0.355	25.910	67	0.387	2.586
CI.1803	0.302	22.822	71	0.321	3.111
CI.1804	0.322	27.751	71	0.391	2.558
CI.1902	0.322	23.985	70	0.343	2.918
CI.1906	0.291	20.522	68	0.302	3.314
CI.2002	0.302	22.755	70	0.325	3.076
CI.2004	0.258	19.407	71	0.273	3.658
CI.2103	0.333	28.925	75	0.386	2.593
CI.2105	0.307	21.523	64	0.336	2.974
Averag	**0.283**	**21.313**	**67.605**	**0.316**	**3.225**
Min	**0.212**	**16.500**	**49.000**	**0.246**	**2.304**
Max	**0.366**	**28.925**	**76.000**	**0.434**	**4.060**
Std	**0.037**	**3.024**	**4.151**	**0.044**	**0.434**
Median	**0.271**	**20.560**	**69.000**	**0.304**	**3.295**

Table 15 Correlations between syllable measures, age and working memory measures (shading indicates corresponding scatterplot included)

Correlations - CI Group

		Number of Syllables Produced	Average Syllable Duration	Median Syllable Duration	Average Syllable Lengthening Ratio	Age	CELF Num Rep	Visual Digit Span
NumSylls	Pearson Correlation							
	Sig. (2-tailed)							
	N							
avg syll dur	Pearson Correlation	-.225						
	Sig. (2-tailed)	.051						
	N	76						
med Syll Dur	Pearson Correlation	-.182	.913**					
	Sig. (2-tailed)	.115	.000					
	N	76	76					
avg syll dur ratio	Pearson Correlation	.190	-.044	-.086				
	Sig. (2-tailed)	.100	.705	.462				
	N	76	76	76				
Age	Pearson Correlation	.124	-.236*	-.271*	-.295**			
	Sig. (2-tailed)	.287	.041	.018	.010			
	N	76	76	76	76			
CELF Num Rep	Pearson Correlation	.380**	-.088	-.012	.159	-.228*		
	Sig. (2-tailed)	.001	.452	.921	.171	.048		
	N	76	76	76	76	76		
Vis Digit Span	Pearson Correlation	.263*	-.209	-.252*	-.233*	.441**	.340**	
	Sig. (2-tailed)	.022	.071	.028	.043	.000	.003	
	N	76	76	76	76	76	76	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 16 Correlations between syllable measures, age, and audiologic information (shading indicates corresponding scatterplot included)

Correlations- CI Group

		Age at 1st CI	Duration of Acoustic Experience	Unaided PTA-Acoustic Ear	Unaided LF PTA	Aided PTA-Acoustic Ear	Aided LF PTA
NumSylls	Pearson Correlation	-.101	.018	-.068	-.181	-.038	-.100
	Sig. (2-tailed)	.387	.880	.560	.117	.744	.388
	N	76	76	76	76	76	76
avg syll dur	Pearson Correlation	-.009	-.097	.033	.047	.114	.103
	Sig. (2-tailed)	.938	.404	.775	.689	.325	.374
	N	76	76	76	76	76	76
med Syll Dur	Pearson Correlation	-.056	-.131	.080	.126	.185	.158
	Sig. (2-tailed)	.630	.258	.492	.279	.110	.174
	N	76	76	76	76	76	76
avg syll lengthening ratio	Pearson Correlation	-.038	.045	-.056	-.178	-.100	-.080
	Sig. (2-tailed)	.742	.699	.633	.124	.388	.495
	N	76	76	76	76	76	76
Age	Pearson Correlation	.000	.188	.050	.096	.127	.199
	Sig. (2-tailed)	1.000	.103	.671	.411	.273	.085
	N	76	76	76	76	76	76

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

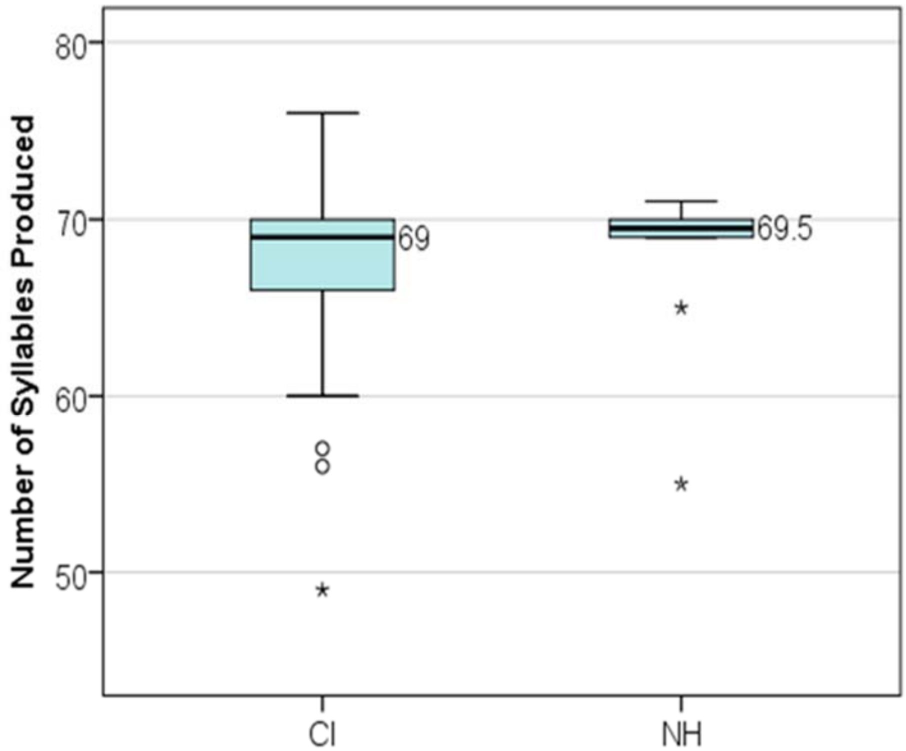


Figure 1 Boxplot of number of syllables produced for NH and CI groups. The upper edge of the box is the upper quartile of the distribution, the lower edge is the lower quartile of the distribution, the middle line is the median, and the whiskers represent the maximum and minimum of the distribution. The middle 50% for the NH group ranges from 69-70 and ranges from 66-70 for the CI group.

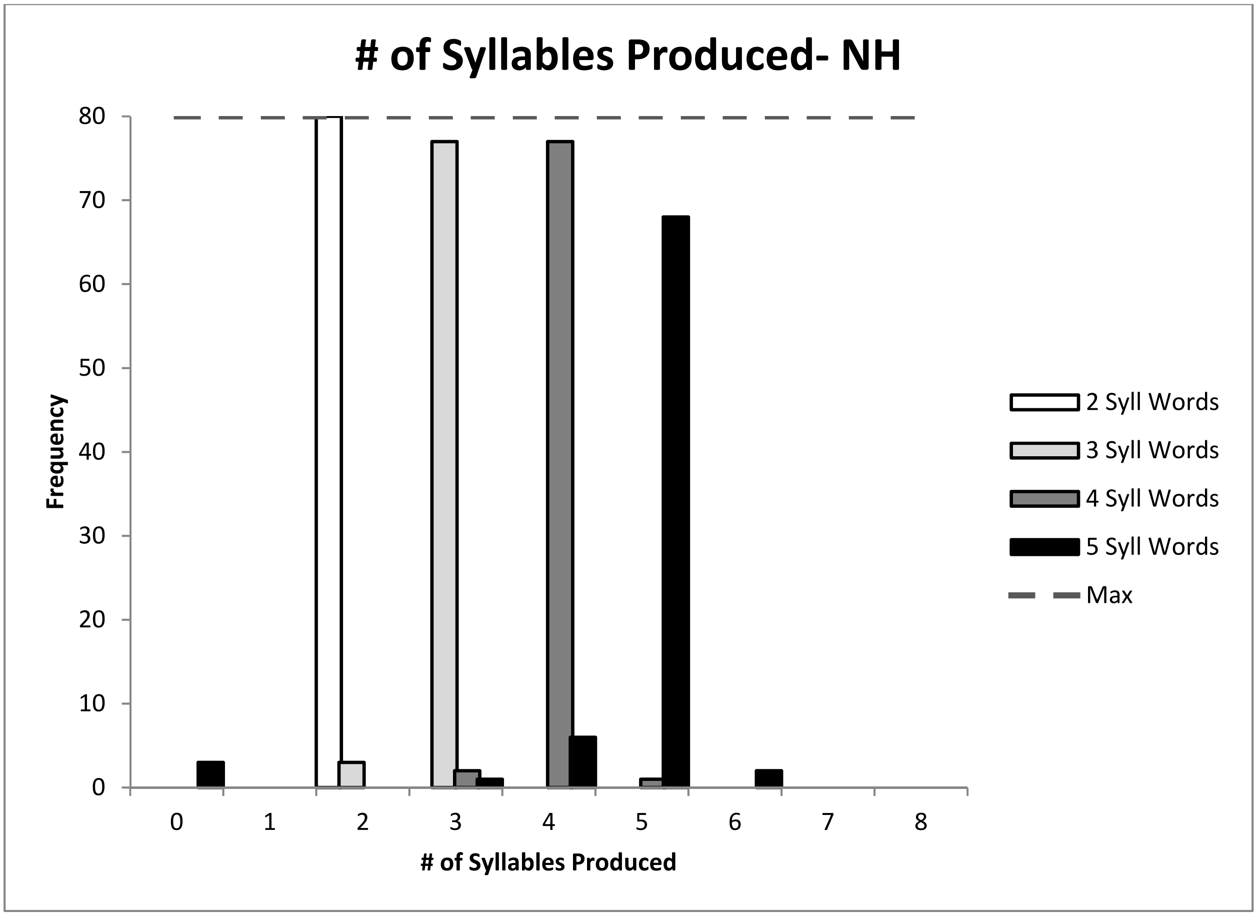


Figure 2 Distribution of the number of syllables produced for the NH participants

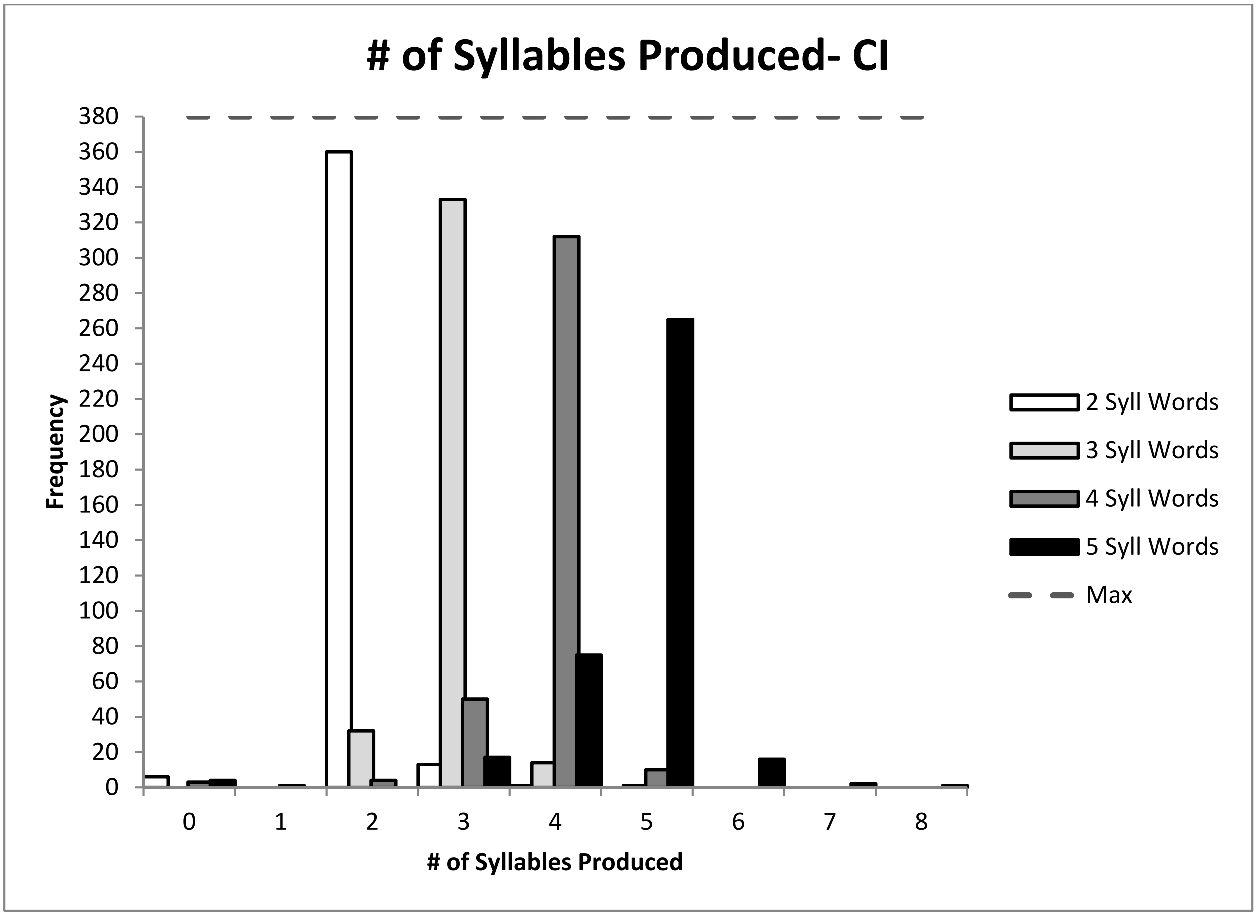
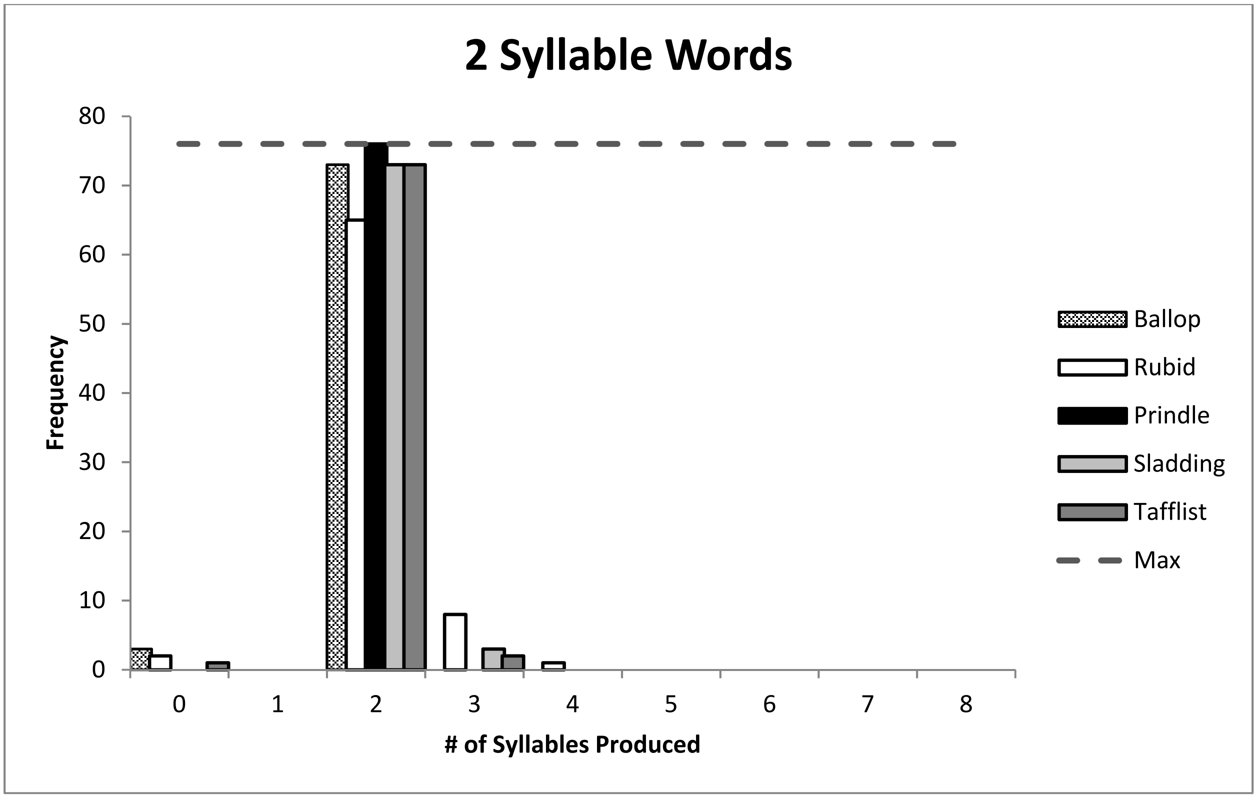
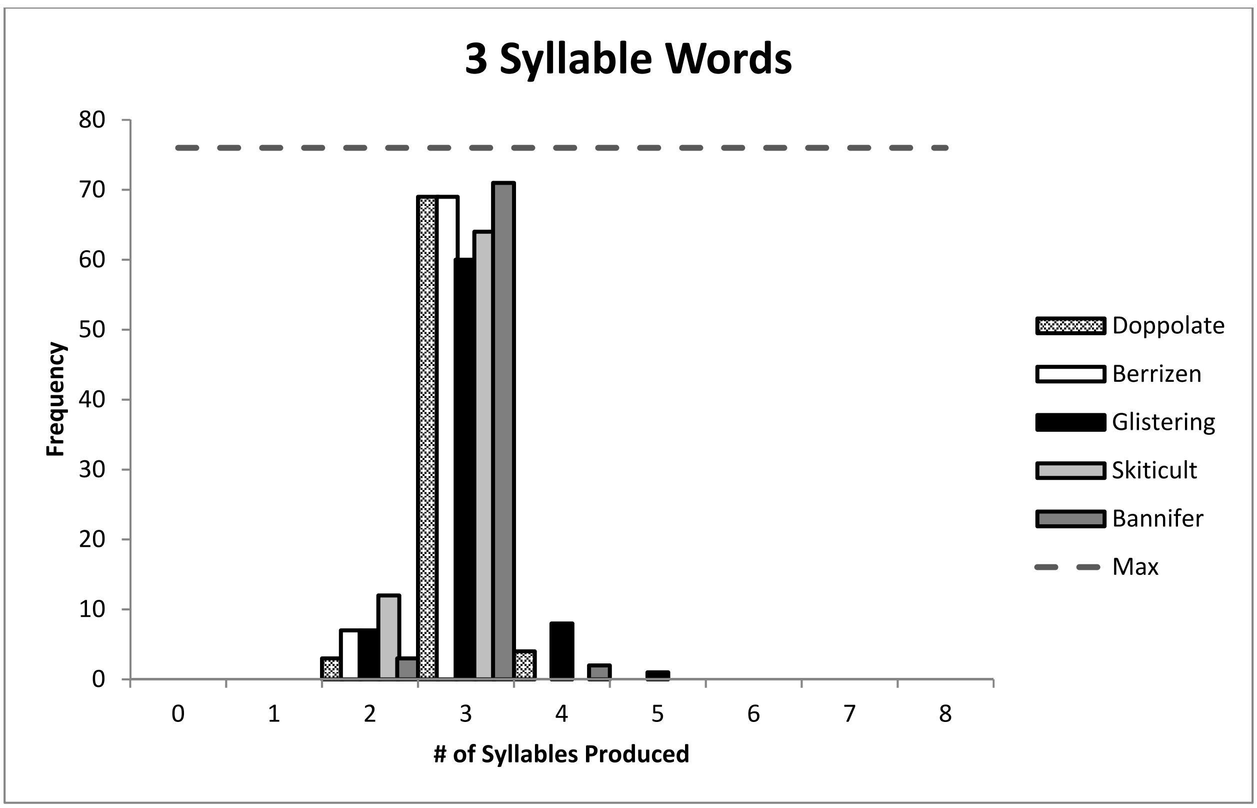
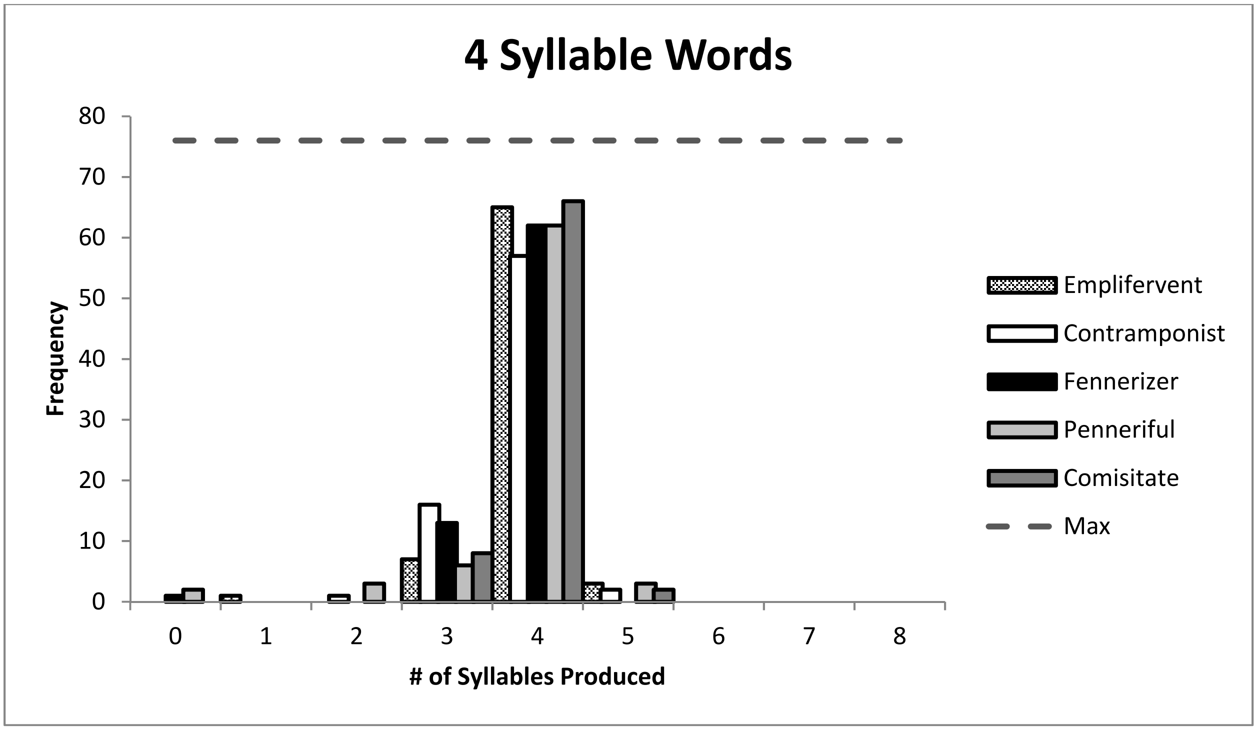


Figure 3 Distribution of the number of syllables produced for the CI participants


2 Syllable Words
80
70
60
50
40
30
20
10
0
Frequency
0
1
2
3
4
5
6
7
8
# of Syllables Produced
Ballop
Rubid
Prindle
Sladding
Tafflist
Max


3 Syllable Words
80
70
60
50
40
30
20
10
0
Frequency
0
1
2
3
4
5
6
7
8
# of Syllables Produced
Doppolate
Berrizen
Glistering
Skiticult
Bannifer
Max



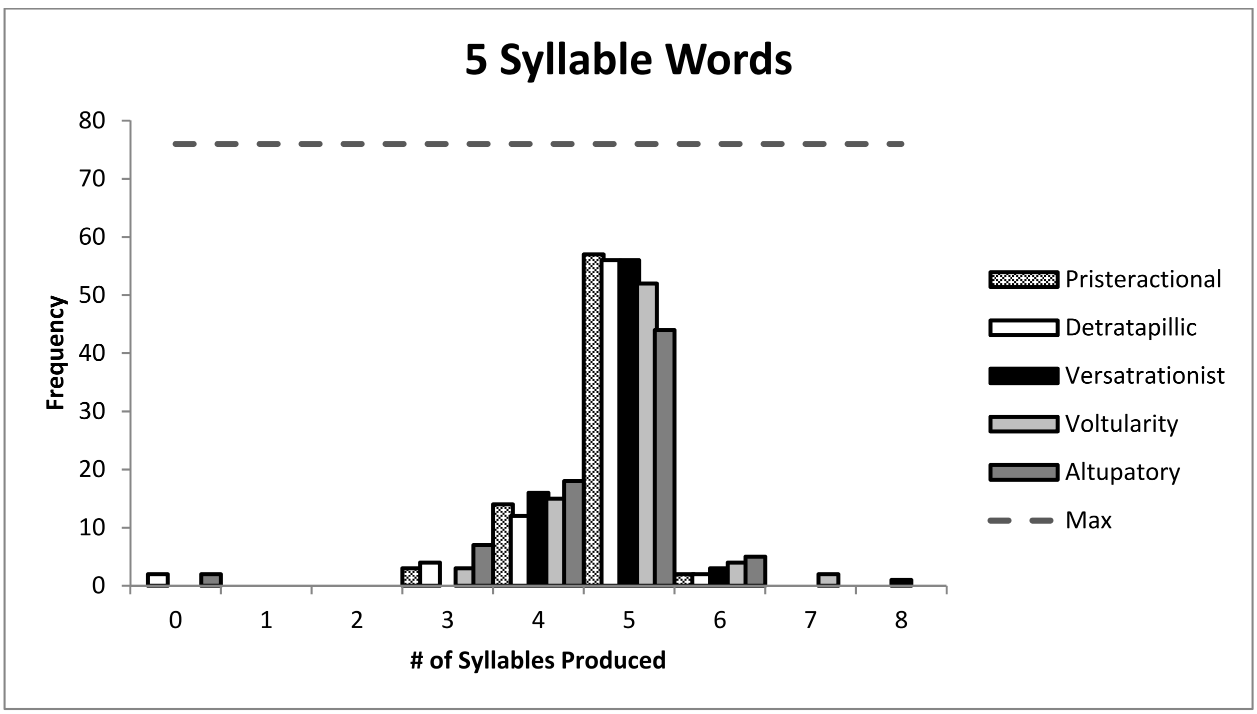


Figure 4 Distributions of the number of syllables produced for the CI participants. Each panel represents data for non-word with different syllable-lengths.

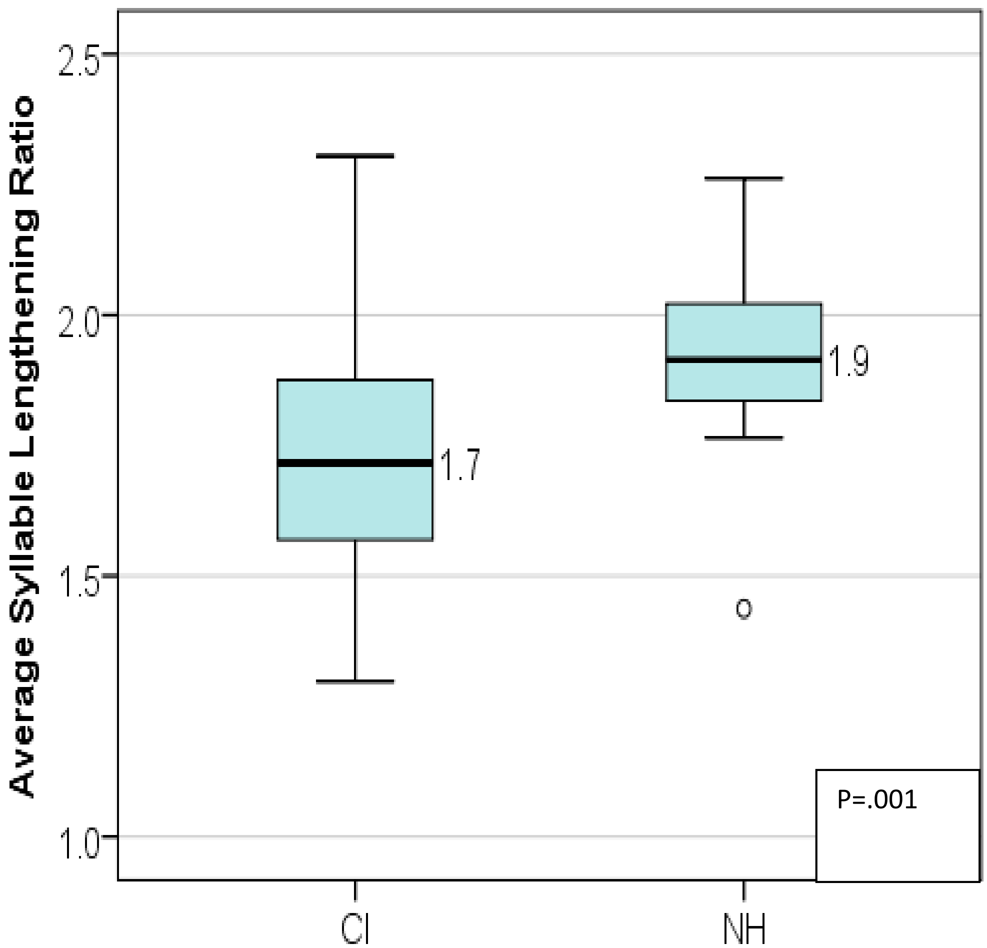


Figure 5 Boxplot of final-syllable-lengthening ratio for NH and CI groups. The upper edge of the box is the upper quartile of the distribution, the lower edge is the lower quartile of the distribution, the middle line is the median, and the whiskers represent the maximum and minimum of the distribution.

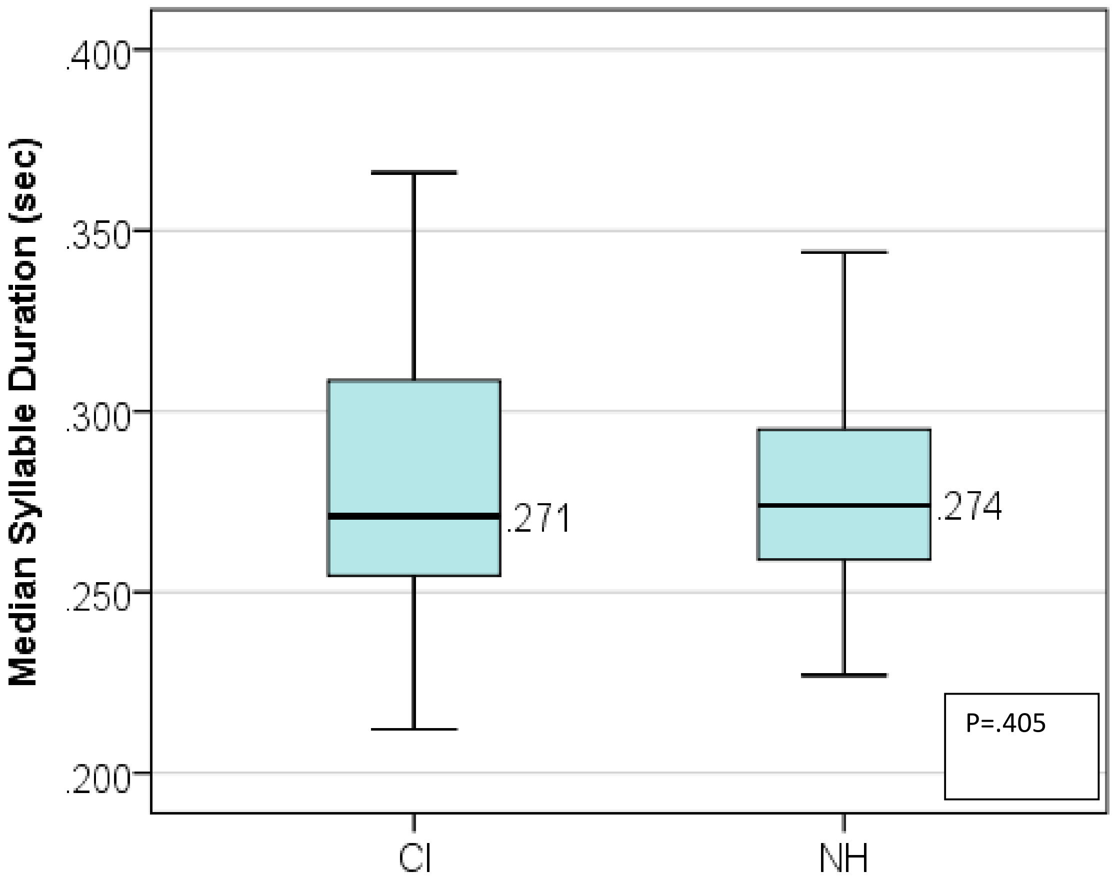


Figure 6 Boxplot of median syllable duration in msec for NH and CI groups. The upper edge of the box is the upper quartile of the distribution, the lower edge is the lower quartile of the distribution, the middle line is the median, and the whiskers represent the maximum and minimum of the distribution.

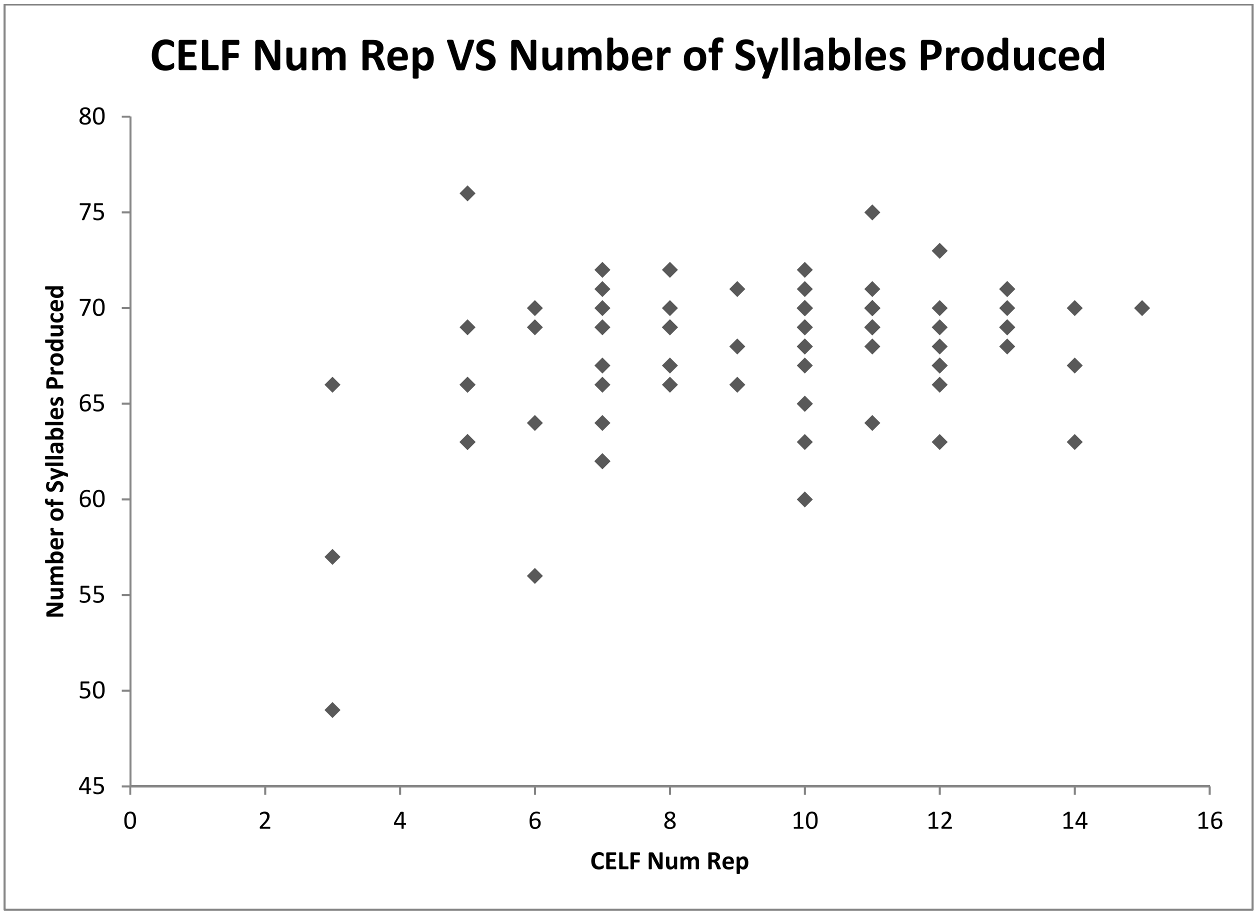


Figure 7 Scatterplot of number of syllables produced vs CELF Num Rep score for the CI participants. (r=.380, p=.001)

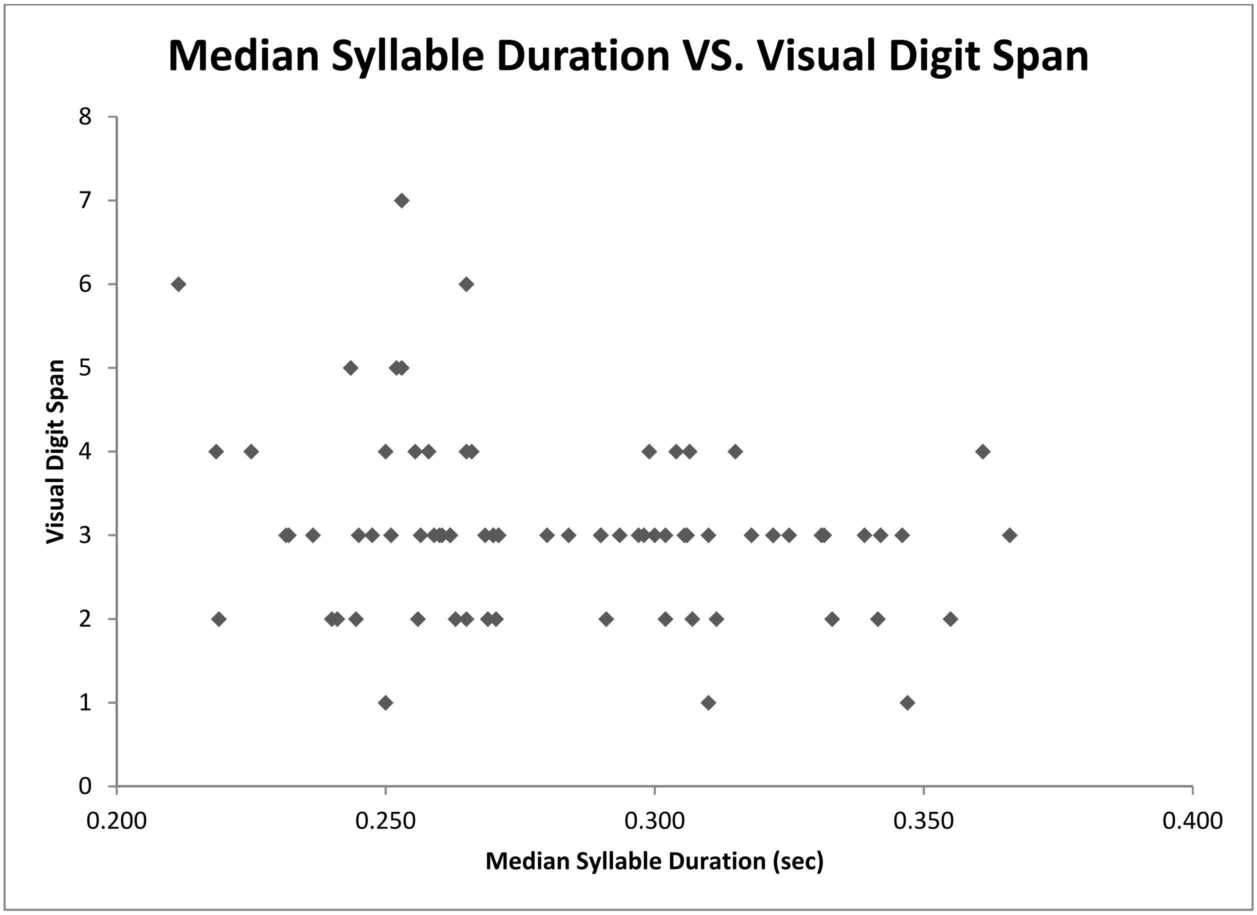


Figure 8 Scatterplot of Visual Digits Span vs median syllable duration for the CI participants. (r=-.25, p=.028)

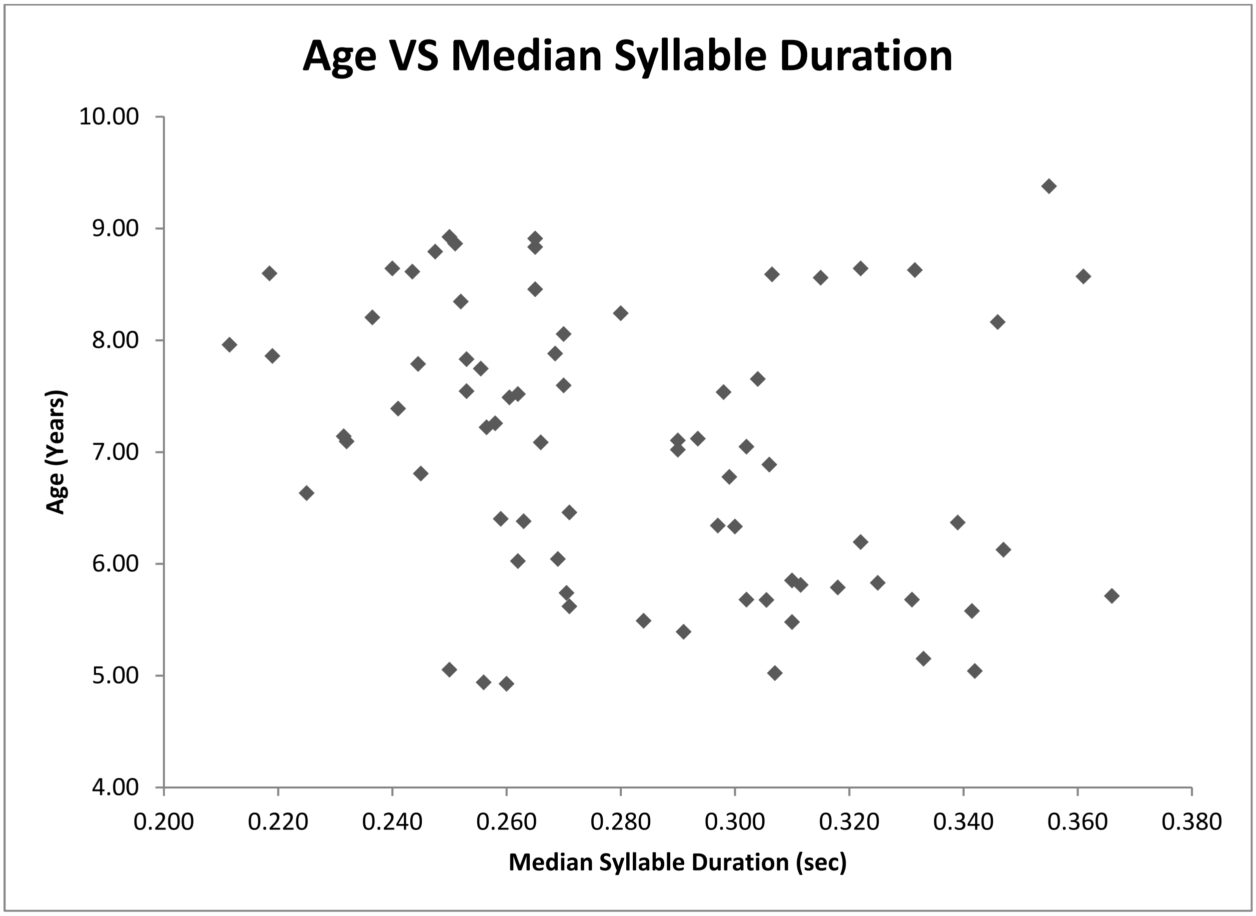


Figure 9 Scatterplot of Age vs median syllable duration for the CI participants. (r=-.271, p=.018)

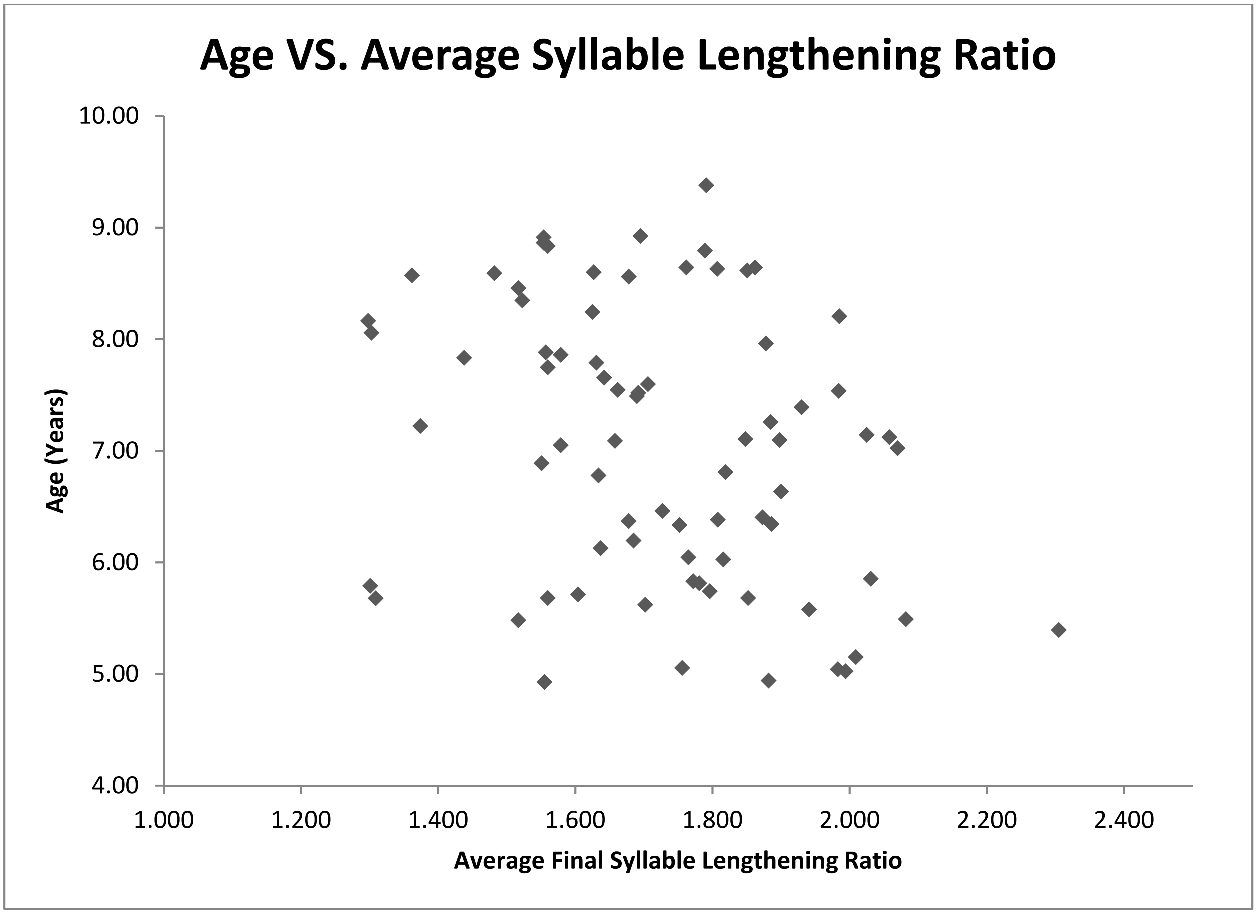


Figure 10 Scatterplot of Age vs average final-syllable-lengthening ratio for the CI participants. (r=-.295, p=.010)

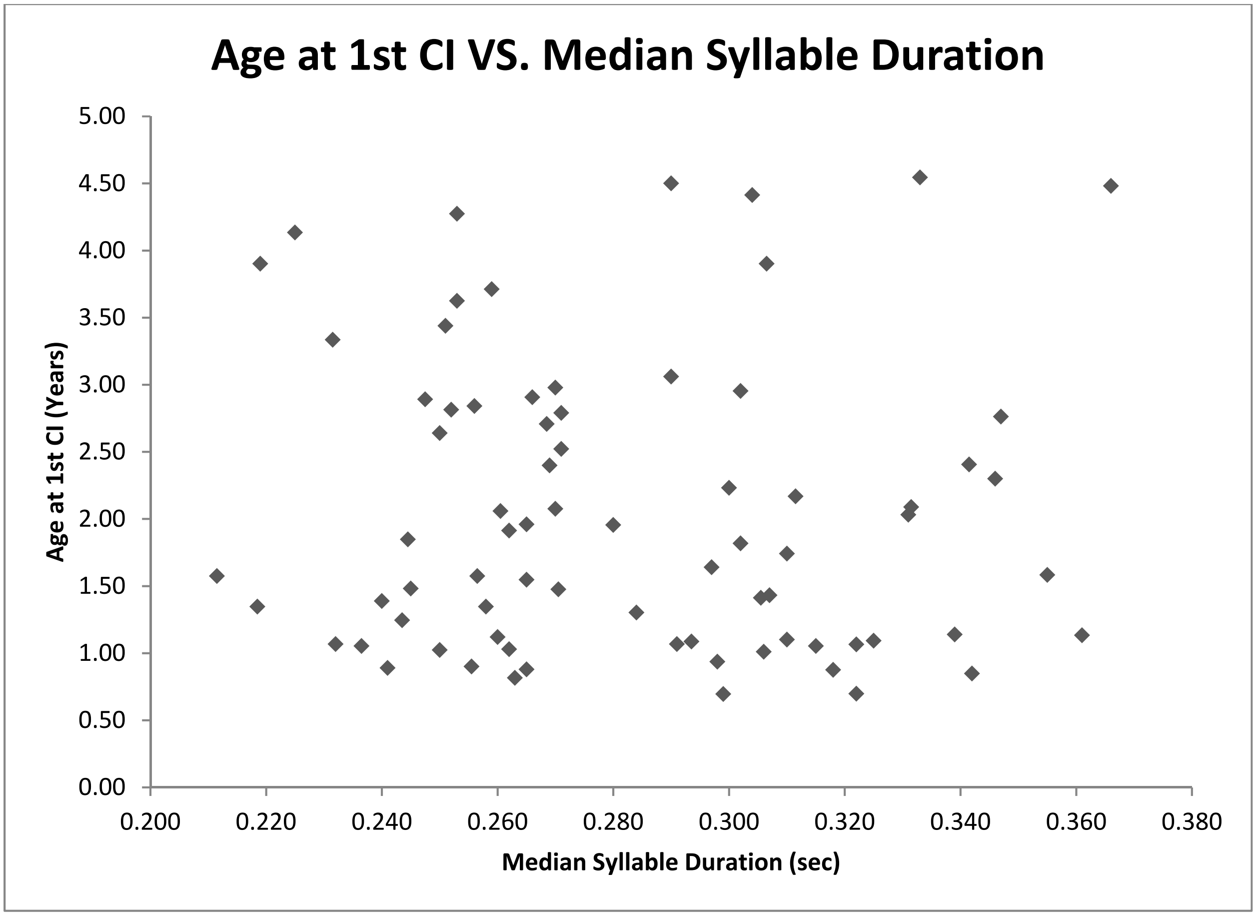


Figure 11 Scatterplot of age at 1st implant vs median syllable duration for the CI participants. (r=-.056, p=.630)

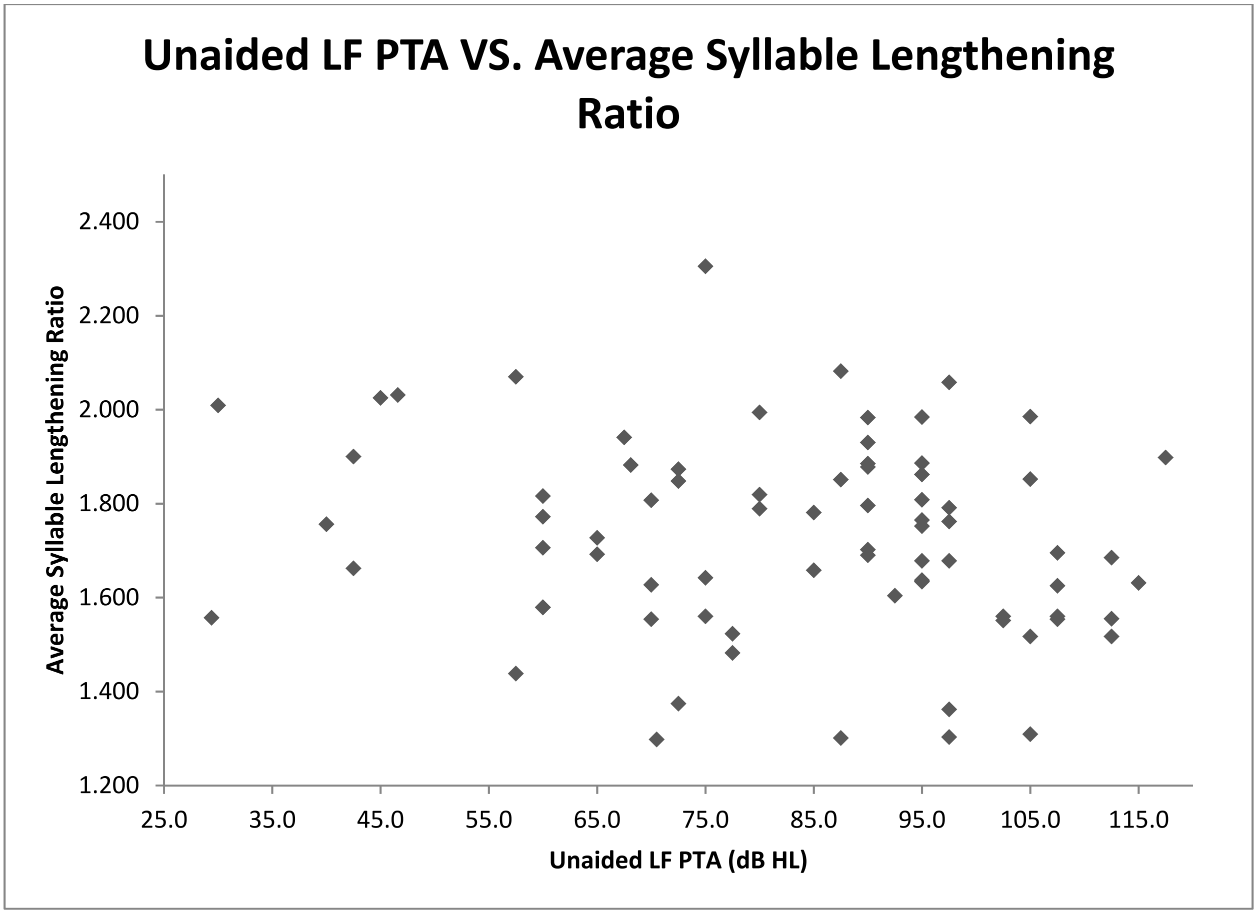


Figure 12 Scatterplot of average final-syllable-lengthening ratio vs unaided low-frequency PTA for the CI participants. (r=-.178, p=.124)

Appendix A

	Non-word	Syllables
1	ballop	bal | lop
2	prindle	prin | dle
3	rubid	ru | bid
4	sladding	sla | dding
5	tafflist	ta | fflist
6	bannifer	ba | nni | fer
7	berrizen	be | rri | zen
8	doppolate	do | ppo | late
9	glistering	glis | ter | ing
10	skiticult	ski | ti | cult
11	comisitate	co | mi | si | tate
12	contramponist	con | tram | po | nist
13	emplifervent	em | pli | fer | vent
14	fennerizer	fe | nne | ri | zer
15	penneriful	pe | nne | ri | ful
16	altupatory	al | tu | pa | to | ry
17	detratapillic	de | tra | ta | pil | lic
18	pristeractional	pris | ter | ac | tio | nal
19	versatrationist	ver | sa | tra | tio | nist
20	voltularity	vol | tu | la | ri | ty

RULES

- If a stop is at the beginning of a syllable, include closure
- If a stop is at the end of a syllable, include closure
- Liquids at the end or beginning of syllables- use judgement for the middle (vowels around them will be ‘colored’)

Appendix B

Written by Will Styler, November 2014; Modified by Rosalie Uchanski, Mar 2016

```
# For Kate Johnson AuD Capstone; duration of syllables of words produced for Nonword
Repetition (LSD R01)
#   Tier 1 = WORD;  Tier 2 = SYLLABLE


# THIS SCRIPT is for an individual .wav FILE -- FOLDER (directory$) & NAME (in strings)
must be HARD-CODED below

# Specify the directory where the INDIVIDUAL .wav file is
directory$ = "\\PCFNAS.PCF.WUSTL.EDU\OTO_Secure\Davidson\R01
Project\Data\NonWord Rep\Recordings\2014.02.08.Memphis.DR"

#  EDIT this line -- once for each .wav (+ TextGrid) file-pair for which Tier1 and Tier2 data-lists
are desired
#  NOTE  - seemingly MUST keep a "*" (wild-card) in this command
strings = Create Strings as file list: "list", directory$ + "/*401.22.wav"

# Specify (the directory) where you want the OUTPUT to live
directoryRes$ = "U:\My Documents\Praat Scripts\Praat-temp2"

# Header of text at top of OUTPUT file
header_row$ = "SoundFile" + tab$ + "IntNum" + tab$ + "Label" + tab$ + "VStart" + tab$ +
"VEnd"

number_files = Get number of strings
# This opens all the files one by one; will write separate OUTPUT for each INPUT .wav file
# NOTE:   number_files SHOULD BE Exactly "1"
for j from 1 to number_files
	selectObject: strings
	filename$ = Get string: j
	Read from file: directory$ + "/" + filename$
	# Works on whatever sound is selected in the objects window.  Make sure the Textgrid is
in the objects window too.
	sn$ = selected$ ("Sound")
	resultfile1$ = directoryRes$ + "/" + sn$ + "-Tier1.txt"
	resultfile2$ = directoryRes$ + "/" + sn$ + "-Tier2.txt"
	appendFileLine: resultfile1$, header_row$
	appendFileLine: resultfile2$, header_row$
	gridfile$ = directory$ + "/" + sn$ + ".TextGrid"
	if fileReadable (gridfile$)
		Read from file: gridfile$
		selectObject: "TextGrid 'sn$'"
```

```
        # for TIER 1 (WORD LABELS)
        numint1 = Get number of intervals: 1
        # Start the 1st loop
        for i1 from 1 to numint1
            label = ""
            selectObject: "TextGrid 'sn$'"
            label$ = Get label of interval: 1, 'i1'
            if label$ <> ""
                vstart = Get start point: 1, 'i1'
                vend = Get end point: 1, 'i1'
                # Spit the results into a text file
                result_row$ = sn$ + tab$ + "'i1'" + tab$ + label$ + tab$ +
"'vstart:4'" + tab$ + "'vend:4'"
                appendFileLine: resultfile1$, result_row$
            endif
        endfor
        # for TIER 2 (SYLLABLE LABELS)
        numint2 = Get number of intervals: 2
        # Start the 2nd loop
        for i2 from 1 to numint2
            label2$ = ""
            selectObject: "TextGrid 'sn$'"
            label2$ = Get label of interval: 2, 'i2'
            if label2$ <> ""
                vstart = Get start point: 2, 'i2'
                vend = Get end point: 2, 'i2'
                # Spit the results into a text file
                result_row$ = sn$ + tab$ + "'i2'" + tab$ + label2$ + tab$ +
"'vstart:4'" + tab$ + "'vend:4'"
                appendFileLine: resultfile2$, result_row$
            endif
        endfor

    endif
endfor
```