Published in final edited form as:

Ear Hear. 2018 ; 39(5): 980–991. doi:10.1097/AUD.0000000000000560.

Word learning in children with cochlear implants: Examining performance relative to hearing peers and relations with age at implantation

Hannah Pimperton¹ and Elizabeth A. Walker²

¹University College London, Institute of Cognitive Neuroscience

²University of Iowa, Department of Communication Sciences and Disorders

Abstract

Objectives—This study had two key objectives. First, to examine whether children who receive cochlear implants (CIs) before the age of three years and who are experienced implant users (mean length of CI use = 6 years; range = 4 – 9 years) show deficits on a word learning task relative to their hearing peers. Second, to examine whether variation in age at implantation within the first three years of life relates to later word learning abilities.

Design—Twenty-one 6–10 year old children with CIs, 21 chronological age-matched (AM) hearing children and 21 vocabulary-matched (VM) hearing children completed an auditory word learning task in which they were required to learn the names of eight rare animals. Comprehension and production probes tested their learning of these unfamiliar words.

Results—The children with CIs performed similarly to age-matched peers on the comprehension phase of the word learning task. Their production performance was significantly poorer than the AM group, but was in line with that of their younger vocabulary-matched hearing peers. Differences between the CI and AM groups were accounted for by differences between the groups in terms of their existing vocabulary knowledge. Within the CI group there was no evidence of an association between age at implantation and performance on the word learning task, but existing vocabulary size showed strong positive correlations with word learning performance, after adjustment for chronological age.

Conclusions—When implanted by the age of three years, and with over four years CI experience, 6–10 year old children are able to perform similarly to their age-matched hearing peers in terms of their comprehension of newly learned words. Producing accurate phonological forms of newly learned words may be a more challenging task for children with CIs, but their production performance is consistent with their vocabulary size. This cross-sectional study provides support for a relationship between existing vocabulary size and novel word learning skills in children with CIs; future longitudinal studies should test the hypothesis that this relationship is developmentally reciprocal.

Address correspondence and reprints to: Elizabeth A. Walker, 250 Hawkins Drive, University of Iowa, Iowa City, IA 52252, 319-335-6851, elizabeth-walker@uiowa.edu.

Conflicts of Interest:

The authors have no conflicts of interest to declare.

INTRODUCTION

Spoken language acquisition requires access to acoustic-phonetic cues (Gómez 2002; Hart & Risley 1995; Hoff & Naigles 2002; Maye et al. 2002; Onnis et al. 2004; Rost & McMurray 2009). Children born with severe-to-profound hearing loss have minimal to no access to these acoustic-phonetic cues. This limited access to the sounds of speech has a substantial impact on their ability to acquire spoken language (Moeller et al. 2007). As a result, children who are deaf often show significant delays in their spoken language abilities relative to their hearing peers (Lederberg et al. 2013). The advent of cochlear implant (CI) technology has made it possible for these children to perceive speech and, in some cases, achieve language outcomes within the average range of their same-age peers with normal hearing (Geers et al. 2003; Nicholas & Geers 2007). CIs have become a well-accepted aural habilitation approach; however, we also see substantial variability in children's speech and language outcomes following implantation (Fagan et al. 2007; Sarant et al. 2015), with approximately 50% of children with CIs reported not to be achieving age-appropriate language skills by school entry (Geers et al. 2009). In the current study we use a dynamic word learning task to examine the underlying mechanisms associated with variability in spoken language development in children who use CIs.

Substantial research attention has been directed to identifying the factors associated with this variability in order to optimise outcomes for children following cochlear implantation (Boons et al. 2012; Duchesne et al. 2009; Geers et al. 2003; Svirsky et al. 2004). One factor that has consistently been identified as contributing to variability in language outcomes is the age at which the child's auditory nerve is first stimulated with the CI, commonly referred to as an age at implantation effect (Dunn et al. 2014; Holt & Svirsky 2008; Nicholas & Geers 2007). Researchers have suggested that age at implantation effects are the result of a 'sensitive period' of maximal plasticity of the central auditory system during early childhood (Sharma & Dorman 2006; Sharma et al. 2005; Sharma et al. 2002).

Researchers have employed various statistical methods to demonstrate the effect of age at implantation on speech and language outcomes, including growth curve analyses (Connor et al. 2006; Dettman et al. 2007; Niparko et al. 2010; Svirsky et al. 2004; Tomblin et al. 2005), group differences (Leigh et al. 2013; Nicholas & Geers 2013), and multiple regression analyses (Geers et al. 2008; Harrison et al. 2005; Nicholas & Geers 2007; Nicholas & Geers 2013). The majority of studies that have documented age at implantation effects on language outcomes have done so in children within the first few years following implantation. The question of whether these early advantages for earlier implanted children persist with longer duration of implant use has been less comprehensively addressed. Cross-sectional studies looking at the relationship between age at implantation and language outcomes in older children with longer duration of implant use have shown mixed findings (Geers et al. 2003; Geers & Nicholas 2013; Geers et al. 2008). Long-term longitudinal research utilizing growth curve analysis suggests that the influence of age at implantation on language outcomes may diminish over time (Dunn et al. 2014).

Although the statistical techniques used differ across the studies outlined above, they have been consistent in their use of end-point, standardized test measures as the dependent

variable (Pisoni 2000). These end-point measures (e.g., vocabulary tests) provide a static assessment of accumulated language knowledge and do not allow for an opportunity to test the mechanisms that underlie differences in language outcomes (i.e., they tell us where a child is at in terms of their language knowledge at a particular point in time but not how they got there). In the vocabulary domain, evidence from studies using dynamic word learning paradigms that assess children's ability to learn novel or unfamiliar words offer the opportunity to examine more directly the mechanisms that may underlie age at implantation effects.

Dynamic Word Learning Tasks

Compared to the many studies that have relied on standardized test measures as the dependent variable, a smaller number of studies have examined the online process of language learning in children with CIs. In the domain of word learning, such studies have used dynamic experimental paradigms that assess the ability of these children to efficiently pair novel words with their referents in real time, and have examined associations between performance on these paradigms and age at implantation (Davidson et al. 2014; Havy et al. 2013; Houston et al. 2012; Quittner et al. 2016; Tomblin et al. 2007; Walker & McGregor, 2013). By using novel or unfamiliar words, these experiments control for variations in language experience in a way that standardised vocabulary assessments do not.

Studies using these word learning paradigms have consistently demonstrated word learning deficits in children with CIs compared to their hearing peers. Havy et al. (2013) examined word learning abilities in 3–6 year old children with CIs. In their word learning paradigm, children were trained on two word-object pairings and then heard one of the two words and were required to pick the object that corresponded to that word. The children with CIs performed significantly less well than a comparison group of children with normal hearing (NH) on the task overall. Walker and McGregor (2013) used a didactic novel word learning procedure that assessed fast mapping and retention and compared children with CIs to age-matched and vocabulary-matched hearing groups. They found no significant fast mapping deficits for the CI group relative to their age-matched peers for comprehension or production, but significant deficits for the CI children relative to their age-matched peers in terms of both comprehension and production of the word-referent pairs following a delay of 1–3 days. The CI children did not show any comprehension or production deficits relative to the younger vocabulary-matched group, either in terms of fast mapping or retention, suggesting their word learning skills were in line with their vocabulary level.

Walker and McGregor (2013) and Havy et al. (2013) showed evidence of word learning deficits for toddlers and preschoolers with CIs relative to their age-matched hearing peers in explicit learning tasks. Other studies have employed incidental exposure paradigms, which may place greater demands on auditory/phonological processing and working memory abilities. Tomblin et al. (2007) used an incidental learning procedure to assess word learning in preschool-age children with CIs and NH. In this task, children were asked to hide a novel object that was paired with a novel word (“Hide the koob”). This procedure was repeated with two other novel word-referent pairs (“dat” and “sachoon”). The children with CIs did significantly poorer than their age-matched peers with NH on this task. Tomblin and

colleagues did not include a vocabulary-matched control group so it was not possible to determine whether the word learning deficits shown by the children with CIs were consistent with their extant vocabulary levels.

Davidson et al. (2014) examined older school-age children with CIs. Children were exposed to six novel words in the context of six successive animated stories. The children with CIs showed significantly lower novel word learning performance than their age-matched peers with NH. Taken together, previous findings indicate that children with CIs have difficulty learning words in both explicit and implicit learning contexts, relative to their same-age peers.

Age at Implantation Effects on Word Learning

While the advantage for hearing children over same-age children with CIs on word learning paradigms has been consistent across studies, the evidence to date regarding the relationship between age at implantation and word learning performance within the CI group has been more mixed. Tomblin et al. (2007) reported a significant negative relationship between fast mapping (learning the novel word-referent pairs after a single exposure) and age at implantation; earlier implanted children showed superior fast mapping skills compared to later implanted children. This relationship was no longer significant after partialling out duration of CI experience, suggesting that greater duration of word learning experience may have contributed to the beneficial effects of earlier implantation on novel word learning performance. Davidson et al. (2014) examined age at implantation effects on word learning in older children. In their sample of 6–12 year old children implanted between the ages of 10 months and five years, Davidson et al. found a significant negative relationship between age at implantation and performance on the novel word learning task, indicating superior word learning scores for the earlier implanted children. They did not test whether this relationship remained significant after adjusting for duration of CI experience, a variable which also showed a significant correlation with word learning performance. Finally, in a recent longitudinal study, Quittner et al. (2016) reported that children implanted prior to 2 years of age identified significantly more newly learned words on a novel word learning task than children implanted after 2 years of age, after controlling for duration of CI experience.

In Walker and McGregor's (2013) study with 3–6 year old children with CIs implanted between the ages of 1 and 3 years, they assessed age-at-implantation effects on word learning by conducting a multiple regression analysis, with chronological age, receptive vocabulary raw scores, and age at implantation as predictor variables and a total word learning score for retention as the outcome variable. After controlling for chronological age, only existing vocabulary size accounted for a significant proportion of the variance in word learning ability. Havy et al. (2013) examined relationships between age at implantation and performance on their word learning task in 3–6 year olds who were implanted between the ages of 9 months and four years. They also found no evidence of a relationship between age at implantation and performance. Instead they found a significant effect of duration of implant use on word learning performance. In sum, there have been mixed results regarding the association between age at implantation and later word learning ability. This may have resulted from variability in the range of age at implantation included in the studies, with

those studies where age at implantation range extended beyond the 3.5 year ‘sensitive period’ identified by Sharma and colleagues more likely to see age at implantation effects. Duration of implant use was consistently identified as having a relationship with word learning performance; variability in duration of use and whether it was adjusted for in analyses may also have contributed to differences in results between studies.

The Current Study

In the current study we capitalized on a dynamic word learning paradigm (Bishop & Hsu, 2015) to explore how word learning processes in 6–10 year old children with CIs compare to those of their hearing peers, and to examine relationships between word learning performance and age at implantation. Children with CIs were selected to have an age at implantation below 3.5 years to examine whether variability in age at implantation within this auditory sensitive period was associated with differences in word learning abilities. The 3.5 year cut-off is also within the timeframe in which the majority of children with congenital hearing loss now receive CIs (Ching et al. 2013; Lammers et al. 2015; Raine 2013). Based on the results of previous studies (e.g., Havy et al. 2013; Walker & McGregor 2013), we predicted that the children with CIs in this study would show word learning deficits relative to their age-matched hearing peers. A majority of these studies also found evidence of age at implantation effects on word learning across a range of ages, therefore we predicted that within the group of children with CIs age at implantation would relate to word learning ability. These studies also indicated that duration of implant use could be an important factor in word learning performance, therefore we examined the influence of this variable alongside age at implantation.

MATERIALS AND METHODS

Participants

Twenty-one children ($M = 8$ years, $SD = 22$ months) with CIs participated. To qualify for participation in this study, children were required to be between 6 and 10 years old, implanted within the established sensitive period for development of the central auditory system (i.e., < 3.5 years), and experienced CI users with at least four years of CI use. Of the 21 eligible children with CIs, 18 had bilateral CIs, one was bimodal (CI with hearing aid in contralateral ear) and two had a unilateral CI. Age at initial stimulation ranged from 10 to 31 months ($M = 16.24$, $SD = 5.85$). Duration of CI experience ranged from 57 to 119 months ($M = 80.57$, $SD = 21.09$). Pre-operative unaided thresholds were available for 18 out of 21 children (3 children had no-response auditory brainstem response test results or aided thresholds that suggested severe-to-profound hearing loss; however, unaided thresholds were not available). For the 18 children with pre-operative threshold data, the mean better-ear pure-tone average was 104.5 dB ($SD = 16.11$). Table 1 provides descriptive data regarding age at initial stimulation, duration of CI experience, and pre-operative hearing. All the children used spoken English as their primary mode of communication. Children with CIs were recruited from two pediatric cochlear implant centers in the United States (University of Iowa and Boys Town National Research Hospital).¹ After obtaining consent and acquiring additional information on audiological history, seven additional children with CIs were excluded from the study for the following reasons: pre-operative better-ear pure-tone

average of less than 80dB ($n = 2$), non-congenital hearing loss ($n = 4$), or implanted after 3.5 years ($n = 1$).

Fifty-two children with normal hearing also provided data for this study. From that pool of 52 children we selected 21 age-matched (AM) and 21 vocabulary-matched (VM) children to act as comparison groups for the 21 participating children with CIs. Each child with a CI was individually matched to one hearing child from the available pool that was closest in age (to form the AM group) and one that was closest in PPVT-4 raw score (to form the VM group). Children with normal hearing were recruited through word of mouth and a pre-existing database of children who had participated in previous studies and had agreed to be contacted for additional research.

Procedure

All study procedures were approved by the University of Iowa Institutional Review Board. Participants were administered the following measures via spoken English by a trained researcher.

Receptive vocabulary—Spoken vocabulary knowledge was assessed with the PPVT-4 (Dunn et al. 2007), a standardised measure of receptive vocabulary. In this assessment the examiner says a word that describes one of the pictures on a page, and the participant identifies the correct picture. A standard score of 100 represents average performance ($SD = 15$).

Non-verbal ability—The Matrix Reasoning subtest of the *Wechsler Abbreviated Scale of Intelligence – Second Edition* (WASI-2; Wechsler 2011) was used to assess non-verbal cognitive ability. This measure comprises a series of progressively more difficult pattern completion items; children are shown a pattern with a piece missing and must choose the correct piece from five possible alternatives. A t-score of 50 represents average performance ($SD = 10$).

Word learning Task—We used a word learning task presented via a computer and developed by Bishop and Hsu for use with children with Specific Language Impairment (Bishop & Hsu 2015; code to run task available at osf.io/xrmjk/) in which the children were required to learn the names of eight rare animals (phonetic transcriptions in parentheses): ayeaye (/aiai/), saki (/saki/), dugong (/dugɒŋ/), anole (/ənoʊl/), caiman (/keimən/), iwi (/iwi/), kyloe (/kailo/), jennet (/dʒenət/). Stress is produced on the first syllable for all words with the exception of “anole.” Bishop and Hsu selected unfamiliar word-referent pairs over novel word-referent pairs for this task because of ethical concerns regarding asking children with language delays to spend time learning words that were not real words. The selected animal names were all bisyllabic, low-frequency words with a duration between 650 and 1000ms. All words were presented through an auditory-only condition, with no written or speechreading cues. Figure 1 shows the design of the task.

¹One child previously participated in another word learning study (Walker & McGregor, 2013) 4.5 years prior to the current study. The stimuli and procedures were different between the two studies, and given the length of time between experiments, it seems unlikely that there would be any potential implications from participating in the two word learning studies.

Familiarisation Phase: Children completed two familiarisation trials at the beginning of the task, which used known vocabulary to familiarise them with the format of the comprehension trials. They heard a word (e.g., drum) and had to click on the corresponding picture from a choice of four, all of which were present on the screen at the same time (see Figure 1 for sample trial). The familiarisation phase was also used to adjust the volume of the stimuli to a comfortable listening level for the participants and ensure they could access the auditory stimuli.

Exposure Phase: After the familiarisation trials, the task began with an exposure phase in which the child saw a screen with pictures of all eight of the target animals presented simultaneously. The experimenter clicked on each animal in turn and it was highlighted with an arrow on the screen and the name of the animal was played twice consecutively (e.g., “anole, anole”) through the computer speakers. Thus, children heard each of the eight animal names paired with the corresponding picture before the next phase of the experiment (Comprehension Phase).

Comprehension phase: Following the exposure phase, children began the trials in which they heard an animal name (the target) and had to choose the corresponding picture from a choice of four: one target and three distractors from the set of eight animals, all of which were present on the screen at the same time (see Figure 1 for sample trial). If the child made an incorrect response, the selected picture disappeared and the child chose again. When they selected the correct response, they heard the name of the animal again and received a visual reward. The program then moved on to the next trial. As a result of this trial design, the name of the animal was always reinforced for each child in each trial, regardless of whether they were correct on the first attempt or not. The trial was scored as correct only if the child chose the correct response on the first attempt. Two options were available to participants to support their learning on the comprehension trials. First, there was a button that allowed the children to replay the word before making their choice. Second, there was a button that highlighted the correct answer if the children wanted help (i.e., rather than guessing if they did not know, they could press this button and be provided with the correct answer). If they used this ‘help’ button, the trial was scored as incorrect.

The participants completed four blocks of 24 comprehension trials and were exposed to each of the eight animal words in a pseudorandom order three times during each block. The first eight trials of Block 1 therefore assessed the ability of the participants to learn the new animal words after only a single exposure; the equivalent of ‘*fast-mapping*’. Participants had a break of 45–90 minutes between the first two blocks of the comprehension trials and the second two blocks of the comprehension trials (see Figure 1) which enabled us to assess whether the groups differed in their retention of the words over this period of time (as would be evidenced by an interaction between group and block). Standardised tests were administered during these breaks. The length of the break varied randomly, as it depended on various factors (e.g., how long it took for participants to take the standardised tests, additional testing at the CI visit, whether the child wanted to eat lunch or a snack).

Production phase: We modified Bishop and Hsu’s (2015) original task to include an additional production phase. After the children had completed the final block of the word

learning task they were shown a printed picture of each of the eight animals and asked to produce the corresponding phonological form of the animal names. They were encouraged to guess if they were not sure. Their responses were audiorecorded and scored offline. We used a strict scoring criteria in which children received a point for each animal name they produced correctly (all phonemes had to be correct for credit to be given), giving a maximum possible score of eight. Scores were also calculated based on the total number of phonemes correct across the eight items out of a maximum of 32 (16 vowels and 16 consonants).

Repetition phase: We also included a repetition phase after the production phase in order to examine whether any differences between the groups on the production phase could be driven by differences in their ability to articulate the words. The children saw and heard the experimenter say the name of each animal and simply had to repeat it back. As with the production task, they received a point for each animal name they produced correctly (all phonemes had to be correct for credit to be given), giving a maximum possible score of eight, and a total phonemes correct score out of a maximum of 32.

RESULTS

Descriptive Analyses for CI, AM, and VM Groups

Table 1 shows descriptive statistics for the three groups in terms of their age, vocabulary scores and non-verbal ability. The matching process resulted in very similar means on the matched variables (age for the CI and AM groups and vocabulary raw score for the CI and VM groups), but the variability for the CI group was higher than that of the VM group for PPVT raw score. Differences between the groups in demographic variables and outcome measures were analysed using independent-sample t-tests (with Welch's adjustments for unequal variances, when appropriate). There were no significant differences in chronological age between the CI and AM groups, $t(40) = .25$, $p = .80$. The CI group was significantly older than the VM group, $t(26.6) = 4.94$, $p < .001$. When comparing raw scores on the PPVT-4, the AM group showed significantly higher scores relative to the CI group, $t(40) = -3.16$, $p = .003$. There were no significant differences between the CI and VM groups on PPVT-4 raw scores, $t(40) = -.01$, $p = .99$.

With respect to PPVT-4 standard scores, the AM and VM groups showed significantly higher scores relative to the CI group ($t(40) = -4.24$, $p < .001$ and $t(40) = -4.84$, $p < .001$, respectively). However, it is also important to note that the average PPVT-4 standard scores are within the average range of the test norms for the CI group, albeit below the normative test mean of 100 ($M = 92.48$). In terms of non-verbal cognitive abilities relative to their age (WASI Matrix Reasoning t-scores), there were no significant differences between the CI and AM groups, $t(40) = -1.41$, $p = .17$. The VM demonstrated significantly higher scores on the WASI compared to the CI group, $t(40) = -2.87$, $p = .007$.

Word Learning Task Performance

Comprehension phase—Total scores on the comprehension phase for the three participant groups are shown in Table 2. Figure 2 plots the performance of the three

participant groups over the four blocks of the comprehension phase. The scores on the word learning task showed significant deviation from the normal distribution in block 4, with ceiling effects introducing a negative skew to the distribution. Therefore to examine differences between the performance of the CI, AM and VM groups across the four blocks of the word learning task, we followed Bishop and Hsu (2015)'s approach to address this lack of normality and used a bootstrap-t procedure to analyse the data using R (R Core Team 2015). In this statistical procedure, random samples are repeatedly drawn from the original data set (with replacement), with each sample providing an estimate of the mean and standard deviation. These estimates are then combined into a sampling distribution. In this case a bootstrap-t procedure using the R function "bwtrimb" (Wilcox 2012) was used with block (1 vs. 2 vs. 3 vs. 4) as a within-subjects factor and group (CI vs. VM vs. AM) as a between-subjects factor. The procedure was run with 1000 bootstrap repetitions with the alpha level set at .05 and means were trimmed by 5%. Results indicated a significant main effect of block ($p < .001$), with performance improving incrementally from block 1 through block 4 (see Figure 2). The main effect of group was not significant ($p = .42$). The interaction between block and group was also not significant ($p = .50$) suggesting that the groups were showing similar patterns of performance across the four blocks.

Scores on the first eight 'fast mapping' trials (i.e., the first eight trials of the Comprehension phase) which directly assessed the children's ability to recognise new words following only a single exposure are shown in Table 2. A one-way ANOVA with fast mapping score as the dependent variable showed a significant main effect of group ($F(2,62) = 4.93, p = .01, \eta^2 = .14$), and Bonferroni post-hoc tests indicated that the VM group showed significantly lower scores than the AM group ($p = .008, d = 0.89$). There were no significant differences between the fast mapping scores of the CI and AM groups ($p = .50, d = 0.47$) or between the CI and VM groups ($p = .27, d = 0.54$).

Production phase—The mean production scores (out of a possible 8) and the equivalent scores in terms of number of phonemes correct are shown in Table 2. The production words-correct and phonemes-correct scores were highly correlated ($r = .90, p < .001$), but more variability was possible within the phonemes-correct score. We therefore used the phonemes-correct score as the 'production score' for all subsequent analyses.

A one-way ANOVA indicated a significant difference between the groups in terms of production scores ($F(2,60) = 5.73, p = .005, \eta^2 = .16$), and Bonferroni post-hoc tests confirmed that the AM group showed significantly higher scores on the production task than the CI ($p = .02, d = 0.83$) and VM ($p = .01, d = 0.91$) groups. The CI and VM groups did not differ significantly from each other ($p = .99, d = 0.08$). To determine whether this group difference was accounted for by the differences in vocabulary between the groups, the effect of group was tested in an ANCOVA with PPVT raw score entered as a covariate. When adjusting for vocabulary, there was no longer a significant effect of group on production scores ($F(2,59) = 1.22, p = .30, \eta^2_p = 0.04$).

Repetition phase—One child with a CI did not complete the repetition task due to an administrative error, therefore results on this task are reported for 20 CI participants (Table 2). As with the production scores, the item and phoneme repetition scores were highly

correlated ($r = .93$, $p < .001$) and the phoneme scores are used to index 'repetition score' in all subsequent analyses. Only a very small number of repetition errors were made in each of the three participant groups, and an independent samples Kruskal-Wallis Test showed no significant differences between the groups in terms of their repetition scores ($\chi^2(2, N = 62) = 4.21$, $p = .12$), thus indicating that differences in the ability of the groups to articulate the target words were not driving the differences in production performance.

Relationships with Age at Implantation

To examine relationships within the CI group between age at implantation, performance on the different elements of the word learning task (fast-mapping, comprehension, production), and performance on the standardised vocabulary measure, we carried out bivariate correlations between these variables, as well as with duration of implant use, pre-operative hearing thresholds, age and non-verbal intelligence. These are reported in Table 3a. Due to deviation of variables from the normal distribution, bias corrected accelerated bootstrapped 95% confidence intervals (see Carpenter & Bithell 2000, for more detail) using 1000 bootstrap samples were also calculated. As the fast-mapping phase of the word learning task shares data with the comprehension phase (i.e., the fast-mapping phase is comprised of trials 1–8 of the comprehension phase) we recalculated the comprehension totals for trials 9–96 only to enable us to examine these as independent variables within the same analysis.

Age at implantation did not show significant correlations with any of the word learning measures or with PPVT raw or standard scores. It also showed no significant relationships with age, pre-operative unaided hearing thresholds, non-verbal intelligence or duration of implant use (Table 3). Duration of implant use, age and non-verbal intelligence raw scores all showed significant positive correlations with PPVT raw scores, and duration and non-verbal intelligence raw scores also correlated significantly with performance on the production phase of the word learning task. Therefore to examine whether any relationships between age at implantation and word learning were confounded by the effects of duration of implant use, age or non-verbal intelligence, we re-ran the bivariate correlations as partial correlations (Table 3b), adjusting for each of the three potential confounding variables in turn. In each case, the pattern of results was unchanged and the correlations between age at implantation and the word learning measures remained non-significant.

In the bivariate correlations, raw scores on the PPVT showed the most consistent relationships with word learning performance, with significant positive correlations between PPVT scores and all three elements of the word learning task (comprehension, production and fast mapping; see Table 3a). To examine whether these relationships between PPVT and word learning were confounded by the effects of duration of implant use, age or non-verbal intelligence, we re-ran the bivariate correlations as partial correlations, adjusting for each of the three potential confounding variables in turn (Table 3b). In each case, the correlations between PPVT and the word learning measures remained significant.

To set the findings for the CI group in context, relationships between word learning performance, vocabulary, age and non-verbal intelligence were also examined for the hearing participants and bivariate correlations are shown in Table 4a. PPVT raw scores were significantly positively correlated with performance on all elements of the word learning

task. Age and non-verbal intelligence showed significant positive correlations with word learning performance and also with PPVT raw scores, therefore the relationships between word learning scores and PPVT raw scores were re-examined in partial correlations adjusting for the potentially confounding variables of age and non-verbal intelligence (Table 4b). These relationships all remained significant with the exception of the relationship between PPVT raw score and performance on the production element of the word learning task, which was no longer significant ($p = .09$) after adjustment for chronological age.

DISCUSSION

This study examined performance on a word learning task in a group of children with CIs and two groups of hearing children, one matched on chronological age and one matched on vocabulary age. The first prediction that this study tested was that 6–10 year old children with CIs implanted before three years of age would show significant word learning deficits relative to their hearing peers. We found that, in contrast to this prediction, their performance was not significantly different from hearing children of the same chronological age in terms of both the fast mapping score (comprehension after a single exposure) and total score on this comprehension component of the word learning paradigm. The children with CIs did, however, do significantly less well than the age-matched hearing group on the production component of the task (a more challenging task which required them to view a picture of the target and produce the corresponding phonological label for it). Although the performance of the CI group on the production task was below that of their age-matched hearing peers, it was in line with that of younger vocabulary-matched children.

The current findings add to the small but growing literature on word learning in children with CIs. Unlike previous studies (Tomblin et al. 2009), our data suggested that comprehension performance in children with CIs did not differ significantly from that of their age-matched hearing peers in an auditory-only word learning task. These results are consistent with the findings of Walker and McGregor (2013), in which early school-age children with CIs (3.5 to 6.75 year olds) did not show statistically significant differences in fast mapping comprehension compared to age-matched peers. These data paint a positive picture of the resilience of the children with CIs to the effects of missing out on early word learning experiences, as well as receiving impoverished phonological information via their CIs. In keeping with this, their mean PPVT standard score ($M = 92$) was within 1 SD of the standardization sample for the test, indicating mean performance that, while below the hearing average, was within the normal range. These results are theoretically consistent with studies that have demonstrated that, at a group level, vocabulary development in children with CIs keeps pace with the number of years of cochlear implant experience, but rarely catches up to age level. Thus, children with CIs may be able to acquire new words at comparable rates to their hearing peers, but are not able to compensate for missing out on early word learning opportunities (e.g., Thal et al. 2007; Fagan & Pisoni 2010; Holt et al. 2012). We observed wide variability in vocabulary standard scores for the CI group, with individual scores ranging from below average to above average, which is also consistent with previous research (Fagan et al. 2007; Geers et al. 2009; Sarant et al. 2015).

It is important to note that the children completed this experiment in a quiet room without the significant competing background noise which might characterise more typical situations in which they learn new words. Furthermore, the words in the current study were taught in isolation in an explicit learning task, as opposed to an implicit learning paradigm (Tomblin et al. 2007; Davidson et al. 2014). Implicit learning places greater demands on phonological processing and working memory skills, but may be more representative of how children learn words in the real world. Such word learning conditions are likely to be much more challenging for children with cochlear implants. One important clinical contribution of the current results is that they highlight the need for explicit vocabulary building interventions, which support the word learning process in more optimal environments.

The high level of performance shown by the CI group in the repetition task, when provided with a live model, suggests that the production deficit relative to their age-matched peers was unlikely to have been driven by the children with CIs being unable to articulate the phonological forms of the target words. Instead, the observed pattern of results on the comprehension and production tasks suggests that the children with CIs (as well as the younger, VM group) may have had access to enough phonological information about the target words to succeed at the comprehension task, but this information was not sufficiently well-specified to support the more challenging task of production of the word form. If the words included in the task had been less phonologically distinct (i.e., had required more distinct phonological representations to support comprehension), as was the case with the stimuli used by Havy et al. (2013) which were pairs of words separated by only a single phoneme, then it is possible that the CI group would have shown deficits relative to the AM group on the comprehension component of the task too. The locus of the poorer specification of the phonological forms of the words for the children with CIs compared to the AM group warrants further investigation to establish whether it takes effect at encoding, storage or retrieval of the phonological information, and whether this locus differs for the CI group compared to their younger vocabulary-matched peers.

The finding that children with CIs performed significantly less well than their AM peers but not their VM peers on the production element of the word learning task contrasts with the results from Walker and McGregor's (2013) study which showed no significant group difference in production scores between the CI, AM, and VM groups at the first test visit. However, the lack of significant differences in that earlier study was likely driven by floor effects on the task. Follow-up testing 1 to 3 days later revealed a similar pattern to the current results, in that the CI group performed similarly the VM group and significantly worse compared to the AM group. These results suggest that having a more diverse lexicon may support lexical acquisition, a possibility we discuss further below in the context of associations between word learning ability and extant vocabulary knowledge within the CI group.

The second prediction that this study tested was that age at implantation would show an association with word learning performance in the group of children with CIs. Our data did not support the prediction that age at implantation relates to word learning ability in children implanted within a relatively restricted early window (< 3 years). First, we found no significant relationships between age at implantation and performance on a standardised

vocabulary task (the PPVT). This finding is consistent with the longitudinal findings of Dunn et al. (2014), which indicated that children implanted between 2 and 3.9 years of age showed no significant differences in receptive language performance compared to their earlier implanted peers by the time they were 8 years old. By contrast, we did find strong and significant correlations between both chronological age and duration of implant use and PPVT raw scores, indicating that duration of word learning experience may be important in determining vocabulary size, as would be expected.

In line with the lack of detectable relationship between age at implantation and performance on the standardized vocabulary test, we also found no significant relationships between age at implantation and performance on any elements of the word learning task in this sample. The variables of duration of implant use, age and non-verbal ability all varied substantially within the group of children with CIs and the bivariate correlations indicated significant relationships between these variables and some elements of word learning performance. For this reason, partial correlations were conducted to examine the relationships between age at implantation and word learning after adjusting for each of these potentially confounding variables. The age at implantation-word learning relationships remained non-significant after adjusting for the age, duration of implant use and non-verbal ability. It is important to be cautious in interpreting these negative finding in terms of implying an absence of relationship, especially given the relatively small sample size that inevitably leads to wide confidence intervals on the correlations; replication of these results in larger samples will be an important next step.

The findings regarding a lack of detectable age at implantation effect on word learning are consistent with those of Walker and McGregor (2013) and Havy et al. (2013), both of which found no evidence of a relationship between age at implantation and word learning performance in 3–6 year old children. However, our findings are inconsistent with those of word learning studies with similar sample sizes but with younger children and less experienced CI users (Houston et al., 2012; Tomblin et al., 2007), which found evidence of a relationship between age at implantation and word learning efficiency. It may be the case that age at implantation effects on word learning are most readily observable in the first two or three years immediately following implantation, as suggested in the studies by Houston et al. and Tomblin et al.

It is important to note that Davidson et al. (2014) included children of a similar age range to the current study, the majority of whom were experienced CI users, and did find a relationship between age at implantation and word learning performance. Differences between the two studies in terms of the range of ages at implantation included may account for these discrepant findings. All the children in this study received their CI < 3.5 years, within the period of maximal plasticity of the central auditory system development identified by Sharma and colleagues (Sharma & Dorman 2006; Sharma et al. 2005; Sharma et al. 2002). The same was true for all the children in the Walker and McGregor (2013) study and for all but two of the children in the Havy et al. (2013) study, both of which found no evidence of age at implantation effects on novel word learning performance. By contrast, Davidson et al. included a wider range of age at implantation, with the latest implanted children receiving their implants at five years old. The same was true in the Quittner et al.

(2016) study, with age of implantation ranging from 7 months to 5 years in those children. Thus it may be the case that age at implantation effects on word learning are more easily detectable when the range of ages spans beyond 3.5 years. It is possible that if there had been children implanted at these later ages included in the present study, we would have seen a detrimental impact of later age at implantation on word learning efficiency at 6–10 years and > 4 years after implantation.

In the present study existing vocabulary size, as indicated by PPVT raw scores, showed a significant relation with performance on each of the three elements of the novel word learning task. These relationships remained significant after adjusting for the potential confounding effects of age, duration of implant use and non-verbal intelligence. This finding is consistent with that of Walker and McGregor (2013) in slightly younger children with CIs, as well as with our group comparisons, which indicated that differences between the CI group and their age-matched hearing peers were accounted for by vocabulary differences (i.e., when vocabulary score was adjusted for, the group difference was no longer significant). The importance of existing vocabulary and oral language knowledge in predicting word learning performance was also clear from the study of Quittner et al. (2016) who found a strong positive relationship between the two variables. We also saw significant relationships between existing vocabulary size and word learning performance in the group of hearing children who participated in this study, with these relationships surviving adjustment for chronological age for fast mapping and comprehension performance, though not for production performance.

The cross-sectional nature of the present study does not allow us to disentangle the directionality of the relationship between vocabulary size and word learning ability. Better word learning skills and faster information-processing abilities clearly support the development of a larger vocabulary (Fernald & Marchman 2012; Fernald et al. 2006; Marchman & Fernald 2008). However, it is also possible that a larger extant vocabulary size facilitates the learning of new words and that this relationship is a reciprocal one (see Walker and McGregor [2013] for discussion). It is also likely that the strength of the relationship may be influenced by third factors which act to drive both vocabulary size and word learning performance. One factor is quality and complexity of parental linguistic input and maternal sensitivity (Quittner et al. 2016; Szagun & Schramm 2015; Szagun & Stumper 2012). Another possible moderating factor for children with CIs is aided hearing prior to implantation. Pre-implant aided hearing can be measured with hearing aids in two ways: the aided Speech Intelligibility Index (SII) and aided sound field PTA. We did not have aided SII data for any of the participants, and we only had aided PTAs for 8 participants; therefore, we were unable to examine the potential contributions of early acoustic experience on word learning. Future research examining the role of these variables in predicting word learning would be informative.

The finding that age at implantation was not significantly related to word learning outcomes in this study does not diminish the importance of early implantation. Earlier implantation maximises the amount of time available to the child to be exposed to and learn language. In combination with high quality language input, earlier implantation is likely to result in the best possible outcomes for children with severe-profound hearing loss.

Conclusions

The results of this study showed that 6–10 year old children implanted before three years of age were able to perform comparably to their age-matched hearing peers on the comprehension component of a word learning task, suggesting that word learning in the receptive domain is a relative strength for these children, compared to production skills. Children with CIs performed more poorly on the production component of the word learning task compared to the AM group; however, their performance on the production component was in line with that of their younger vocabulary-matched hearing peers, potentially implicating a role for extant lexicon size in the production of newly learned words.

Within the CI group, we found no evidence for a relationship between age at implantation and performance on any of the components of the word learning task, but duration of CI use related to word learning production. Extant vocabulary size showed strong and significant relationships with word learning comprehension and production, including after adjustment for chronological age, duration of CI use and non-verbal intelligence. The lack of a detectable relationship between age at implantation and the ability to learn new words in the present study compared to previous studies may have been driven by differences between studies in the age range, duration of CI use, or range of age at implantation of the participants or in the type of task used. A combination of early implantation and high quality language input is likely to offer a child with a CI the best chance of optimising their spoken language development.

Acknowledgments

This work was supported by grants from the National Institutes of Health NIH-NIDCD (P50 DC000242; principal investigator, Bruce J. Gantz), the British Academy Leverhulme Fund (SG131650; principal investigator, Hannah Pimperton), the Experimental Psychology Society (Study Visit Grant), and the University of Iowa Obermann Center for Advanced Studies (Interdisciplinary Research Grant). The content of this project is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute on Deafness and Other Communication Disorders or the National Institutes of Health. The following people provided support, assistance, and feedback at various points in the project: Jacob Oleson, Marcia St. Clair, Camille Dunn, J. Bruce Tomblin, Dorothy Bishop, Julie Hsu, Kelsey Klein, Margaret Dallapiazza, and Marlea O'Brien. Special thanks go to the families and children who participated in the research.

Source of Funding:

The authors had full editorial control of this work and manuscript.

References

- Bishop DVM, Hsu HJ. The declarative system in children with specific language impairment: a comparison of meaningful and meaningless auditory-visual paired associate learning. *BMC Psychology*. 2015; 3:3–15. [PubMed: 25780564]
- Boons T, Brokx JPL, Dhooge I, et al. Predictors of Spoken Language Development Following Pediatric Cochlear Implantation. *Ear and Hearing*. 2012; 33:627–639.
- Carpenter J, Bithell J. Bootstrap confidence intervals: when, which, what? A practical guide for medical statisticians. *Statistics in Medicine*. 2000; 19:1141–1164. [PubMed: 10797513]
- Ching TY, Dillon H, Marnane V, et al. Outcomes of early- and late-identified children at 3 years of age: findings from a prospective population-based study. *Ear and Hearing*. 2013; 34:535–552. [PubMed: 23462376]

- Connor CM, Craig HK, Raudenbush SW, et al. The age at which young deaf children receive cochlear implants and their vocabulary and speech-production growth: is there an added value for early implantation? *Ear and Hearing*. 2006; 27:628–644. [PubMed: 17086075]
- Davidson LS, Geers AE, Nicholas JG. The effects of audibility and novel word learning ability on vocabulary level in children with cochlear implants. *Cochlear Implants International*. 2014; 15:211–221. [PubMed: 23998324]
- Dettman SJ, Pinder D, Briggs RJ, et al. Communication development in children who receive the cochlear implant younger than 12 months: risks versus benefits. *Ear and Hearing*. 2007; 28:11S–18S. [PubMed: 17496638]
- Duchesne L, Sutton A, Bergeron F. Language achievement in children who received cochlear implants between 1 and 2 years of age: Group trends and individual patterns. *Journal of Deaf Studies and Deaf Education*. 2009; 14:465–485. [PubMed: 19461113]
- Dunn CC, Walker EA, Oleson J, et al. Longitudinal speech perception and language performance in pediatric cochlear implant users: the effect of age at implantation. *Ear and Hearing*. 2014; 35:148–160. [PubMed: 24231628]
- Dunn LM, Dunn DM. *Peabody Picture Vocabulary Test*. Fourth. Minneapolis, MN: Pearson Education Inc.; 2007.
- Fagan MK, Pisoni DB. Hearing experience and receptive vocabulary development in deaf children with cochlear implants. *Journal of Deaf Studies and Deaf Education*. 2010; 15(2):149–161. [PubMed: 20130017]
- Fagan MK, Pisoni DB, Horn DL, et al. Neuropsychological correlates of vocabulary, reading, and working memory in deaf children with cochlear implants. *Journal of Deaf Studies and Deaf Education*. 2007; 12:461–471. [PubMed: 17556732]
- Fernald A, Marchman VA. Individual differences in lexical processing at 18 months predict vocabulary growth in typically developing and late-talking toddlers. *Child Development*. 2012; 83(1):203–222. [PubMed: 22172209]
- Fernald A, Perfors A, Marchman VA. Picking up speed in understanding: Speech processing efficiency and vocabulary growth across the 2nd year. *Developmental Psychology*. 2006; 42(1):98–116. [PubMed: 16420121]
- Geers A, Brenner C, Davidson L. Factors associated with development of speech perception skills in children implanted by age five. *Ear and Hearing*. 2003; 24:24S–35S. [PubMed: 12612478]
- Geers A, Tobey E, Moog J, et al. Long-term outcomes of cochlear implantation in the preschool years: From elementary grades to high school. *International Journal of Audiology*. 2008; 47:S21–S30. [PubMed: 19012109]
- Geers AE, Moog JS, Biedenstein J, et al. Spoken language scores of children using cochlear implants compared to hearing age-mates at school entry. *Journal of Deaf Studies and Deaf Education*. 2009; 14:371–385. [PubMed: 19155289]
- Geers AE, Nicholas JG. Enduring advantages of early cochlear implantation for spoken language development. *Journal of Speech, Language, and Hearing Research*. 2013; 56:643–655.
- Geers AE, Nicholas JG, Moog JS. Estimating the Influence of Cochlear Implantation on Language Development in Children. *Audiological Medicine*. 2007; 5:262–273. [PubMed: 21243079]
- Geers AE, Nicholas JG, Sedey AL. Language skills of children with early cochlear implantation. *Ear and Hearing*. 2003; 24:46S–58S. [PubMed: 12612480]
- Gómez RL. Variability and detection of invariant structure. *Psychological Science*. 2002; 13:431–436. [PubMed: 12219809]
- Harrison RV, Gordon KA, Mount RJ. Is there a critical period for cochlear implantation in congenitally deaf children? Analyses of hearing and speech perception performance after implantation. *Developmental Psychobiology*. 2005; 46:252–261. [PubMed: 15772969]
- Hart B, Risley TR. *Meaningful differences in the everyday experience of young American children*. Paul H Brookes Publishing; 1995.
- Havy M, Nazzi T, Bertoni J. Phonetic processing during the acquisition of new words in 3-to-6-year-old French-speaking deaf children with cochlear implants. *Journal of Communication Disorders*. 2013; 46:181–192. [PubMed: 23295076]

- Hoff E, Naigles L. How children use input to acquire a lexicon. *Child Development*. 2002; 73:418–433. [PubMed: 11949900]
- Holt RF, Beer J, Kronenberger WG, Pisoni DB, Lalonde K. Contribution of family environment to pediatric cochlear implant users' speech and language outcomes: some preliminary findings. *Journal of Speech, Language, and Hearing Research*. 2012; 55(3):848–864.
- Holt RF, Svirsky MA. An exploratory look at pediatric cochlear implantation: is earliest always best? *Ear and Hearing*. 2008; 29:492–511. [PubMed: 18382374]
- Houston DM, Stewart J, Moberly A, et al. Word learning in deaf children with cochlear implants: effects of early auditory experience. *Developmental Science*. 2012; 15:448–461. [PubMed: 22490184]
- Lammers MJW, Jansen TTG, Grolman W, et al. The influence of newborn hearing screening on the age at cochlear implantation in children. *The Laryngoscope*. 2015; 125:985–990. [PubMed: 25676285]
- Lederberg AR, Schick B, Spencer PE. Language and literacy development of deaf and hard-of-hearing children: successes and challenges. *Developmental Psychology*. 2013; 49:15–30. [PubMed: 22845829]
- Leigh J, Dettman S, Dowell R, et al. Communication development in children who receive a cochlear implant by 12 months of age. *Otology & Neurotology*. 2013; 34:443–450. [PubMed: 23442570]
- Marchman VA, Fernald A. Speed of word recognition and vocabulary knowledge in infancy predict cognitive and language outcomes in later childhood. *Developmental Science*. 2008; 11(3):F9–F16. [PubMed: 18466367]
- Maye J, Werker JF, Gerken L. Infant sensitivity to distributional information can affect phonetic discrimination. *Cognition*. 2002; 82:B101–B111. [PubMed: 11747867]
- Moeller MP, Tomblin JB, Yoshinaga-Itano C, et al. Current state of knowledge: Language and literacy of children with hearing impairment. *Ear and Hearing*. 2007; 28:740–753. [PubMed: 17982362]
- Nicholas JG, Geers AE. Will they catch up? The role of age at cochlear implantation in the spoken language development of children with severe to profound hearing loss. *Journal of Speech, Language, and Hearing Research*. 2007; 50:1048–1062.
- Nicholas JG, Geers AE. Spoken language benefits of extending cochlear implant candidacy below 12 months of age. *Otology and Neurotology*. 2013; 34:532–538. [PubMed: 23478647]
- Niparko JK, Tobey EA, Thal DJ, et al. Spoken language development in children following cochlear implantation. *JAMA*. 2010; 303:1498–1506. [PubMed: 20407059]
- Onnis L, Monaghan P, Christiansen MH, et al. Variability is the spice of learning, and a crucial ingredient for detecting and generalizing in nonadjacent dependencies. *Proceedings of the 26th annual conference of the Cognitive Science Society*; Lawrence Erlbaum; Mahwah, NJ. 2004. 1047–1052.
- Pisoni DB. Cognitive factors and cochlear implants: Some thoughts on perception, learning, and memory in speech perception. *Ear and Hearing*. 2000; 21:70–78. [PubMed: 10708075]
- Quittner AL, Cejas I, Wang N-Y, et al. Symbolic Play and Novel Noun Learning in Deaf and Hearing Children: Longitudinal Effects of Access to Sound on Early Precursors of Language. *PLoS ONE*. 2016; 11:e0155964. [PubMed: 27228032]
- R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2015.
- Raine C. Cochlear implants in the United Kingdom: awareness and utilization. *Cochlear Implants International*. 2013; 14:S32–S37.
- Rost GC, McMurray B. Speaker variability augments phonological processing in early word learning. *Developmental Science*. 2009; 12:339–349. [PubMed: 19143806]
- Sarant JZ, Harris DC, Bennet LA. Academic Outcomes for School-Aged Children With Severe–Profound Hearing Loss and Early Unilateral and Bilateral Cochlear Implants. *Journal of Speech, Language, and Hearing Research*. 2015:1–16. [PubMed: 25749240]
- Sharma A, Dorman M. Central auditory development in children with cochlear implants: clinical implications. *Advances in Oto-Rhino-Laryngology*. 2006; 64:66–88. [PubMed: 16891837]

- Sharma A, Dorman MF, Kral A. The influence of a sensitive period on central auditory development in children with unilateral and bilateral cochlear implants. *Hearing Research*. 2005; 203:134–143. [PubMed: 15855038]
- Sharma A, Dorman MF, Spahr AJ. A sensitive period for the development of the central auditory system in children with cochlear implants: implications for age of implantation. *Ear and Hearing*. 2002; 23:532–539. [PubMed: 12476090]
- Svirsky MA, Teoh S-W, Neuburger H. Development of language and speech perception in congenitally, profoundly deaf children as a function of age at cochlear implantation. *Audiology and Neurotology*. 2004; 9:224–233. [PubMed: 15205550]
- Szagun G, Schramm SA. Sources of variability in language development of children with cochlear implants: age at implantation, parental language, and early features of children's language construction. *Journal of Child Language*. 2015; 43:505–536. [PubMed: 26597734]
- Szagun G, Stumper B. Age or experience? The influence of age at implantation and social and linguistic environment on language development in children with cochlear implants. *Journal of Speech, Language, and Hearing Research*. 2012; 55:1640–1654.
- Thal D, DesJardin JL, Eisenberg LS. Validity of the MacArthur–Bates Communicative Development Inventories for measuring language abilities in children with cochlear implants. *American Journal of Speech-Language Pathology*. 2007; 16(1):54–64. [PubMed: 17329675]
- Tomblin JB, Barker BA, Hubbs S. Developmental constraints on language development in children with cochlear implants. *International Journal of Audiology*. 2007; 46:512–523. [PubMed: 17828667]
- Tomblin JB, Barker BA, Spencer LJ, et al. The effect of age at cochlear implant initial stimulation on expressive language growth in infants and toddlers. *Journal of Speech, Language, and Hearing Research*. 2005; 48:853–867.
- Walker EA, McGregor KK. Word learning processes in children with cochlear implants. *Journal of Speech, Language, and Hearing Research*. 2013; 56:375–387.
- Wechsler D. Wechsler Abbreviated Scale of Intelligence. Second. Minneapolis, MN: Pearson Education Inc.; 2011.
- Wilcox R. Introduction to Robust Estimation and Hypothesis Testing. 3. San Diego: Elsevier Academic Press Inc.; 2012.

Figure 1. Structure of word learning task and sample trials from the Familiarisation and Comprehension phases

Figure 2. Mean performance of the CI, AM, and VM groups across the four blocks of the Comprehension phase of the word learning task. Block 1 includes the fast mapping trials (trials 1 – 8). Error bars show ± 1 SEM

Table 1

Data for chronological age, age at CI initial stimulation, duration of CI experience, vocabulary standard and raw scores and matrix reasoning standard and raw scores for the CI, AM and VM groups.

	CI (N = 21)			AM (N = 21)			VM (N = 21)		
	M	SD	Range	M	SD	Range	M	SD	Range
Chronological age (months)	96.81	22.24	72–131	95.10	21.62	69–131	70.86	9.18	60–94
PPVT Standard Score ^a	92.48	15.80	55–130	112.67	15.08	73–132	112.71	10.85	83–126
PPVT Raw Score	115.95	31.28	38–170	143.05	23.79	87–180	116.05	21.61	71–158
WASI Matrix t-score ^b	44.43	8.10	33–62	48.14	8.99	21–61	51.14	7.03	40–65
WASI Matrix Raw Score	10.90	6.18	2–24	12.67	7.43	3–25	9.10	4.10	3–18
Age at CI (months)	16.24	5.85	10–31	N/A			N/A		
Duration of CI experience (months)	80.57	21.09	57–119	N/A			N/A		
Pre-operative better-ear PTA (dB HL) ^c	104.50	16.11	80–119	N/A			N/A		

Note. CI = Cochlear implant; AM = Age-matched; VM = Vocabulary-matched; PPVT = Peabody Picture Vocabulary Test-4; WASI = Wechsler Abbreviated Scales of Intelligence, PTA = pure-tone average.

^aThe normative mean for the PPVT standard score = 100, SD = 15

^bThe normative mean for the WASI Matrix Reasoning t-score = 50, SD = 10

^cBetter-ear pure-tone average was calculated using four frequencies for 12 children, three frequencies for three children, two frequencies for two children, and one frequency for one child. Unaided thresholds were unavailable for three children.

Table 2
Descriptive statistics for performance on the word learning task for the CI, AM and VM groups.

	CI (N = 21)		AM (N = 21)		VM (N = 21)	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Comprehension Total _(Trials 1–96)	61.67	18.49	68.76	20.04	61.57	16.75
Fast Mapping Total _(Trials 1–8)	3.86	1.53	4.67	1.91	2.86	2.13
Production Total Correct	2.57	1.47	4.14	2.01	2.76	1.55
Production Phonemes Correct	13.38	6.90	19.71	8.25	12.86	6.67
Repetition Total Correct	7.50	0.61	7.81	0.51	7.62	0.59
Repetition Phonemes Correct	31.45	0.69	31.81	0.51	31.57	0.81

Table 3

a: Bivariate correlations between demographic variables, standardised assessments and performance on the word learning task for the children with cochlear implants (N = 21).											
	1	2	3	4	5	6	7	8	9	10	11
1. Age											
2. WASI M raw score	.68 (.001) * [.37, .86]										
3. WASI M standard score	-.42 (.08) [-.78, .001]	.49 (.03) * [-.03, .75]									
4. Pre-operative PTA δ	-.07 (.79) [-.48, .35]	.001 (.99) [-.51, .47]	.15 (.55) [-.34, .65]								
5. Duration of implant use	.97 (<.001) * [.92, .99]	.73 (<.001) * [.44, .89]	-.32 (.20) [-.71, .11]	-.01 (.97) [-.48, .39]							
6. Age at implant	.32 (.15) [-.05, .73]	-.08 (.75) [-.34, .29]	-.45 (.06) [-.73, -.13]	-.21 (.40) [-.57, .10]	.06 (.79) [-.29, .53]						
7. PPVT raw score	.63 (.002) * [.37, .86]	.85 (<.001) * [.68, .94]	.36 (.11) [-.23, .72]	-.06 (.81) [-.50, .46]	.66 (.001) * [.37, .91]	.01 (.95) [-.26, .35]					
8. PPVT standard score	-.22 (.38) [-.60, .18]	.45 (.04) * [-.17, .73]	.77 (<.001) * [.41, .92]	.02 (.93) [-.38, .66]	-.14 (.57) [-.52, .21]	-.32 (.20) [-.72, .12]	.66 (.001) * [.24, .84]				
9. Fast mapping	.08 (.74) [-.49, .65]	.42 (.06) [-.07, .75]	.38 (.12) [-.20, .77]	-.27 (.28) [-.63, .20]	.10 (.66) [-.33, .50]	-.09 (.71) [-.40, .23]	.59 (.005) * [.11, .86]	.69 (.001) * [.24, .87]			
10. Comprehension total	.03 (.89) [-.38, .44]	.30 (.19) [-.13, .66]	.27 (.27) [-.34, .70]	-.26 (.29) [-.74, .31]	.02 (.93) [-.29, .34]	.06 (.81) [-.25, .40]	.45 (.04) * [-.02, .74]	.39 (.11) [-.15, .75]	.54 (.01) * [-.12, .80]		
11. Production total	.43 (.05) [.07, .75]	.52 (.02) * [.23, .80]	.08 (.77) [-.44, .45]	-.20 (.42) [-.64, .36]	.45 (.04) * [.14, .72]	.02 (.93) [-.29, .34]	.64 (.002) * [.35, .84]	.35 (.15) [-.15, .69]	.40 (.08) [-.02, .69]	.65 (.001) * [.33, .86]	

b: Partial correlations between age at implant and vocabulary scores and performance on the word learning task for the children with cochlear implants (N = 21).		
	Age at implant	PPVT raw scores
<i>Adjusted for chronological age</i>		
Fast mapping	-.12 (.62) [-.46, .25]	.42 (.001) * [.20, .61]
Comprehension total	.05 (.84) [-.25, .37]	.52 (<.001) * [.31, .68]
Production total	-.14 (.56) [-.47, .30]	.46 (<.001) * [.25, .62]

b: Partial correlations between age at implant and vocabulary scores and performance on the word learning task for the children with cochlear implants (N = 21).		
	Age at implant	PPVT raw scores
<i>Adjusted for duration of implant use</i>		
Fast mapping	-.09 (.70) [-.44, .30]	.70 (.001) * [.32, .89]
Comprehension total	.06 (.82) [-.27, .40]	.58 (.007) * [.25, .80]
Production total	-.01 (.97) [-.43, .45]	.51 (.02) * [.09, .78]
<i>Adjusted for WASI Matrices raw score</i>		
Fast mapping	-.06 (.80) [-.41, .27]	.35 (.005) * [.11, .58]
Comprehension total	.08 (.73) [-.22, .37]	.39 (.002) * [.14, .60]
Production total	.07 (.77) [-.34, .49]	.48 (<.001) * [.29, .65]

Note. Figures in round brackets show the corresponding *p* value for the correlation. Figures in square brackets show bias corrected accelerated bootstrapped 95% confidence intervals (1000 bootstrap samples). WASIM = Wechsler Abbreviated Scales of Intelligence, Matrix Reasoning; PPVT = Peabody Picture Vocabulary Test-4.

* = correlations significant at *p* < .05;

*g*_s = only available for *N* = 18 participants.

Note. Figures in round brackets show the corresponding *p* value for the correlation. Figures in square brackets show bias corrected accelerated bootstrapped 95% confidence intervals (1000 bootstrap samples). PPVT = Peabody Picture Vocabulary Test-4.

* = correlations significant at *p* < .05.

Table 4

a: Bivariate correlations between vocabulary and performance on the word learning task for the hearing children (N = 42)							
	1	2	3	4	5	6	7
1. Age							
2. WASI M raw score	.61 (<.001)* [.16, .85]						
3. WASI M standard score	-.21 (.18) [-.59, .19]	.63 (<.001)* [.47, .77]					
4. PPVT raw score	.71 (<.001)* [.42, .87]	.76 (<.001)* [.61, .87]	.25 (.12) [.01, .47]				
5. PPVT standard score	-.17 (.29) [-.51, .17]	.36 (.02)* [.13, .54]	.59 (<.001)* [.28, .77]	.56 (<.001)* [.38, .73]			
6. Fast mapping	.52 (<.001)* [.28, .69]	.44 (.003)* [.15, .67]	.06 (.72) [-.28, .48]	.57 (<.001)* [.28, .76]	.20 (.20) [-.15, .54]		
7. Comprehension total	.28 (.07) [-.07, .55]	.41 (.008)* [.08, .64]	.22 (.15) [-.02, .48]	.54 (<.001)* [.24, .75]	.47 (.002)* [.22, .52]	.70 (<.001)* [.52, .83]	
8. Production total	.49 (.001)* [.22, .68]	.31 (.048)* [-.03, .54]	-.12 (.45) [-.40, .21]	.51 (.001)* [.27, .68]	.16 (.31) [-.13, .44]	.57 (<.001)* [.30, .75]	.71 (<.001)* [.55, .82]

b: Partial correlations between vocabulary scores and performance on the word learning task for the hearing children (N = 42).

	PPVT raw scores
<i>Adjusted for chronological age</i>	
Fast mapping	.33 (.04)* [-.04, .65]
Comprehension total	.50 (.001)* [.22, .71]
Production total	.27 (.09) [.01, .49]
<i>Adjusted for WASI Matrices raw score</i>	
Fast mapping	.39 (.01)* [.03, .66]
Comprehension total	.39 (.01)* [.06, .67]
Production total	.45 (.003)* [.20, .67]

Note. Figures in round brackets show the corresponding *p* value for the correlation. Figures in square brackets show bias corrected accelerated bootstrapped 95% confidence intervals (1000 bootstrap samples). PPVT = Peabody Picture Vocabulary Test-4.

* = correlations significant at $p < .05$.