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The Influence of Word Characteristics on the Vocabulary of Children with Cochlear Implants

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Abstract

The goal of this study was to explore the effects of phonotactic probability, word length, word frequency, and neighborhood density on the words known by children with cochlear implants (CIs) varying in vocabulary outcomes in a retrospective analysis of a subset of data from a longitudinal study of hearing loss. Generalized linear mixed modeling was used to examine the effects of these word characteristics at three time points: pre-implant, post-implant, and longitudinal follow-up. Results showed a robust effect of neighborhood density across group and time, whereas the effect of frequency varied by time. Significant effects of phonotactic probability or word length were not detected. Taken together, these findings suggest that children with CIs may be able to use spoken language structure in a manner similar to their normal hearing counterparts, despite the differences in the quality of the input. The differences in the effects of phonotactic probability and word length imply a difficulty in initiating word learning and limited working memory ability in children with CIs.

The Influence of Word Characteristics on the Vocabulary of Children with Cochlear Implants

Two types of form representations, phonological and lexical, are known to influence word learning (e.g., Gupta & MacWhinney, 1997). Phonological representations consist of the individual sounds in a word form (e.g., /b/, /ɔ/, and /l/ in *ball*). Lexical representations refer to whole-word forms (e.g., /bɔl/). Thus, a given word has both a phonological and a lexical representation, and the effect of each on word learning can be investigated by examining word-specific characteristics. The specific characteristics of words that shed light on the structure and organization of form representations include phonotactic probability, word length, word frequency, and neighborhood density. Phonotactic probability measures phonological characteristics, while word length, word frequency, and neighborhood density measure lexical characteristics. These word characteristics influence word learning in typically developing children with normal hearing (Hollich, Jusczyk & Luce, 2002; Storkel, 2001; 2003; 2004a; 2009; Storkel & Lee, 2011). Moreover, the effects of phonotactic probability and neighborhood density may differ across the three processes of word learning: Triggering, configuration, and engagement (Storkel, 2009; Storkel & Adlof, 2009; Storkel & Lee, 2011).

In the initial stage of word learning (triggering), a listener must recognize a word as novel or known by matching the input with phonological and lexical representations stored in long-term memory. If the input has matching representations in long-term memory, the input will be recognized as known, initiating word recognition. In contrast, if the input does not have matching representations, the input is recognized as novel, triggering word learning. Note that the individual sounds and sound sequences in a novel word are assumed to have exact matches with phonological representations in long-term memory but not with lexical representations. Once word learning is initiated, the configuration process of word learning begins, where a new representation for the novel word is created. This initially created lexical representation may not be refined or detailed; however, repeated exposure to the word may make the representation more robust. Once a new representation is created, the engagement process of word learning begins, where the newly created representation is integrated with existing representations. This third process requires more time and may be dependent on sleep. Thus, the engagement occurs at a post exposure point.

Phonotactic probability is the likelihood of occurrence of a sound sequence. For example, /æ/ and /æp/ in *apple* occur less frequently than /k/ and /kæ/ in *cat.* Children learn words with low phonotactic probability sound sequences (e.g., /æ/ and /æp/ in *apple*) more readily than words with high phonotactic probability sound sequences (e.g., /k/ and /kæ/ in *cat*) because words with low phonotactic probability have an increased mismatch with existing phonological representation so that they can be more easily recognized as new words (Frisch, Large & Pisoni, 2000; Vitevitch, Luce, Charles-Luce & Kemmerer (1997), triggering word learning efficiently (Storkel, 2009; Storkel & Adlof, 2009; Storkel & Lee, 2011).

Lexical characteristics such as word length (the number of sounds in a word), word frequency (the number of times a word is heard), and neighborhood density (the number of known words that sound similar to a given word) influence word learning. For word length, children learn more words with few phonemes (short words) such as the two phoneme words *sew, toy,* and *ear* than words with many phonemes (long words) such as the 12 phoneme words *parallelogram, transportation,* and *communication*. For frequency, children learn more words with high frequency such as *dog, watch,* and *time* than words with low frequency such as *reel, pier,* and *hen*. For neighborhood density, children learn more words with high neighborhood density such as 19 neighboring words for /raɪt/ in *write*: /baɪt/, /faɪt/, /kaɪt/, /laɪt/, /maɪt/, /naɪt/, /saɪt/, /taɪt/, /ræt, /rat/, /rut/, /rɪt/, /rot/, /raɪm/, /raɪs/, /raɪd/, /raɪp/, /raɪ/, and /braɪt/) than words with low neighborhood density such as three neighboring words for /drɔ/

in *draw*: /dru/, / draɪ/, and /rɔ/. (Storkel, 2009). The short word advantage can be explained by the fact that long words are more difficult to hold in working memory (Baddeley, Thomson & Buchanan, 1975). Meanwhile, words with high frequency may better facilitate the association between a word and its referent during word learning when compared to words with low frequency (Rice, Oetting, Marquis, Bode & Pae, 1994). Additionally, words with high frequency may facilitate the creation of a robust lexical representation (Storkel, 2004a). On the other hand, words with high density may have segmentally detailed representations, reflecting a better ability to differentiate similar sounding words (Storkel, 2004a). Also, a novel word with high density may be easier to hold in working memory due to the higher support from the many words in long-term memory (Storkel, Armbrüster & Hogan, 2006; Storkel et al., 2009; 2011), facilitating the configuration process of word learning. Finally, in the engagement process of word learning, new representations that form connections with many existing representations in long-term memory may develop stronger representations than new representations that form connections with fewer existing representations (Storkel et al., 2006; 2011).

Little is known about how these characteristics influence auditory spoken word learning when the acoustic signal cannot be processed in a typical manner, such as in the presence of initial auditory processing problems. Children with cochlear implants (CIs) are of particular interest because their CIs do not enable them to fully recover from their hearing loss, and the input they receive differs from that of children with normal hearing because of the variability in surviving neural structures and the number and location of implanted electrodes. In addition, the cochlear implant itself has limitations because it provides only broad representations of the spectral features of speech (Rubinstein, 2004; Shannon, Fu, Galvin, & Friesen, 2004) and crude temporal information (Lorenzi, Gilbert, Carn, Garnier, & Moore, 2006). Thus, children with CIs may not receive the same benefit from existing spoken language structure as children with normal hearing. For example, the reduced perceptual input via a CI may cause the initiation of spoken word learning to be slow. Specifically, when a spoken novel word is encountered, the reduced perceptual input via the CI might cause difficulty in differentiating a novel sound sequence from existing sound sequences, which may slow the recognition that a new spoken word is present and needs to be learned (Pittman & Schuett, 2013). Regardless of the length or frequency of the spoken words themselves, difficulties with perceptual processing may result in crude phonological or lexical representations. These holistic representations may have implications for working memory as well; working memory may not receive as much support from long-term memory because of difficulty in activating long-term memory from the input (Baddeley, Gathercole, & Papagno, 1998). It might be particularly difficult for children with CIs to learn spoken words with high neighborhood density because of the difficulty they may have with discriminating new spoken words from the many known spoken words that sound similar (Storkel 2004a; Storkel, Maekawa & Hoover 2010). For these reasons, phonological and lexical characteristics may not influence spoken word learning by children with CIs in the same way as children with normal hearing. This study explores this possibility in a post-hoc analysis of a longitudinal sample of vocabulary in children with CIs.

Children with CIs have notable deficits in vocabulary, although language outcomes are heterogeneous (e.g., Geers, Moog, Biedenstein, Brenner & Hayes, 2009; Yoshinaga-Itano, Baca & Sedey, 2010). Some of the variability in language outcomes can be attributed to differences in age of implantation, experience with CIs, family involvement, additional disabilities, cognitive level, and maternal level of education (see, respectively, Connor, Hieber, Arts & Zwolan, 2000; Tomblin, Barker, Spencer, Zhang & Gantz, 2005; Geers & Brenner, 2003; Donaldson, Heavner, & Zwolan, 2004; Edwards & Anderson, 2014; Cupples, et al., 2014). In general, an earlier age of implantation, greater months of CI experience, higher family involvement, no additional disabilities, higher cognitive skills, and higher levels of maternal education result in better vocabulary outcomes. More recently, Yoshinaga-Itano et al. (2010) demonstrated how vocabulary development rates in children with hearing loss (n_{CI} = 49) changed over time. In their study, the Expressive Language subscale of the Minnesota Child Development Inventory (Ireton, 2000) was administered at 36 months to define children's language status as within normal limits or delayed. Moreover, the Test of Auditory Comprehension of Language, 3rd Edition (TACL-3; Carrow-Woolfolk, 1999) and the Expressive One Word Picture Vocabulary Test, 3rd Edition (EOWPVT-3; Brownell, 2000) were administered between three and seven years of age to trace the children's language development. Based on initial performance at three years of age and the language outcomes at seven years of age, the participants were categorized into four language performance groups: Gap Opener, Gap Closer, Age Equivalent, and Delayed. The Gap Opener group (nCI = 1 on the EOWPVT-3) showed a declining rate of language development from three to seven years of age, resulting in a bigger gap between their performance and the age-equivalent group at age seven. The Gap Closer group (nCI = 8 on the EOWPVT-3) showed performance below the age-equivalent group at age three, but improved and became age equivalent by age seven. The Age Equivalent group (nCI = 8 on the EOWPVT-3) maintained an age-equivalent or higher performance between three and seven years of age. The Delayed group (nCI = 16 on the EOWPVT-3) showed a borderline-to-delayed language performance at three years of age and performance below the age-equivalent group at seven years of age. The findings of Yoshinaga-Itano et al. (2010) indicate that some children with CIs have very positive outcomes after implantation while other children show a considerable delay. This variability may result from the way children with CIs use language structure to learn new words before and after implantation.

The goal of the current study is to explore the effects of spoken word characteristics such as phonotactic probability, word length, word frequency, and neighborhood density on the spoken words known by children with CIs in a retrospective analysis of Yoshinaga-Itano's Colorado longitudinal study of hearing loss (Yoshinaga-Itano et al., 2010).

To meet this overall goal, three research questions are proposed: (1) Do spoken word characteristics influence the spoken words known by children with CIs? These findings will shed light on whether spoken word characteristics influence spoken word learning in children with CIs in the same way as typically developing children; (2) Do these effects of spoken word characteristics vary across groups with different spoken language outcomes? The answer to this question will provide evidence of whether children with CIs who experience different language outcomes use phonological and lexical information in a different way to learn new words; and (3) Do the effects of spoken word characteristics change over time as children gain experience with their implant and acquire greater language skills? This question addresses whether the way children with CIs use phonological and lexical information to learn new words varies over time as the children gain experience with CIs and expand their language skills.

Method

Participants

The current study selected a subset of children from the Yoshinaga-Itano et al.'s (2010) study of 49 participants with CIs. Because the focus of the current study is spoken vocabulary acquisition, the records of each of these participants were examined by the fourth author to determine whether they were administered vocabulary tests at the three test points of interest. Of these children, 33 had expressive vocabulary data from the MacArthur Communicative Development Inventories (CDI-I, developed for eight- to 16-month-old infants; CDI-II for 16- to 30-month-old toddlers; and CDI-III for 30- to 36-month-old children, Fenson, Marchman, Thal, Dale, Reznick, & Bates, 2006) and the EOWPVT-3. Out of this group, the maternal level of education was considered because maternal level of education is known to be associated with different language outcomes (e.g., Dollaghan et al., 1999). The most prevalent level of maternal education in the 33 children was 16 years or greater. This high level of maternal education may minimize the effects of the environment on the current results. Restriction of maternal education to 16 years or greater yielded 17 cases and age of implantation was comparable across groups. Out of these 17 children, data from 14 children were selected because only 14 of them had sufficient vocabulary data at the three test points of interest for analysis. Among these 14 children, five were in the Gap Closer group, five were in the Age Equivalent group, and four were in the Delayed group; two of this last group scored below the 10^{th} percentile and the remaining two scored above the 10^{th} percentile despite performance that was consistently below age expectations. The Gap Opener group was not included in the current study because of insufficient children meeting our criteria. The hearing information of the 14 selected children is presented in Table 1. There is no significant difference in the age of identification of hearing loss, $F(3, 10) = .43$, $p = .74$, $\eta^2_p = .12$, age of intervention, $F(3, 10) = .51$, $p = .69$, $\eta^2_p = .13$, age first fitted with a hearing aid, $F(3, 10) = .64$, $p = .61$, $\eta^2_p = .16$, duration of hearing aid before CIs, $F(3, 10) = 1.92$, $p = .19$, $\eta^2_p = .37$, age of CI activation, $F(3, 10) = .83$, $p = .51$, $\eta^2_p = .20$, or duration of CI use, $F(3, 10) = 1.04$, $p = .42$, $\eta^2_p = .24$, across groups. In addition, some participants exclusively used oral productions whereas others used oral production and sign language as communication modalities.

[Table 1 Location]

Test Points and Language Outcome Measures

The information on the test points and the vocabulary outcome measures administered to each child is presented in Table 2. The three test points were pre-CI (M_{age} =

2;0 years, *SD* = 1;3, age range: 0;9-4;5 years), post-CI (M_{age} = 3;10 years, *SD* = 1;4, age range: 2;3-6;0 years), and latest post-CI (M_{age} = 6;10 years, *SD* = 0;5, age range: 5;9-7;1years). Pre-CI data were collected approximately one year before children received CIs; post-CI data were collected approximately one year after they received CIs; and the latest post-CI data were collected when the children were approximately seven years of age.

[Table 2 Location]

As shown in Table 2, the language outcome measures were not equally available for each child across the three test points. At pre-CI, each child was tested on one of the CDIs or the EOWPVT-3. At post-CI, nine children were tested on one measure (CDI or EOWPVT-3) and five were tested on two measures (CDI and EOWPVT-3). However, at the latest post-CI, all of the children were tested on the EOWPVT-3. Note that these two measures differ in terms of test administration: the CDIs are parent reports while the EOWPVT is a clinician-elicited measure. However, validation studies of the CDI using clinician-elicited measures such as the EOWPVT revealed that parent report via the CDIs is a valid tool for assessing early language development for typically developing children (Dale, 1991; Dale, Bates, Reznick, & Morisset, 1989), for children with specific language impairment (Thal, O'Hanlon, Clemmons, & Fralin, 1999), and for children with CIs (Thal, DesJardin, & Eisenberg, 2007). Due to this variability in outcome measures across test points and children, variables were normalized (see analysis section).

Variables

Phonotactic probability, word length, word frequency, and neighborhood density were calculated by the first author via an on-line calculator (www.bncdnet.ku.edu/cml/info_ccc.vi) developed by Storkel and Hoover (2010) on the basis of the child corpora of approximately 5,000 different words spoken by kindergarten and/or first-grade children (Kolson, 1960; Moe, Hopkins & Rush, 1982). These word characteristics were computed based on the target pronunciation rather than the children's actual pronunciation because the research focused on the spoken words known by children and not on the children's articulation.

Phonotactic probability. Positional segment average and biphone average were utilized to measure phonotactic probability. Positional segment average is computed by adding the positional segment frequencies for each phoneme in a spoken word and dividing by the number of phonemes in the word. Positional segment frequency is computed for each phoneme in the word (e.g., the first sound /b/ in the word ball) by summing the log frequency of all the words in the on-line child dictionary that contains the target sound in the same position (e.g., /b/ in the initial position) and dividing by the sum of the log frequency of all of the words in the on-line child dictionary that contain any sound in the same position. Biphone average is computed by adding the biphone frequencies for each pair of phonemes in a word and dividing by the number of pairs in the word. Biphone frequency is computed by summing the log frequency of the words in the on-line child dictionary that contain the target pair of phonemes in the target word position (e.g., /bɔ/ in the initial position) and dividing by the sum of the log frequency of the words in the on-line child dictionary that contain any pair of sounds in the target position.

Word length. The number of phonemes in the on-line child dictionary transcription was used for spoken word length. For example, the word *ball* /bɔl/ consists of three phonemes, thus the word length for *ball* is three.

Word frequency. The log frequency was provided by the on-line calculator and was based on words spoken by kindergarten and/or first-grade children (Kolson, 1960; Moe et al., 1982).

Neighborhood density. Neighborhood density is defined as the number of spoken words in the on-line child dictionary that differ from a target word by a substitution, addition or deletion of one sound in any position (Luce & Pisoni, 1998).

Correct and incorrect responses. Correct and incorrect responses were coded for the CDIs and the EOWPVT-3. On the CDIs, a correct response was defined as a spoken word; an incorrect spoken response was defined as a sign-only response or no response. On the EOWPVT-3, a correct response was defined as a correctly responded word; an incorrect response was defined as an incorrectly responded word, no response, or marked by an examiner as signed. On the CDIs, all items were counted as correct or incorrect, whereas on the EOWPVT-3, items were counted only up to the last item at which a ceiling was established and the items above the ceiling were ignored. Some items on the EOWPVT have multiple correct responses. For these items, the spoken word characteristics were computed for each possible response and then averaged to yield one value for the item. Note that the specific response provided by the child was not typically noted so only this average item valued could be analyzed. The coding for correct or incorrect responses was entered by the first author and then checked by the first author at a later time (i.e., intrajudge verification). However, interjudge verification was not performed.

Analysis

Since the current study examined the data from different vocabulary tests across test points, normalization was necessary for comparison. The mean and standard deviation for each word characteristic were calculated for each test. For example, the mean word length for all the items on the CDI-I is 3.86 and the standard deviation is 1.39. Then, a z-score was calculated for each word. For example, 'dog' on the CDI-I has a length of 3 phonemes. Thus, the z-score would be (item value – M)/SD, which for this specific example is (3-3.86)/1.39. This results in a word length z score for 'dog' of -0.62 on the CDI-I. The final data set for each child consisted of the test words at each test time (pre-CI, post-CI, latest post-CI), the z score for each word characteristic (phonotactic probability, length, frequency, neighborhood density) for each word, and the response code for each word (correct, incorrect). Additionally, each child's language group (Gap Closer, Age Equivalent, Delayed Above 10th percentile, and Delayed Below 10th percentile) was coded.

Results

Generalized linear mixed modeling was used to examine the effects of spoken word characteristics, participant group, test time, and potential interactions among these factors in our clustered longitudinal data. Correct/incorrect spoken responses were repeatedly observed for a collection of words and participants. The random effects of participants and words were crossed at the same level (level-2) to account for nested sources of variability in the data. The fixed effects included word characteristics, group, time, and interactions of group x time, group x each word characteristic, and time x each word characteristic. The model parameters were estimated using restricted pseudo-likelihood estimation (Wolfinger & O'Connell, 1993) implemented in SAS PROC GLIMMIX (SAS Institute, 2002-2010).

Since some spoken word characteristics for proper nouns or words were not computed in the child corpora (Kolson, 1960; Moe et al., 1982), prior to modeling, Monte Carlo Markov Chain (MCMC) multiple imputation technique was used to handle missing values (0.01% to 1.04%) of each word characteristic. Two hundred imputed datasets were created via expectation-maximization estimates as priors for a subsequent MCMC procedure (Enders, 2010). Next, modeling results from each of the 200 imputed datasets were combined to make a valid statistical inference (Rubin, 1987). All of the word characteristics for two unspecified proper nouns (i.e., the child's own name and a sitter's name) were not obtained, and excluded from the analysis.

[Table 3 Location]

Table 3 shows the parameter estimates for random effects and fixed effects. The random effects of participants and words were significant, suggesting that the response probability varied among the participants (z = 2.21, p = .04) as well as across the test words (z

= 13. 86, $p < .001$) even after accounting for the other variables in the model. For fixed effects, a significant main effect of neighborhood density ($p = .01$) and significant interactions of group x time ($p < .001$) and time x frequency ($p = .01$) were observed. . To illustrate these significant interactions, the mean expected probability of correct responses was plotted with error bars representing the 95% confidence limits (CLs) of the means.

Do Spoken Word Characteristics Influence the Spoken Words Known by Children With CIs?

Results showed a strong effect of neighborhood density across group and time whereas no other spoken word characteristics showed a significant main effect in the absence of significant interactions with group or time. In terms of neighborhood density, a one-point (1 *SD*) increase in neighborhood density increased the probability of a correct response by 71% (odds ratio = 1.71, $p = .01$). This result indicates that as neighborhood density increases, children with CIs are more likely to learn that particular spoken word, which mirrors the results of children with normal hearing (Storkel, 2009).

Do These Effects of Spoken Word Characteristics Vary Across Groups With Different Spoken Language Outcomes?

The results showed no group differences in the effects of spoken word characteristics on word learning. However, the changes in word learning in each group over time were observed, suggesting different patterns of word learning in children with CIs varying in vocabulary outcomes.

[Figure 1 Location]

Figure 1 shows the interaction of group x time as a function of time (left panel) and as a function of group (right panel). In the left panel, all four groups had nearly a zero probability of a correct response at pre-CI (range of means = 0 - .07). The probability of correct response for the Age Equivalent group increased rapidly from pre-CI to post-CI (Δ =

.73) and increased slowly to latest post-CI (Δ = .19), reaching a probability of 1. The probability of a correct response for the other three groups increased relatively slowly from pre-CI to post-CI (Δ = .07 - .37) and then rapidly from post-CI to latest post-CI (Δ = .43 - .62) with the highest probabilities found for the Gap Closer group, followed by the Delayed Above 10th percentile group, and lowest for the Delayed Below 10th percentile group. However, the probabilities did not reach the level of the Age Equivalent group at post-CI or latest post-CI. In the right panel, a significant difference in the probability of correct responses was observed between pre-CI and post-CI in the Age Equivalent group, between pre-CI and latest post-CI in the Gap Closer group, the Age Equivalent group, and the Delayed Below 10th percentile group. No significant difference was observed between post-CI and latest post-CI in any group. These results suggest that only children with CIs in the Age-Equivalent group learn words rapidly with just one year of CI experience, while children with CIs in the Gap Closer group need longer CI experience to learn words. Children in the two Delayed groups show large variability in word learning throughout the post CI period.

Do the Effects of Spoken Word Characteristics Change Over Time as Children Gain Experience With Their Implant and Acquire Greater Language Skills?

Results showed that only the effect of frequency changed over time. Figure 2 shows the interaction of time x frequency as a function of word frequency.

[Figure 2 Location]

The probability of a correct spoken response at pre-CI was almost zero with very small variability at all values of word frequency between -2 and +2. In contrast, the probability of a correct spoken response at post-CI increased steadily as spoken word frequency increased, but did not reach the level shown at latest post-CI. Thus, there was a linear effect of frequency on spoken word learning at post-CI, mirroring what is observed in normal hearing children. The increase of the probability of a correct spoken response at latest post-CI decelerated as frequency increased, and the probability almost reached the ceiling. That is, there was still an effect of frequency on word learning at latest post-CI, but it was curvilinear with high frequency words having a high probability of being known. This is consistent with the strong effect of frequency found in children with normal hearing (Storkel, 2009).

Discussion

Problems in initial auditory processing are known to influence the formation of linguistic representations. CI users who experience coarse and distorted auditory input through their CIs may not receive the same benefit from the existing linguistic representations as people with normal hearing. The goal of this study was to investigate the effects of phonological and lexical characteristics on the spoken words known by children with CIs who were categorized into four groups based on their language outcomes in a longitudinal study. While significant effects were not found for phonotactic probability or word length, neighborhood density showed a robust effect across group and time and the effect of frequency varied by time. Hence, this complex set of findings pinpoints similarities and differences between children with CIs and typically developing children with changes across CI experience and language ability.

The results of the current study demonstrate that phonotactic probability may not influence the words known by children with CIs. This finding contrasts with previous findings from typically developing children and adults with normal hearing, who show a low phonotactic probability advantage in the initial stage of word learning processes (Storkel, 2009; Storkel et al., 2006; 2009; 2011). Words with low probability sound sequences sound like novel words (Frisch et al., 2000; Vitevitch et al., 1997), triggering word learning. If listeners could not distinguish known words from novel words, they would treat all words as known or novel (Pittman & Schuett, 2013). Pittman and Schuett (2013) found a problem with triggering word learning in children with mild to moderately severe hearing loss. Therefore, the lack of a phonotactic probability effect in the current study suggests that children with CIs may not optimally use this phonological cue to identify a heard word as known or novel, resulting in an inefficient word learning process due to delayed triggering of word learning. It is noted that the results of non-significance of phonotactic probability were obtained based on the outcome data of spoken word learning while prior results showing a significant phonotactic probability effect were obtained from experimental studies of the word learning process as it unfolds in real time for typically developing children with normal hearing. Given that phonotactic probability is predicted to influence the very first step in word learning (i.e., triggering), examination of word learning outcomes, as in the current study, may have obscured the role of phonotactic probability in word learning by children with CIs. Thus, future experimental studies of the word learning process in real time may shed light on how children with CIs use phonological information in the process of word learning.

In contrast to the effect of phonotactic probability, the effect of neighborhood density was robust, favoring words with a high density. The high density advantage reflects an ability to differentiate similar sounding words. Hence, the results of the current study suggest that children with CIs may be able to use spoken language structure in a manner similar to typically developing children with normal hearing even though the perceptual input through their CIs is degraded. The findings of the current study suggest that children with CIs may be able to capitalize on similar spoken words in long-term memory to facilitate later stages of word learning (i.e., configuration and engagement, see Storkel et al., 2006; 2009; 2011 for detailed explanation). Taken together, the auditory information through CIs seems to influence the recognition of individual sounds (phonotactic probability) in the initial stage of spoken word learning more than the retention of whole-word similarity to other words (neighborhood density) in long-term memory in the later stage of spoken word learning.

In regard to the effect of spoken word length, children with CIs learned a word regardless of its length, which contrasts with findings in children with normal hearing who learned shorter spoken words more accurately than longer words. Given the short word advantage in holding words in working memory (Baddeley, Thomson & Buchanan, 1975), the result of this study suggests that children with CIs may not use a word length cue because of delayed or impaired working memory development (Pisoni & Cleary, 2003; Pisoni, Kronenberger, Roman, & Geers, 2011). This study did not directly investigate the relationship between spoken word length and working memory development in children with CIs over time. However, the results did not show a short spoken word advantage at any test point or in any language group, implying continuously delayed development of working memory across all groups compared to typically developing children.

Turning to the interaction of time x frequency, immediately following implantation, children showed a clear and strong facilitative effect of frequency. This finding parallels prior studies showing that high frequency words are typically learned earlier than low frequency words, as frequency likely relates to the number of exposures as well as the ease of language processing (e.g., Oldfield & Wingfield, 1965). Importantly, the current results also show that this frequency effect begins to taper off by the latest post-CI point. Although high frequency words are still learned more than low frequency words at the latest post-CI, this high frequency advantage is diminishing, suggesting that the benefit of high frequency is somewhat limited.

Clinical implications are driven from the theoretical inquiry into how children with CIs use phonological and lexical cues in learning spoken novel words. The findings suggest that children with CIs learn specific types of words (i.e., high density and high frequency words) more easily than others (i.e., low density and low frequency words). This may inform teachers and clinicians working with this population of the types of words that will be easy or difficulty to learn, helping teachers and clinicians identify words that are likely to need more extensive practice and direct instruction. In addition, this study provides indirect evidence regarding which stage of spoken word learning (i.e., triggering) children with CIs have difficulty with. Thus, teachers and clinicians may want to consider how to overtly highlight new vocabulary words to facilitate triggering. For example, the finding of Pittman and Schuett (2013) may be informative to teachers and clinicians. Pittman and Schuett (2013) found that children with mild to moderately severe hearing loss were better able to identify nonwords in the meaningful sentences than in the nonsense sentences. This finding implies that semantic context helps children with mild to moderately severe hearing loss recognize a word as novel or known, facilitating triggering of word learning. The benefit of semantic context to children with CIs is open to future research.

Limitations and Future Directions

One limitation of the current study is that it investigated the outcomes of spoken word learning, and did not observe the spoken word learning process itself. Thus, any inferences about how spoken word learning processes are affected by CI use are necessarily tentative. Future direct investigation of the spoken word learning process in children with CIs will be necessary to validate the hypotheses that (1) children with CIs have a problem with using a phonotactic probability cue, resulting in a difficulty in triggering of spoken word learning; and (2) density influences configuration and/or engagement by children with CIs in a manner similar to normal hearing children.

Another issue is that our phonotactic probability and neighborhood density computations were based on the adult target pronunciation. Yet there is no direct evidence concerning the nature of lexical representation in the participating children. In general, there is controversy over how children represent spoken words in long-term memory: are the child's lexical representations based on the adult-target production (e.g., Dinnsen, 2002;

Dinnsen, O'Connor, & Gierut, 2001; Storkel, 2004b) or are the child's lexical representations based on the child's production (e.g., Macken, 1980; Maxwell, 1984)? These two theories are dichotomous in nature, but a child's lexical representation could exist on any point along this continuum (Storkel, Maekawa, & Aschenbrenner, 2013). Future research is necessary to investigate the nature of lexical representation in children with CIs to determine whether computations based on adult targets are appropriate for this group.

In addition, further exploration of how age of implantation might affect the role of phonotactic probability and word length in word learning is needed. The participants in this study would be considered later implanted given that most children today are implanted at about 12 months of age. Thus, the effects of phonotactic probability and word length in the earlier implanted children is open to future research.

Lastly, it is noted that in the original study (Yoshinaga-Itano et al., 2010), 70% of eligible children in the state of Colorado participated in the study. This is an extremely high proportion of success in recruitment. Yet the absolute number of children was still relatively small, as expected, given the prevalence of hearing loss and CI intervention. In general, this is a major challenge in studying this population. In addition, since children were drawn from a single state with a consistent treatment protocol for children receiving CIs (see Yoshinaga-Itano, 2003), the variation in language outcomes may have been more limited than in a sample with wider variation in treatment. Future research with a larger and more diverse sample would be useful in determine how robust the current findings are. Specifically, larger individual differences might be observed with a more diverse sample.

Conclusion

The investigation of the words known by children with CIs reveals that children with CIs show no effect of phonotactic probability, possibly indicating a lack of sensitivity to phonological information and/or a problem identifying which spoken words need to be learned. Likewise, children with CIs show no effect of spoken word length, possibly implying a lack of sensitivity to spoken word length information due to delayed or impaired working memory development. In contrast, children with CIs show strong and robust effects of neighborhood density, suggesting that spoken word similarity influences spoken word learning in a manner similar to normal hearing children, even though perceptual information continues to be degraded. Likewise, spoken word frequency was a robust predictor of spoken word learning, especially immediately following implantation, similar to normal hearing children. Overall, a striking number of similarities were observed in the effects of neighborhood density and word frequency between children with CIs and normal hearing children. The clear differences were the absence of the effect of the phonological variable of phonotactic probability and the absence of the effect of word length.

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Table 1

Hearing Information

Group		Child	Degree of HL	Type of HL	Age of ID (months)	Age of Intervention (months)	Age of HA (months)	Age of CI activation (months)	Duration of CI use (months)
Gap Closer		1	Severe	Unknown	2[b]	3	3	18	54
		2	Severe	Sensorineural	0.5	5	2	21	48
		3	Profound	Sensorineural	0.5	0.75	2	22	62
		4	Severe	Sensorineural	24	27	26	49	36
		5	Severe to Profound	Unknown	15	16	16	59	25
			Group mean		9	11.35	10.4	33.8	45
Age Equivalent		6	Severe	Sensorineural	1.5	2	2	28	54
		7	Profound	Sensorineural	1	1	2	29	56
		8	Profound	Sensorineural	1.25	2	2	32	51
		9	Severe	Mixed	21	23	23	40	44
		10[*]	Moderate to Severe	Sensorineural	0.75	2	2	60	23
			Group mean		4.95	5.8	5.9	37.8	45.6
Delayed	above 10th percentile	11[*]	Severe to Profound	Unknown	16	18	17	35	49
		12	Profound	Unknown	6	10	10	64	19
	below 10th percentile	13[*]	Profound	Unknown	2	3	5	16	69
		14[*]	Severe	Unknown	27	28	28	33	51

Group mean	12.75	14.75	15.25	37	47
Overall mean	8.62	10.34	10.18	36.14	54

* : received CI in the other ear before the last test point

HL: hearing loss; ID: identification with HL; HA: hearing aid; CI: cochlear implant

Table 2

Test Points and Language Outcome Measures

Group		Child	Test Point*			
			Pre-CI	Post-CI		Latest Post-CI
			Language Outcome Measure			
Gap Closer		1	CDI-I	CDI-II	EOWPVT-3	EOWPVT-3
		2	CDI-I	CDI-II	EOWPVT-3	EOWPVT-3
		3	CDI-II	CDI-II		EOWPVT-3
		4	CDI-II		EOWPVT-3	EOWPVT-3
		5	CDI-III		EOWPVT-3	EOWPVT-3
Age Equivalent		6	CDI-I		EOWPVT-3	EOWPVT-3
		7	CDI-I	CDI-II	EOWPVT-3	EOWPVT-3
		8	CDI-II	CDI-II		EOWPVT-3
		9	CDI-I	CDI-II		EOWPVT-3
		10	EOWPVT-3		EOWPVT-3	EOWPVT-3
Delayed	above 10th percentile	11	CDI-II	CDI-III	EOWPVT-3	EOWPVT-3
		12	CDI-II		EOWPVT-3	EOWPVT-3
	below 10th percentile	13	CDI-I	CDI-I		EOWPVT-3
		14	CDI-I	CDI-II	EOWPVT-3	EOWPVT-3

CDI-I, II, III: The MacArthur Communicative Development Inventories-I, II, III

EOWPVT-3: Expressive One-Word Picture Vocabulary Test-3

*: The time difference between pre-CI and post-CI was approximately two years; the time difference between post-CI and latest post-CI was approximately three year.

Table 3

Parameter estimates of generalized linear mixed modeling

Parameter	Estimate	*SE*	LCL	UCL	*OR*	*F*	*p*
Intercept	0.75	1.33	-1.85	3.36			
Length (L)	-0.12	0.27	-0.64	0.40	0.89	0.44	.51
Frequency (F)	0.95	0.25	0.46	1.44	2.59	15.22	<.001
PPS (S)	0.13	0.24	-0.35	0.61	1.14	0.08	.78
PPB (B)	-0.20	0.23	-0.65	0.24	0.82	2.61	.11
ND	0.54	0.26	0.03	1.05	1.71	6.48	.01
Group (G)						2.00	.11
Gap Closer (G1)	1.60	1.56	-1.46	4.67	4.98		
Age Equivalent (G2)	2.35	1.56	-0.71	5.42	10.51		
Delayed: >10th percentile (G3)	0.14	1.86	-3.51	3.78	1.14		
Time (T)						294.63	<.001
Pre-CI (T1)	-9.28	0.80	-10.85	-7.71	0.00		
Post-CI (T2)	-3.39	0.35	-4.07	-2.71	0.03		
G x T						44.96	<.001
G1, T1	3.57	0.82	1.97	5.17			
G1, T2	0.63	0.37	-0.10	1.35			
G2, T1	2.77	0.81	1.18	4.37			
G2, T2	1.46	0.38	0.72	2.20			
G3, T1	5.84	0.83	4.22	7.47			
G3, T2	1.55	0.45	0.67	2.43			
L x G						1.82	.14
L, G1	0.33	0.15	0.03	0.62			
L, G2	0.19	0.15	-0.10	0.49			
L, G3	0.18	0.19	-0.19	0.55			
F x G						0.53	.66
F, G1	-0.09	0.12	-0.32	0.15			
F, G2	-0.14	0.12	-0.37	0.09			
F, G3	-0.13	0.15	-0.43	0.17			
S x G						0.11	.95
S, G1	-0.08	0.14	-0.35	0.19			
S, G2	-0.06	0.14	-0.33	0.21			
S, G3	-0.08	0.17	-0.42	0.25			
B x G						0.09	.97
B, G1	0.07	0.14	-0.20	0.34			
B, G2	0.05	0.14	-0.22	0.31			
B, G3	0.04	0.17	-0.29	0.38			
ND x G						0.38	.77
ND, G1	0.13	0.15	-0.16	0.42			
ND, G2	0.07	0.15	-0.22	0.35			
ND, G3	0.03	0.18	-0.32	0.39			
L x T						0.69	.50
L, T1	-0.24	0.25	-0.73	0.25			
L, T2	-0.15	0.24	-0.61	0.32			
F x T						5.34	.01
*F*T1*	-0.77	0.24	-1.23	-0.30			
*F*T2*	-0.66	0.23	-1.11	-0.20			
S x T						0.33	.72
S, T1	-0.04	0.23	-0.49	0.42			
S, T2	-0.10	0.22	-0.53	0.32			
B x T						0.43	.65
B, T1	-0.05	0.21	-0.47	0.37			
B, T2	0.04	0.20	-0.36	0.43			
ND x T						1.95	.14
ND, T1	-0.49	0.25	-0.97	0.00			

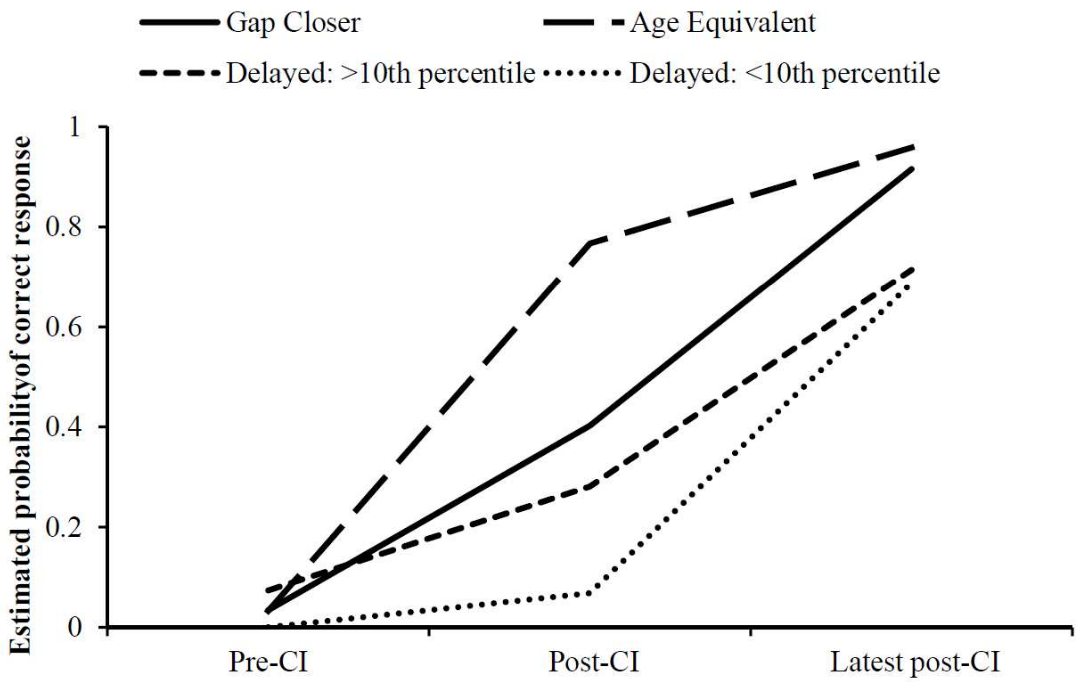
Parameter	Estimate	*SE*	LCL	UCL	*OR*	*F*	*p*
ND, T2	-0.41	0.23	-0.87	0.05			
Random variance components							
Participant intercept	3.32	1.50					
Word intercept	3.41	0.25					

SE: standard error; LCL: lower value of 95% confidence limits of the estimate; UCL: upper value of 95% confidence limits of the estimate; OR: odds ratio, CI: cochlear implant; PPS: phonotactic probability positional segment average; PPB: phonotactic probability biphone average; ND: neighborhood density

Figure 1. Group x time interaction. In the left panel, the mean expected probabilities of a correct response are presented for the four participant groups at Pre-CI, Post-CI, and Latest Post-CI. In the right panel, the mean expected probabilities of a correct response are presented for Pre-CI, Post-CI, and Latest Post-CI within each group. The error bars represent 95% confidence limits of the means.

Figure 2. Time x frequency interaction. The mean expected probabilities of a correct response are presented for Pre-CI, Post-CI, and Latest Post-CI over the word frequency values from -2 to +2. Each shaded area represents 95% confidence limits of the means for a time point.

(left panel)


Gap Closer
Age Equivalent
Delayed: >10th percentile
Delayed: <10th percentile
Estimated probabilityof correct response
1
0.8
0.6
0.4
0.2
0
Pre-CI
Post-CI
Latest post-CI

(right panel)

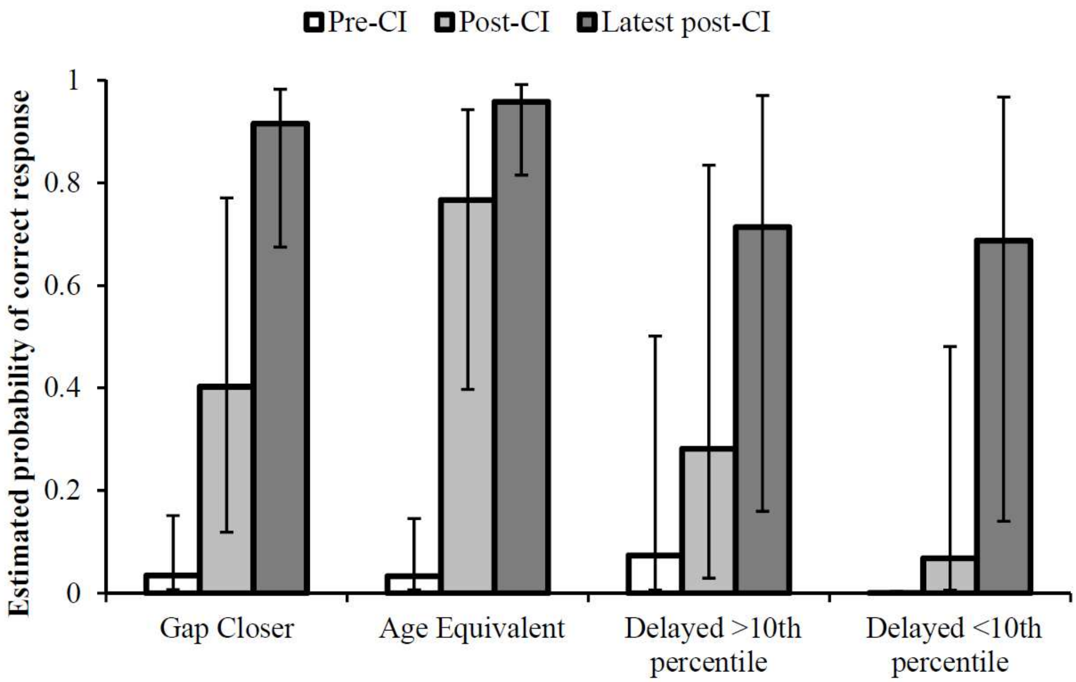


Figure 1. Group x time interaction.

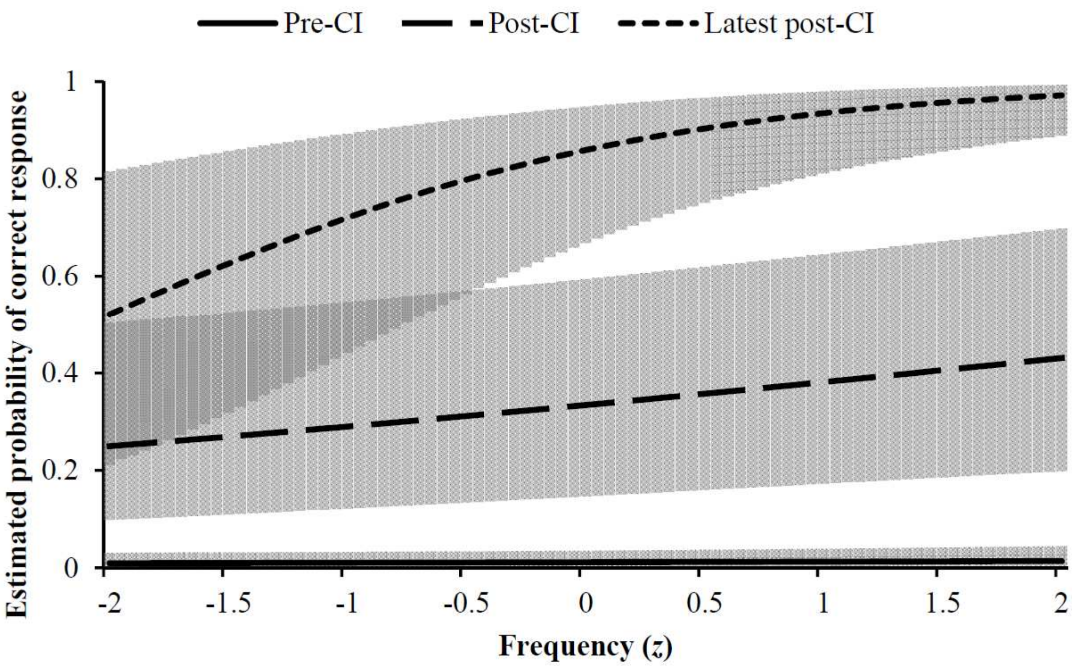


Figure 2. Time x frequency interaction.